COMPRESSED AIR ILLNESS

DR. E. HUGH SNELL

With the Author's Compliments.

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OR

SO-CALLED CAISSON DISEASE

BY

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PREFACE.

No book has yet appeared in this country dealing with the subject of Compressed Air Illness; the only available publications treating on the question are foreign ones, and of these the most recent was founded on observations made more than a quarter of a century ago.

The London County Council, in appointing a medical officer to take charge solely of the compressed air work carried on at the Blackwall Tunnel, and in obtaining powers to compensate men injured by the compressed air, has gone out of its way to meet the dangers incurred by the workmen, and in so doing has placed me in a somewhat unique position so far as the opportunity of observing the nature of these strange illnesses is concerned. I have felt compelled, therefore, to undertake the task of recording my observations, however imperfect those observations may be.

The matter has been approached from a purely clinical standpoint; the physiological problems concerned are better dealt with in the midst of the quiet and resource of the physiological laboratory; any serious attempt to solve them in the rush and roar of a large engineering undertaking would indeed be futile.

The incompleteness of our literature on this subject, and the scattered and often inaccessible nature of the communications that have from time to time been made, have made it advisable that I should give a short *résumé* of the facts observed and the conclusions drawn by others. It will be seen that I have collated the results of most of my predecessors in this branch of medicine. Few of those of French and German origin have previously appeared in English. Where I have been unable to obtain access to the original writings of authors, I have frequently obtained extracts of those writings from the masterly works of the late M. Paul Bert, whose history of the subject up to 1870 is very valuable and complete. My indebtedness to his comprehensive genius has indeed been great.

My sincere thanks are due to Mr. William J. Bull, the chairman of the Bridges Committee of the London County Council, for very kindly looking through the proof-sheets for me, and for several useful suggestions.

E. H. S.

LYNWOOD, NEW PARK ROAD,
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Page 115. Last line, *for* "membrans" *read* "membrane."

Page 137. In fourth column of table, *for* "per man' *read* "per minute."

COMPRESSED AIR ILLNESS.

CHAPTER I.

HISTORY.

In subaqueous engineering works an artificially compressed atmosphere is generally employed for the purpose of keeping out the water. Indeed, were it not for such a device, many works which are now successfully carried out in water-bearing soils, would be quite impracticable. A brief review, therefore, of the gradual development of the utilisation of compressed air for such purposes will be of interest, even if it be not absolutely essential to the right understanding of the conditions under which the workmen carry out these undertakings.

In the beginning of the sixteenth century the diving-bell was invented by Sturmius. This was the first and simplest apparatus in which compressed air was used as an atmosphere in which men worked; by its means works of a trivial nature could be carried on under water. It was soon recognised, however, that the difficulty in its application to useful purposes arose from the lack of a supply of fresh air. If men remained in the bell for more than a very short space of time symptoms of suffocation presented themselves: these symptoms were at first attributed to the increased heat of the air in the bell, which was the most obvious alteration in the physical conditions of the confined air. The increase in density of the air did not at once attract attention, and probably the depths reached were not then great. They afterwards attempted to renew the supply of air by sending down bottles full of air, which were then broken in the bell.

Halley—an English physician—used kegs, which were passed down to the bell, opened at will by the labourer, and the foul air allowed to escape by a valve at the top of the bell. He also devised the means by which the workman could leave the interior of the bell, continuing to breathe the air contained in it; this was effected by a tube communicating with a sort of cowl over the head.

Spalding introduced some mechanical improvements; he, however, met with his death in his own apparatus in 1785.

Brizé-Fradin, in whose work[1] a review of the diving-bell up to that time appears, sums up the effects of a sojourn in the apparatus in this way:—

1. Acute and unbearable pain in the ear, due to the compression of the partition of the tympanum.

2. Alteration of the air by the respiration of the workers, whence asphyxia.

3. The majority of physicians have found a third inconvenience: they believe that the compressed air compresses the blood vessels and produces hæmorrhages; this, however, says Brizé-Fradin, is opposed to the

[1] "La chimie pneumatique appliquée aux travaux sous l'eau," p. 170. Paris, 1808.

teachings of Halley and to the experience of all the workers in diving-bells.

Dr. Hamel, in 1820, in a letter[1] to Professor Pictet on the diving-bell, describes his descent to a depth of about 30 feet in a diving-bell at Howth near Dublin. He experienced no other inconvenience than violent pains in the ears, as if a probe were being forcibly introduced; this ceased on swallowing his saliva. From this fact it occurred to Hamel that some cases of deafness due to obstruction of the Eustachian tube might be cured by the diving-bell.

In the same year Dr. Colladon descended in the same bell to the same depth. He is a little more explicit.[2] He says: "We descended so silently that we did not notice the movement of the bell; but immediately that it was plunged into the water we experienced in the ears and on the forehead a feeling of pressure, which continued to increase for some minutes. I did not, however, experience the pains in the ears; but my companion suffered so much that we were obliged to suspend the descent for some minutes. To remedy this inconvenience the workmen recommended us to swallow our saliva after having firmly closed the nostrils and mouth, and to stop breathing for some seconds, in order to allow the compressed air to enter the Eustachian tube. My companion was little relieved by this proceeding. When we were again descending he suffered much; his lips were blanched, and he looked as though he were going to faint. His faintness was due, no doubt, to the violence of the pain, added to a feeling of fear that he could

[1] *Bibl. Univ. de Genève*, 1820, vol. xiii., pp. 230-234.

[2] "Relation d'une descente en mer dans la cloche du plongeur," p. 8. Paris, 1826.

not ascend when he wished. This experiment produced on me a contrary effect. I was excited, as though I had been drinking alcohol. I did not suffer; I only experienced a strong pressure round the head, as though an iron band encircled it. In talking with the workmen I could scarcely hear them. This difficulty in hearing increased so much that for three or four minutes I could not hear them speak. I could not hear myself, although I spoke as loudly as possible; and soon the noise caused by the strength of the current against the sides of the bell no longer reached my ears. At length we arrived at the bottom, and then the disagreeable sensations ceased almost entirely. We respired with great ease during the whole time of our stay under the water; our pulses underwent no alteration. In ascending, our sensations were very different from those which we experienced in descending: our heads seemed to be getting larger; the bones of the head felt as if they would separate,—this inconvenience was not of long duration."

Colladon further observes (p. 14) that "none of the labourers become deaf: it appears, rather, that in certain cases the action of the bell on the ears may serve as a remedy for deafness. One of the labourers who habitually had a difficulty in breathing was completely cured a short time after having undertaken work in the diving-bell."

From the diving-bell to the modern caisson, with a compressed air chamber in its lower portion, does not appear to be a large step, but three hundred years elapsed between the invention of the former and the employment of the latter. A caisson, or caissoon, is a cylinder which is sunk or driven vertically into a water-containing soil with the object of forming a shaft or space which is free from water. If the inrush of water at the lower end be not too great it may be removed by pumping as it comes in. If pumps are unequal to the task, other means are necessary: these now consist in the formation of an air-tight diaphragm somewhere in the course of the cylinder, and the forcible introduction of air into the lower chamber so formed, until the air pressure is sufficient to prevent the entry of water; it is, in effect, a cylindrical diving-bell prolonged upwards. To allow of the entry and exit of men and materials the diaphragm must be provided with a lock or chamber with an inner and an outer air-tight door, both opening towards the compressed air, and cocks, by means of which the pressure in the lock may be gradually increased or diminished to permit descent or ascent respectively.

A French engineer—M. Triger—was the first to employ this ingenious method for the boring of wells and the fixing of piles for bridges.

The suggestion, however, of this invention seems certainly to have been made by Denis Papin in 1691, as the following quotation by M. Trouessart[1] shows:—"One could continually inject fresh air into the diving-bell by the aid of strong bellows. Thus, the bell remaining empty, and resting on the ground, the bed would be always dry, and work could be carried on as in the open air; and I have no doubt that that would save much expense when it is necessary to build under water. Also, in the event of leather bellows not proving powerful enough to force air to great depths, this could be easily remedied by using air pumps."

In 1830 Cochrane (afterwards Lord Dundonald) took out a patent for using compressed air to keep back the

"Rapport sur les puits à air comprimé de M. Triger." *Bul. de la Soc. Industr. d'Angers et du Départ. de Maine-et-Loire*, 1845.

water met with in driving shafts or tunnels. The method was, however, first put into practical execution by M. Triger in 1839, when a shaft was sunk at Chalonnes through a layer of quicksand to reach an extensive bed of coal that was known to exist there. In this undertaking Triger was completely successful, and he then announced numerous applications of the principle which were possible. His complete report appears in a memoir presented by him in 1841 to the Académie des Sciences.[1] The physiological phenomena received very little attention from the celebrated engineer. He refers to the pains in the ears both on going into and coming out of the compressed air. The only other observations of a physiological nature that he makes are the following:—

1. The difficulty of whistling, which is absolute at 3 atmospheres.

2. The nasal tone of the voice in the compressed air.

3. A miner, deaf since the siege of Antwerp, has always been able to hear better than the others when in the compressed air.

4. The labourers mount steps easier in the compressed than in the open air.

Professor Trouessart, appointed by the Industrial Society of Angers to examine the practical results of Triger's apparatus, reported his researches in an interesting memoir in 1845.[2] He treats little of physiological matters. His observations are, however, worthy of notice because they are the first that have been made on man under a

[1] "Mémoire sur un appareil à air comprimé pour le percement des puits de mine, et autres travaux sous les eaux et dans les sables submergés."

[2] "Rapport sur les puits à air comprimé de M. Triger." *Bull de la Soc. Industr. d'Angers et du Dépar. de Maine-et-Loire*, 1845.

pressure of 3 atmospheres in addition to the atmospheric pressure. He says that "it is not without a certain apprehension that one descends for the first time into the apparatus to be submitted to a pressure of 3 atmospheres. These 32 kilogrammes, in addition to the atmospheric pressure which one is going to support, are sufficient to make the most robust fearful." He studies first the pains in the ears. He says: "One phenomenon most difficult to comprehend is that deaf persons not only hear better in the compressed air than in the open air, but they hear better than persons with normal ears. One of the most singular results is that under a pressure of 2¾ to 3 atmospheres the power of whistling is lost. The functions of nutrition, respiration, and circulation do not appear to be sensibly modified in compressed air. From our first visit we had expected to find an acceleration in the pulse beats of all persons submitted to the experiment; but on our second visit the result of a more exact observation, made by a person well trained in feeling the pulse, was completely negative. Respiration is neither slower nor more rapid, . . . and, in a word—and this is most surprising—there is very little modification in the vital functions. The labourers ascend ladders more easily in the compressed air than in the open air. . . . On the other hand, they contend that they have become more easily fatigued by working in the compressed air than is the case in the open air. We believe that this is due to the greater humidity of wells—a humidity which hinders the insensible perspiration, and more rapidly provokes the formation of sweat among those who in such a medium have to use muscular effort. It is this humidity which explains also perhaps the severe pains in the joints which some labourers have experienced a few hours after coming out. We may conclude that there is no serious danger in remaining several consecutive hours on succeeding days in compressed air at a pressure of 3 atmospheres."

This author says nothing of the duration of decompression; he appears to occupy himself rather with the passing from a feeble to a high pressure. He says only that the air cock is opened gradually.

In a second communication to the Académie des Sciences M. Triger[1] repeats his former observations. Speaking of the nasal voice, and the difficulty of whistling, he relates that he took a violin into the compressed air, and found that at 3 atmospheres a large part of the intensity of the sound was lost. Then he first refers to the serious accidents of decompression. He says: "I ought to declare here that two workmen, after having spent seven consecutive hours in the compressed air, experienced severe pain in the joints half an hour after coming out. The first complained of extremely acute pain in the left arm, and the second of a similar pain in the knees and left shoulder. Rubbing with spirits of wine caused the pain to disappear in both cases; they did not continue their work on the following days."

In 1846 M. de la Gournerie,[2] to extract some rocks from the channel of the port of Croisic, used an apparatus proposed in 1778, consisting of a boat carrying a metal chamber, open below, and from which the water was forced by means of compressed air. He only immersed it to a depth of 3 or 4 metres. It is not surprising, therefore, as M. Paul Bert says, that "The workers never found

[1] "Lettre à M. Arago." *Comptes rendus de l'Académie des Sciences*, 1845, vol. xx., pp. 445-449.

[2] "Mémoire sur l'extraction des roches de la passe d'entrée du port du Croisic." *Ann. des Ponts et Chaussées*, 1848, vol. i., pp. 261-315.

themselves inconvenienced. Occasionally a slight pain in the ears, lasting a few seconds, was caused. The frequency of the pulse was not sensibly increased."

It was in the mines at Douchy that the method employed by Triger was first imitated ; the first information of this work was contained in a report of the engineer Blavier, who was sent to examine this new invention.[1] He points out first the pains in the ears, and the impossibility of whistling. To speak, it is necessary to make a certain effort. "It appears to us that in the diatonic scale the voice loses a tone, or a tone and a half, in the shrill notes without regaining them in the bass." He found no difference between the frequency of the pulse before entering and while in the apparatus. "The majority of workmen, although chosen from among the most robust and most healthy, have frequently experienced, some hours after coming out, either a heavy feeling in the head or pains in the limbs ; one only of these has had an absolute powerlessness in the arms and legs lasting twelve hours. The director of the mines has stated to us that the effects experienced nearly always coincided with some excess committed in the interval of the shifts." However, he himself (Blavier), after having been submitted to a pressure of 2·6 to 3 atmospheres, was the subject of an accident as serious as the above.

"The morning following our visit, on December 5th, severe pain came on in the left side, and we felt the pain for several succeeding days. As a cold or some cause other than the compressed air might have been the origin, when we were completely free from pain—on December 28th

[1] "Rapport sur le procédé suivi à Douchy pour traverser des nappes d'eau considerables." *Ann. des Mines*, 1846, 4th series, vol. ix., pp. 349-364.

—we again tried the experiment, and took, on leaving the compressed air, every precaution against catching cold. In spite of this care, on the following day, at the same time as before—twenty hours after leaving the compressed air—we had in the right side a pain similar to that felt before, and which incapacitated us for four or five days."

The first memoir written by physicians on these accidents was by MM. Pol and Watelle,[1] written in 1847, and presented a little time after to the Society of Douchy. During the work the pressure was raised to $4\frac{1}{4}$ atmospheres, compression was effected in a quarter of an hour, and decompression in half an hour. Sixty-four workmen were engaged; they ordinarily remained four hours in the compressed air, and they worked two shifts of four hours each day. The authors have described the physiological effects as noted on themselves, and the pathological effects as seen in the workmen.

Physiological effects.—Pains in the tympanic membranes; a lessened frequency of respiration; and, above all, a diminution in the amplitude of thoracic expansion, which expansion becomes scarcely perceptible; a lessened frequency of the pulse (*e.g.*, from 70 to 55 per minute); an increase of urinary secretion. "A muscular feeling of a resistance to be overcome, the unusual density of the surrounding atmosphere impeding progression." The impossibility of whistling felt above 3 atmospheres is also attributed to an unexpected resistance experienced by the muscles of the tongue in the presence of a condensed atmosphere. During the decompression

[1] "Mémoire sur les effets de la compression de l'air appliquée au creusement des puits à houille." *Ann. d'Hygiène Publique et de Médecine Légale,*" 1854, 2nd series, vol. i., pp. 241-279.

they experienced a lively sensation of cold, some shortness of breath, and the pulse mounted to 85 per minute.

Pathological effects.—Of the 64 workmen, 47 stood the work more or less well, 25 left the employment, and 2 died. Going more into detail concerning the illnesses, 14 experienced trivial accidents, 16 experienced more or less grave accidents, and 2 died. On the other hand, 2 benefited by the employment: one of these suffered from asthma, and breathed better in the compressed air; the other—a chloro-anæmic—having previously had frequent hæmoptysis, saw his ill health disappear, and his mucous membranes became less anæmic.

The accidents, without exception, accompanied or followed decompression. "The danger is not in going into the compressed air. It is not a disadvantage to stop there a longer or shorter time. The decompression only is to be feared. *One only pays on coming out.*"

They then examine the accidents, which may occur, seriatim. First there are the pains in the ears; and M. Pol states that these are caused to disappear more easily by blowing the nose than by swallowing; the other symptoms are treated of as they occurred in different individuals, and are divided into the following classes:—

CATEGORY I.—Workers in the compressed air from the commencement.

1. An asthmatic, breathes better in the compressed air. Coming out he has violent respiratory oppression, with circulatory reaction exaggerated. Discharged.

2. Has been in the compressed air up to a pressure of 4½ atmospheres. Respiratory embarrassment; diminution of appetite; indigestion; pain in the limbs; black stools. Very ill.

3 and 4. Same effects.

5. Above 3 atmospheres, muscular pains, cramps, and general numbness; vomiting of black matter on coming out of the compressed air. One day, an hour after coming out he felt ill; was put to bed, and then lost consciousness; bronchitic râles. Bled; purged; and sinapised; after four hours regained consciousness; well in three days. Discharged.

6. Worked without inconvenience until the pressure reached $4\frac{1}{4}$ atmospheres. One evening, after having gone to bed apparently well, he was seized with muscular pains, with contractions of a tetanic character. Skin cold; pulse small and soft; urine excessive, and of light specific gravity; respiration troubled; auscultatory signs same as No. 5. A bath at 30° C. increased the pain, and the patient could not remain in; friction brought on perspiration, and he was then easier; better next day. Resumed work.

7. Pressure 3·3 atmospheres; cerebral troubles resembling drunkenness, hebetude, stammering; respiration and pulse accelerated; pupils dilated. He had two similar attacks; from the one he recovered in nine days, from the other in fifteen days. There remained diplopia and vertigo, with deafness on one side. Discharged.

8. Presented to excess two common features: suppression of the functions of the skin, and increase of the urinary secretions during compression; increased rapidity of the heart-beats after decompression; pulse mounted from 58 to 130.

9-17. Nothing important to note.

18. Healthy and vigorous; experienced several times acute pains in the limbs and the chest; respiratory trouble increased with the pressure, as well as the muscular pain, which became very severe. Discharged. Afterwards he descends into the compressed air without permission; works

there without complaining; comes out with the rest, and washes; falls immediately unconscious, and dies in a quarter of an hour. An autopsy showed congestion of the lungs, liver, spleen, and kidneys; brain normal, except for scattered patches of congestion.

19. Violent respiratory oppression; rapid pulse; skin cold; cough continual; clonic contractions of the limbs; better after five hours of attention. At another time, to these symptoms were added dilatation of the pupils, helplessness of the limbs, muttering delirium, and coma. Three consecutive bleedings. Better. Discharged. The blood from the vessels was noted to be red.

20. Same as No. 7. Remains equally deaf on one side, with sight feeble. Discharged.

21. Vision dim and double; hearing gone; respiration troubled; cough frequent; pulse hard and bounding. Bled. Better.

22 and 23. Pains in the head; vertigo; cramps. Discharged.

24 and 25. Nothing important.

26. Respiration troubled, and cerebral symptoms; better after free perspiration was induced.

SPECIAL CATEGORY.—Men who worked only one day, and without preparation, at a pressure of 2·8 atmospheres. Nine men came out without complaining of anything; but, soon after, eight of these experienced very severe muscular pains in the limbs, which disappeared in the night, except in one case, where they lasted several days.

CATEGORY II.—Men who only commenced work when the pressure reached 2·9 atmospheres.

1, 3, 4, and 6. No effect.

2. Muscular pains in the left thigh, which yielded to cold water.

5. Moderate muscular pains which persisted from one shift to the next. The recompression caused them to disappear at once.

7. Twenty-eight years old; athletic. Pressure 3·8 atmospheres to commence with. After working for ten days without complaint he lost consciousness; had violent trismus; pulse rapid. Bled eight hours after; purged and blistered. The following day, all at once, consciousness returned. Cured, but remained very deaf.

CATEGORY III.—Men who commenced at 4·154 atmospheres.

1, 2, and 8. No effect.

3. Had previously had hæmoptysis. Better.

4, 5, and 6. Nothing beyond muscular pains.

7. Forty years old; very robust; only went into compressed air once; took twenty minutes in decompression, and died almost immediately afterwards. Autopsy thirty-six hours after death: general subcutaneous emphysema (the authors note that this existed before putrefaction commenced); cerebrum and cerebellum normal; congestion of the lungs, with a general black colour; fluid and black blood in the heart; liver, spleen, and kidneys engorged.

9. Moderate muscular pains.

10. Very violent muscular pains, lasting several days. Discharged.

11. The same.

12-19. Nothing except slight muscular pains. They worked in a pressure of 4¼ atmospheres for three months.

20. Went into compressed air only once; came out too

rapidly. Some minutes after coming out had the aspect of a cadaver: face livid; icy cold; eyes dull; pupils dilated; troubled respiration. On listening to the heart only a vague agitation was heard; pulse imperceptible; intelligence abolished; micturition involuntary; black vomit; complete muscular impotence. Hot baths; blankets; frictions. After half an hour the pulse began to become perceptible; respiration more complete; a little heat returned to the trunk; he began to talk, but incoherently. During the night, when the temperature had returned to the normal, severe pains came on in the muscles; aching pain in the head; blindness, and deafness; pulse poor, 50 per minute. Completely recovered by the following morning; but feeble sight and enormously dilated pupils remained.

21. Only in compressed air once; came out too quickly; severe muscular pains, lasting six days.

22. Only in compressed air once; decompression too rapid; loss of consciousness; respiration troubled; pulse full, hard, 130; bled and sinapised; after four hours consciousness returned. In the night cramps and muscular pains of great violence. Recovered, but with considerable feebleness of sight, and great deafness.

M. Pol himself had the following experience:—Pressure 3·48 atmospheres. At eleven o'clock he had reached home; he felt acute pain in the left shoulder and arm; the wall of the thorax was also painful. It appeared to him that emphysema existed in these regions; he had some shivering, followed by vomiting; he took a cup of tea, and slept; soon there was profuse perspiration. The following morning he was quite well.

The accidents related by Pol and Watelle as liable to follow decompression may be summed up thus:

Difficult respiration ; acceleration and hardening of the pulse ; muscular pains, often very severe (" no one of the effects of the decompression is so general ") ; cerebral symptoms ; hebetude ; loss of consciousness ; deafness and blindness very often permanent ; sudden death.

The above observations show what variety of form and intensity these accidents present even for equal pressures among different individuals, and even in the same individuals.

MM. Pol and Watelle have remarked that young men from 18 to 26 resist the pressure much better than older men. Of the 25 discharged, 19 were over 40, 5 between 30 and 40, and the other 28 years. They do not mention the ages of the men that remained at work. The physicians of Douchy attributed the ill effects to pulmonary, hepatic, renal, and cerebral congestions. We will notice the theories of Pol and Watelle later.

Certain deductions appear to follow from these data :—

1. Pressures up to 4¼ atmospheres are not to be feared in themselves ; they are much better borne than a proportional rarefaction much less considerable. It is the return to the normal pressure which is dangerous, the danger varying with the height of the pressure and the rapidity of the decompression.

2. In the compressed air the venous blood becomes bright-coloured.

3. One is led to hope that a means of certain and prompt relief will be found in rapid recompression.

4. Anæmic and asthmatic people may find relief from compressed air.

This method of sinking wells rapidly extended. Facts analogous to those noticed by Pol and Watelle were observed elsewhere—*e.g.*, at the mine of Strépy-Bracquegnies, in Belgium. A report by Bouhy [1] states that all the workmen, with one single exception, who worked in a pressure of 3·7 atmospheres during four or five hours consecutively, suffered after coming out of the compressed air from pains, more or less acute, seated principally in the articulations —*e.g.*, the knees, shoulders, elbows—sometimes so severe that the men could not sleep for forty-eight hours. Some of the men attacked, and who returned to work while affected, found the pain removed by the recompression, only to return on coming out again.

Besides these effects the author notices the frequent and troublesome formication on the surface of the body and limbs.

The application of this method of sinking caissons to the formation of the foundations of the piers of bridges was first carried out in 1851 by an English engineer, Mr. Hughes, in the construction of a bridge at Rochester over the Medway; [2] the greatest depth here was 61 feet. Afterwards (1843-51), Brunel used it for the bridge at Chepstow over the Wye, and at Saltash 1854-59. Hughes worked both at Chepstow and at Saltash; and he informed Dr. Babington [3] that there were no fatal cases at either Rochester or Chepstow, and only one at Saltash, in a man of broken-down health, who died on leaving the cylinder, in which he had been a very short time. At this bridge the greatest depth attained below high water was

[1] "Creusement à travers les sables mouvants d'un puits de la mine de Strépy-Bracquegnies." *Ann. des Trav. Publ. de Belgique*, 1848, vol. vii.

[2] A detailed account of the plans adopted here is to be found in vol. x. of the *Proceedings of the Institution of Civil Engineers*, May 1851, by Hughes: "The pneumatic method adopted in constructing the foundation of the New Bridge over the Medway at Rochester."

[3] *Dublin Journal of Medical Science*, 1863, xxxvi., pp. 312-318.

87·5 feet, and the maximum pressure 40 lbs. Three-hour shifts were found best.

In 1856 M. Cézanne was engaged in building a bridge at Szegedin (Hungary) for an Austrian railway over the Theiss, a tributary of the Danube. He "stopped at a depth of 20 mètres (65·6 feet) below high water in order not to reach a pressure of 3 atmospheres, when work for men becomes dangerous."[1] M. Cézanne points out that there are three phases to be distinguished : the entrance, the time spent in the compressed air, and the coming out.

1. The pains in the ears in going in, varying in intensity in different individuals.

2. One can remain in the compressed air for several hours without inconvenience. Tone of voice is altered ; respiration is increased in frequency, as in rapid walk ; a cigarette bursts into flame ; candles burn rapidly, but with a smoky flame.

3. The decompression, although less painful for the great majority of individuals, is more dangerous for the workmen. Bleeding may take place in the nose and throat ; certain persons have neuralgia, violent, but short ; others have persistent headache and toothache for days. Workmen who are habitually employed have sallow complexions, but otherwise seem well.

At the building of a bridge over the Garonne at Bordeaux, in 1859, an explosion of the compressed air occurred. From the immediate decompression seven of the workmen suffered no injury ; two were killed, but from causes purely mechanical.[2] M. Regnauld, who records

1 "Notice sur le pont de la Theiss et sur les fondations tubulaires." *Ann. des Ponts et Chaussées*, 1859, vol. i., p. 355.

2 "Mémoire sur la construction du pont métallique sur la Garonne à Bordeaux." *Ann. des Ponts et Chaussées*, 1867, vol. ii., pp. 27–115.

this, does not say under what pressure this accident occurred; but it appears to follow from his report that the depth of the caisson must have been less than 42·3 feet and the pressure therefore about 20 lbs. above the normal.

In 1859 was built the bridge of Kaffre-Azzyat over the Nile.[1] Five Arabs died from the effects of the compressed air; one died in the cage before coming out (the pressure was then 36 lbs.); another "became exhausted in the cylinder," and died after passing through the cage; and the three others in a similar way,—all were said to be men without stamina. Blood is described as having issued from their mouths, ears, and noses: these cases occurred when the pressure was above 30 lbs.; the other men "did not complain of inconvenience, or suffer from accident." A note in the London *Times*, July 7th, 1859, says, concerning the Kaffre-Azzyat bridge, that the average depth of the caisson was 60 feet below the bed of the river, and 85 feet below high water; the internal pressure while sinking ranged from 20 to 34 lbs. per square inch.

At the building of a bridge over the Foyle, at Londonderry, the greatest depth of a cylinder was 75 feet from the surface of the water, and 40 feet below the bed of the river. The pressure, including the atmospheric pressure, varied from 27 to 35 and 38—on one occasion it went up to 43—lbs.; the highest pressure, therefore, excluding the atmospheric pressure, was 28 lbs. A large number of cases of illness appear to have occurred, and among them four deaths. An account of some of the cases is given by Drs. Babington and Cuthbert.[2]

[1] *Dublin Journal of Medical Science*, 1863, xxxvi., pp. 312-318 Article by Babington and Cuthbert.

[2] "Paralysis caused by working under compressed air in sinking the foundations of Londonderry New Bridge." *Dublin Journal of Medical Science*, 1863, xxxvi., pp. 312-318.

CASE I.—October 3rd, 1861. A man, 28 years old, having worked under a pressure of 23 lbs. for four hours, suddenly fell into a state of insensibility on leaving the compressed air. Body cold and livid; right side of face partially paralysed; strabismus of right eye; pupils equal, reacted sluggishly to light; pulse at wrist weak, fluttering, and irregular, about 150 per minute; heart sounds almost inaudible; respirations very irregular, varying from 24 to 44 per minute; inspiration jerky; expiration laboured. Plantar reflexes were present. Venesection was tried, 12 ozs. of blood being slowly taken from the arm. The blood "was black—very black, viscid, and treacly." The respiration became more laboured, and no other effect was noticed. Stimulant enemata were given, but the respiratory movements gradually became more feeble, and he died exactly twenty-four hours after leaving the cylinder.

CASE II.—Almost precisely similar, except that there was no facial paralysis. Died in twenty-four hours.

CASE III.—Twenty-three years old. Soon after leaving the compressed air had pains in legs and thighs, not increased by pressure, but sharp and shooting; could not walk—feet and legs cold and numb; complete anæsthesia in legs; was found with his feet almost in the fire, and several of his toes were considerably burnt without his knowing it. A stimulating liniment was used, and in two days he was well, except for the burns.

CASE IV.—Similar. Well in a few days.

CASE V.—Aged 18. Was at work for four hours. While decompression was proceeding he fell helpless, and became semi-comatose; was able to answer questions when roused, but speedily relapsed into a state of insensibility. The comatose symptoms passed off in about eighteen hours, when he was found to be totally paralysed from the 4th rib; to have retention of urine; loss of sensation. He died a hundred and sixty days afterwards, never having recovered sensation or power of motion. For a long time before his death he had incontinence of urine and fæces, and he "died exhausted from the effects of universal bed-sores."

CASE VI.—Aged 30. Similar to Case V.; but the anæsthesia did not extend above level of 8th dorsal vertebra. He lived thirty days, and died from the effects of bed-sores.

Also many cases of slight paralysis, muscular pains, and other nervous affections occurred, but these cases are not described, neither do any autopsies appear to have been made in the fatal cases.

One of the largest works carried out by the aid of compressed air was the formation of the foundations of a bridge over the Rhine at Kehl in 1859. Two memoirs on this subject exist. The first by Dr. François.[1] He states that the length of the shifts was four hours, followed by eight hours' rest. The pressure was raised to $3\frac{1}{2}$ atmospheres: according to the rules the decompression for 2 atmospheres should last from 6 to 8 minutes, and for 3 atmospheres from 12 to 15 minutes; but the rules were not strictly adhered to by the men.

Physiological effects.—Respiration was said to be increased in frequency, with increased movement of the chest

[1] "Des effets de l'air comprimé sur les ouvriers travaillant dans les caissons servant de base aux piles du pont du grand Rhin." *Ann. d'Hyg. Publ. et de Med. Lég.*, 1860, 2nd series, vol. xiv., pp. 289-319.

("*ce qui s'explique de soi-même*," says François); increased frequency of pulse during compression, slowing afterwards on return to free air; sensible emaciation even among the workmen who did not suffer.

Pathological effects.—Otalgia and otitis, after which the hearing is impaired; pain in the muscles and articulations,—133 of these cases occurred. The pains disappeared at the end of some days; sometimes, it is stated, perceptible local swelling occurred. In one of the cases the left breast of one of the workmen suddenly swelled, but without crepitation, in such a manner that it resembled a well-developed female breast; this painful swelling yielded rapidly to wet cupping. In another case paralysis of the left leg remained.

M. François draws attention to the derangements of the skin, formication, or *les puces*, as the French workmen call it. The itching yields to cold water applications. He explains by congestion of the lungs, heart, liver, and spleen, various obscure symptoms, such as suffocation and palpitation. One of the patients subject to hæmoptysis died some months afterwards. Finally, violent headache and loss of consciousness are attributed to cerebral congestion: these congestions commenced only at the end of a quarter or half an hour after coming out. In one case a workman, having come out of the caisson (pressure 3 atmospheres), fell as if thunderstruck; he was bled repeatedly, and purgatives were given. He recovered, except that for a long time there was considerable feebleness of the lower limbs.

François then gives a description of some "functional" derangements of the spinal cord, among which he places retention of urine, pains in the limbs, and, for one patient, a persistent left-sided paralysis. The pressure was 3 atmospheres. Slight nasal, and even pulmonary, hæmorrhages were sometimes noticed.[1]

The following is an account of a fatal case[2] as recorded by François. The man "had suffered from severe pains in the chest and limbs, which compelled him to give up work. Some time afterwards, when the pressure was 4 atmospheres, he resumed work for a single day—the labour being excessively severe. He suffered no inconvenience apparently, however; and, after leaving the caisson, washed his face and hands as usual. A moment after he fell senseless, and in fifteen minutes was dead. The autopsy was made by a medical commission appointed by the authorities of Valenciennes. The meninges were found to be injected, and the sinuses distended with dark blood. The brain itself was also congested. The spinal cord was not opened. The lungs were somewhat congested, especially at the base, where they were less crepitant than usual, though they still floated in water, even when cut into small pieces. There was general congestion of the abdominal viscera."

M. Bucquoy[3] made some observations at the building of the bridge at Kehl, and these, in several points, are at variance with those of Dr. François. Bucquoy found that, in going in, respiration lost its regularity—it grew more quiet; inspiration shorter than usual; expiration longer; pulse more frequent—though Bucquoy also remarked on the sedative effect of the compressed air on the pulse. He

[1] A *résumé* of the observations of François are given by M. Willemin in "Remarques sur l'emploi de l'air comprimé dans les travaux d'art." *Gaz. Méd. de Strasbourg*, 1860, p. 179.

[2] Quoted by Dr. A. H. Smith—"Compressed Air," 1886.

[3] "De l'air comprimé." *Thèse de Strasbourg*, 1861. Also a short account of Bucquoy's work appears in the *New York Medical Record*, 1863, vol. ii., p. 229.

says: "One of my friends, M. Ritter, having descended with me in spite of a very intense fever, has seen his pulse fall from 95 to 75 at the end of an hour's stay." He considers that this bears out the observations of M. Pravaz on this matter. The respiratory capacity is also increased—as Pravaz pointed out; this increase of respiratory capacity lasts for some hours after coming out. During the process of compression there are pains in the ears as though a foreign body were driven in forcibly. On returning to the open air the breath formed a cloud; there was a sharp feeling of cold; palpitation of the heart; and respiration became less regular. An analysis of the air showed 2·37 per cent. of carbonic acid. Those who had to work for a long time in the compressed air became emaciated. Many labourers lost their appetites, and looked as though they were just recovering from a severe illness. Muscular and rheumatic pains often occurred, and sometimes the effects of congestion of the lungs and of the brain were observed. Blood taken from the veins presented in some instances a bright red colour, and this was especially the case when the person had remained long in the compressed atmosphere. Movements of the limbs appeared to be more easy than in the open air.

A monograph by Dr. Foleÿ,[1] published in 1863, was based on observations made at the building of a bridge, in 1861 at Argenteuil, over the Seine. In addition to many points previously drawn attention to, Foleÿ pointed out that some individuals lose the power of taste and smell in the compressed air. He says that the flattening of the mucous membrane by the compressed air renders hæmorrhage from the respiratory passages impossible, and

[1] "Du travail dans l'air comprimé: étude médicale, hygiénique, et biologique." Paris, 1863.

suddenly cures coryza and hoarseness ; sense of touch is blunted. The pulse in compressed air is small, "filiform," and even indistinguishable ; the *vis a tergo* is lost in the veins ; circulation becomes languid, but the tissues do not become livid—the contrary rather takes place ; the venous blood becomes as bright red as the arterial ; pulmonary capacity increases, and the movements of the sides of the chest diminish. Workers in compressed air feel less fatigue ; hunger comes on quickly ; they sweat much, but never feel thirsty. Foleÿ explains the absence of thirst by the large amount of water in the atmosphere, and which "penetrates into the organism," and refers the excessive sweating to the efforts of the skin to get rid of that moisture which the lungs, in the compressed air, are unable to effuse. He explains the hunger by the excessive consumption of oxygen.

Foleÿ considers the diminished respiration to be due to the arterial condition of the venous blood, and attributes the absence of fatigue to the same cause. He says that the carbonic acid from the lungs is increased considerably ; the secretions of the alimentary glands "generally diminish."

In describing the sensations which he experienced during decompression, Foleÿ notices the moisture in the air and the cold, which increase as the pressure is lowered ; taste and smell do not return at once ; a warm and piquant feeling in the nose, and a smell of blood ; at the same time a taste of salt spreads itself out over the tongue (these last are specially noticed when the mucous membranes are primarily congested) ; occasionally a slight cough comes on, and shivering on account of cold.

Foleÿ divides the period of stay into two parts—the beneficial and the harmful period. In the latter the skin acquires an earthen tint; the conjunctivæ a vinous appearance; appearance of illness; indecision; immobility, and stupor. He attempts to show that engineers and inspectors generally do not suffer from the same effects of compressed air as the men, but the argument is not at all clear.

Pathological effects of decompression.—(1) Epistaxis and hæmoptysis. (2) Effects on the skin, such as pruritus and profuse perspiration. Foleÿ explains the itching by an afflux of blood to the skin vessels: these, he says, become over-loaded, and the papillary nerves stretched. "Inasmuch as this afflux of blood to the skin may prevent afflux to more important organs, these symptoms are a favourable sign." But on the other hand they are of unfavourable augury—"si tout le sang en ébullition ne peut se loger à la péripherie de notre être." (3) "Bends," or *la courbature.* These pains occur in different parts of the body—*e.g.*, femoral muscles, knees, shoulders, pectoral muscles, etc., in different men, and always in that part of the body which has the most exercise during the work. The pain is accompanied by, and is proportionate to, some swelling. Foleÿ says that this swelling is not due either to air, or blood, or rheumatic swelling—for there is an entire absence of crepitation, crackling, coloration, or peregrination—but is due to arterial congestion without extravasation. He considers that the synovial membranes surrounding tendons are affected most; serous membranes less; bones and periosteum scarcely ever, if at all; and he gives one case where the periosteum was supposed to be affected.

Foleÿ generalises thus:—Derangements of the skin and mucous membranes affect everybody; derangements of the locomotor apparatus, the workmen; and those of the nervous system, engineers and overseers. The brain-workers do not suffer from the other effects, but have occasionally a sort of intoxication on entering and leaving the compressed air. (These generalisations are not borne out by other observers.) Foleÿ has never seen any fatal result, paralysis, or apoplexy, caused by the air.

Treatment.—Foleÿ recommends massage and mild rubefacients—*e.g.*, mustard ; hot drinks (*e.g.*, tea, camomile infusion, hot wine) ; also recompression.

Narcotics are harmful, as also is a too prolonged "locking out." He also gives a number of general recommendations relating to the importance of taking rest after coming out. "Cold applications for the pruritus are dangerous." Regarding the "locking-out" process he allows 1 minute for each atmosphere above the normal pressure up to 2½ minutes, and thinks this is long enough for a stay in the cold lock ; beyond this pressure he recommends the use of two locks, and a graduated amount of work in the interval between the locks.

Foleÿ points out the resemblance between the symptoms caused by leaving the compressed air and those caused by ascending altitudes. He himself suffered from neuralgia while going in, while in, and during, and after coming out. His usual observation on the pulse was that the frequency diminished, the pulse wave becoming more incompressible and smaller. He notices that drunkards especially suffer from the compressed air. He records one case of bleeding from the ear.

There are two points on which Foleÿ is in absolute disagreement with every other observer. (1) He says that if the sojourn be prolonged—up to a pressure of 3½ atmospheres—to twelve hours no bad result will accrue: this is because "la réaction nervoso-sanguine est générale." (2) He considers that a rapid decompression makes no difference to the liability to illness: in fact, he goes on to say that a prolonged stay in the cold atmosphere of the lock may be the cause of the subsequent illness.

In 1862 compressed air was used for a viaduct over the Scorff at Lorient, and in 1864 for a railway bridge over the Loire at Nantes. M. Croizette Desnoyers, the chief engineer, gives a most minute account[1] of the engineering details of these two works, but does not speak of the condition of the workmen; he is content with saying that "at great depths the use of compressed air may do injury to the health of the workmen."

M. Paul Bert, however, points out[2] that it is certainly known that considerable accidents occurred at the bridge over the Scorff; the list of workmen who were ill, drawn up by Dr. Nail, contains sixteen names, all of which cases were due to the compressed air; they comprise 1 case of deafness, 6 of articular pains, 1 of muscular pain, 6 of cerebral congestion, and 2 deaths. The two deaths were not simultaneous: the first occurred on March 16th, 1862; and the man is said to have died "of asphyxia on coming out of the caisson": the other case occurred on June 3rd at another pier; the medical memorandum states that he "died, after four hours, of cerebral congestion and of asphyxia." M. Paul Bert was unable to procure any details concerning the circumstances of the deaths, or of the result of the autopsies, if any were made. He found out, however, that at these works decompression was regularly accomplished in ten seconds, and

[1] "Mémoire sur l'établissement des travaux dans les terrains vaseux de Bretagne." *Ann. des Ponts et Chaussées*, 1864, vol. i., pp. 275-396.

[2] "La Pression Barométrique." Paris, 1878.

that the maximum depth of driving the first pile was 18 metres, and of the second 12 metres only. He was unable to ascertain whether the other workmen who came out at the same time as these two men who died suffered from any ill effects.

This double catastrophe was the occasion of legal proceedings against the company, they being charged with homicide with negligence; they were acquitted by the tribunal of Lorient (September 30th, 1862) and by the court of Rennes (December 11th, 1862). The acquittal appeared to rest on the uncertainty which existed as to the true cause of the deaths. Another accident, followed by more litigation, took place at the same bridge. M. Gallois, a civil engineer and agent of the company, descended into the compressed air on May 12th, 1862; on returning to the open air he was seized with "paralysis, vertigo, and nervous shock." The paralysis appeared at first to affect principally the legs and partially the arms. There was paralysis of the bladder and rectum. After some months a weakness of one leg alone remained. He proceeded against the company for damages, which were refused by the Seine tribunal. The counsel for the defence put, in a plain light, the fact that the opinion of Pol and Watelle on the necessity of a slow "locking-out" process was in direct contradiction to that of Foley. The court did not pronounce on the scientific question involved; but pointed out that M. Gallois had not received an order to descend into the caisson, and therefore the company was not responsible. M. Gallois died two years after the accident, and his death was attributed thereto. He had remained in the compressed air for three hours, and the pressure was 2 atmospheres (excluding the normal atmospheric pressure).

In 1862 also was constructed a bridge over the Adour at Bayonne, in which it was necessary to raise the pressure to 3 atmospheres (excluding the normal pressure). M. Counord, aged 20, who directed the work, and who, until then, had experienced no accident, on December 31st, some minutes after having come out of the compressed air, the decompression having taken four or five minutes, was seized with vertigo, followed by loss of consciousness. The pressure was 3 atmospheres; the length of stay one hour. The evening before, he had remained in the compressed air two hours. Three hours afterwards, when he came to himself, he had sensory and motor paralysis in the legs, with loss of sensation in the arms. The details of this case are recorded by Dr. Limousin of Bergerac.[1] He saw M. Counord first on January 12th, 1863. There was complete paralysis of the lower limbs; involuntary micturition and defæcation; no anæsthesia; increased reflex movements in the lower limbs; no mental symptoms; pain in the epigastric and hypochondriac regions eased by external applications of morphia. A bedsore developed over the sacrum, which healed afterwards. Some power of movement in the legs existed on Febuary 20th; defæcation and micturition were then voluntary. In May 1870 he could walk a few steps without support; increased reflexes of the lower extremities remained; diminished sensibility in the left leg. In May 1876 he could mount with difficulty a flight of stairs by the support of one arm: "some tingling sensations in the arms seemed to indicate some lesion in the upper regions of the spinal cord." The bladder and rectum remained quite normal.

Some days after the commencement of this illness a

1 "Action de l'air comprimé: apoplexie de la moelle épinière." *Union Médicale de la Gironde*, 1863, pp. 269-270.

terrible accident, in which three men perished, occurred at the works at Bayonne. The cylinder burst—as at Douchy, and, later, at Chalonnes. The opinion was expressed[1] that the death of the workmen was due to the sudden decompression. M. Paul Bert combated this opinion, and M. Bayssellance undertook, at his request, an inquiry into the facts. The following is a summary of a letter from M. Bayssellance to M. Paul Bert[2]:—

"The pile, being forced deeply into the sand, reached a point more than 30 metres below the level of the water; the internal pressure was therefore about 3½ atmospheres above the normal. It appears that a portion of the iron adjoining the lock gave way, not having been constructed to resist this pressure: the lowering of pressure was therefore sudden in that portion of the apparatus; in the rest of the caisson the decompression was more slow. A sudden and violent current of air was produced from below upwards, carrying with it planks and gravel. According to the foreman, the results were quite different to those which have been stated. *No man was killed as an immediate consequence of the change of pressure.* The wet sand at the bottom, no longer kept back by the air, rose and surrounded one of the men, who was mounting a ladder. In afterwards clearing away the *débris* he was found clinging to the steps in the position of ascension. Another was raised, and carried upwards by the current of air, not knowing how he reached the top. Two others, who were on an intermediate stage, were pressed on mounting against the inferior plate of the lock, and remained nearly asphyxiated, their mouths full of sand;

[1] "Soc. des Sc. Phys. et Nat. de Bordeaux, 1871-75—Procés-verbaux des séances," p. 20.

[2] "La Pression Barométrique." Paris, 1878.

they were taken to the hospital, and died the following day. Finally, five men who were in the same lock were covered with sand, which penetrated even into the skin, and they remained for some seconds stupefied (stunned); but no one was seriously ill. This result does not conform with that which has been related. The man who has given this information was present at an analogous accident at the construction of the bridge at Bordeaux; there again there was no death caused by the sudden decompression, though two men were killed by some fragments of cast iron. A large number of illnesses arose from the compressed air at these works. According to M. Counord 90 per cent. of the men suffered more or less from its effects. One morning, out of eleven men who came out together, nine were ill with muscular pains."

Certainly, says M. Paul Bert, the decompression *may* have had something to do with the death of the two men who were covered with the wet sand, but that is not proved. The most curious item about this accident is that men experienced practically no ill effects whatever from an instantaneous decompression from a pressure of at least 3 atmospheres above the normal.

I may note that we have here no information concerning the length of time that the men had been in the compressed air before the accident occurred.

In 1865 a similar bridge[1] over the Loiret at Chalonnes was built. An accident, which has never been explained, caused the death of two workmen. On February 20th, 1865, at the time when the caisson rested on the rock,—when everything was nearly finished, and the working chamber (crinoline) was filled with concrete, and the tube forming the chimney was equally filled to a height of 5

1 "La Pression Barométrique." Paul Bert. Paris, 1878.

mètres,—all of a sudden a violent explosion took place; the larger part of the cover of the air lock—weighing nearly 500 kilogrammes—was projected to a distance of about 30 mètres. Two workmen who were in the working chamber were killed almost immediately. No one has ever been able to explain this terrible accident. M. Paul Bert considered it probable that for some unknown reason the pressure was raised above that which was required by the attained depth: the force of the explosion made this seem likely. M. Bert was able to give some details furnished him by Dr. Gallard.

"The death of the two workmen," writes Dr. Gallard, "was nearly sudden for one of them; a little slower for the second, who breathed for some moments, though he had already lost consciousness." An autopsy (made by Dr. Gallard, in bad conditions, after exhumation, and a previous autopsy by the doctor at Chalonnes) showed numerous patches of interlobular and vesicular emphysema in the lungs of the two victims; there were, in addition, numerous punctiform ecchymoses under the pleura and pericardium. Dr. Gallard recollected that the blood contained some bubbles of gas, but the notes of the autopsy were lost.

M. Paul Bert says: "Is it to the decompression that we can attribute the death? It is difficult to make an assertion one way or the other in the presence of an incomplete autopsy, and also remembering the fact which we have already reported in speaking of the bridge at Bayonne."

M. Triger was troubled[1] by the accidents which had followed the introduction of his method, and he addressed to the French Government a memoir on this subject, which was submitted to three engineers—Combes, de Hennezel, and Féline-Romany—for report. The report of these

[1] From M. Bert's "La pression barométrique."

engineers,[1] after having rapidly reviewed the most recent works in which compressed air had been employed, declares that "the accidents to which men who work in compressed air are exposed rarely put life in danger, only occasion short interruptions of work, and are indeed few when one considers the number of occasions when men emerge from the compressed air to the open air. The maladies occasioned by these accidents can be prevented by the employment of the means indicated in this report." These measures are, the use of woollen garments, and a slow "locking out." M. Triger asks that the "locking out" shall last seven minutes, and affirms that the accidents then disappear completely. The Commission thought that the length of this time should be varied according to the constitution of the workmen.

The sinking of the coal pits at Trazegnies in Belgium about this time formed the subject of an interesting article by M. Barella.[2] The total maximum pressure was 3·12 atmospheres; the decompression was made in about twenty minutes. M. Barella states that there is a notable diminution in the urinary secretion; a feeling of being able to breathe more easily, and a sensation of dryness in the back part of the mouth.

He noted that the frequency of the pulse was diminished by some pulsations among most of the workmen. The observed accidents were:—

1. In 7 cases epistaxis—not severe.

2. In 11 cases pains in the arms and legs, sometimes excruciating.

[1] *Ann. des. Ponts et Chaussées*, 1867, vol. ii., pp. 116-131.

[2] "Du travail dans l'air comprimé: observations recueillies à Trazegnies, lors de l'enforcement d'un nouveau puits houiller."—*Bull. Acad. de Méd. de Belgique*, 1868, 3rd series, vol. ii., pp. 593-647.

3. Lively itching in the legs, without pain; this was very frequent.

M. Barella remarks that these accidents occurred only on coming out, never while in the compressed air; further, they were never occasioned until the pressure rose above 2·8 atmospheres (? inclusive pressure). He further states that the small wounds that workmen made on themselves while working did not bleed—"ce qui s'explique par la pression que supportent les teguments cutanés."

Among the conclusions of M. Barella the following are the most important:—

1. It is advisable not to go into a pressure above $3\frac{1}{2}$ atmospheres over the normal.

2. Ten minutes' decompression should be allowed for each atmosphere.

In America the first bridge constructed by compressed air was over the great Pee Dee River. No medical records of this work appear to have been published.

In 1870 was commenced the Illinois and St. Louis bridge at St. Louis. In the construction of the piers and abutments of this gigantic work compressed air was employed up to a pressure of 50 lbs. to the square inch above the atmospheric pressure. As the pressure rose, the number of cases of illness and of fatalities increased to such an extent that a St. Louis physician (Dr. A. Jaminet) was appointed to take charge of the health of the men working in the compressed air. A monograph[1] afterwards published by him details the cases that he saw

[1] "Physical effects of compressed air and of the causes of pathological symptoms produced on man by increased atmospheric pressure employed for the sinking of piers in the construction of the Illinois and St Louis bridge over the Mississippi River at St. Louis, Missouri." By A. Jaminet, M.D., St. Louis, 1871.

and the observations that he made. Fourteen fatal cases occurred,[1] only three of which appear to have been seen by Dr. Jaminet. Seventy-seven cases of illness are recorded by Jaminet. Since four of these refer each to two separate attacks, eighty-one cases in all came under his observation. The summary of cases as given by Woodward is as follows:—

Cases seen by Dr. Clark . .	35
„ „ Dr. Eve . . .	3
„ „ Dr. Jaminet . .	81
	119

Six hundred men were employed.

Deaths	14
Crippled	2

A number of other cases appear to have escaped observation. Eads, the chief engineer at the bridge, gives the number of men employed as 352, and the number of deaths as 12.[2]

As soon as a depth of 60 feet was reached some of the men were affected with paralysis of the legs: this was rarely accompanied by pain; as the depth increased the illnesses became more numerous and more severe, and a number of deaths occurred. Jaminet states that the men were taken ill " when coming out of the air lock, or after returning into the normal atmosphere. None were taken sick in the air chambers, and the sufferers were generally taken in from a few minutes to one hour after they returned into the normal atmosphere, and not in the air chambers or caisson."

[1] "The St. Louis bridge." By Professor C. M. Woodward.

[2] "The effects of compressed air on the human body" (Captain Jas. B. Eads)—*Medical Times and Gazette*, 1871, vol. ii., pp. 291-292.

At first each shift lasted for four hours: this was afterwards reduced to three, and then to two hours. At the greatest depth the men were working only one hour twice in the twenty-four hours. In spite of these precautions fatal cases continued to occur. Of the cases given by Jaminet, 53 were described as having paresis or paralysis of the legs, generally accompanied at first by epigastric pain; 13 cases had epigastric pain, with some faintness; 3 men had epigastric pain, and pain in the legs; 3 are said to have had paralysis of the legs and of the left arm. Practically all of these were well in from one day to one week, most of the cases of paralysis of the legs being able to walk within twenty-four hours. Among the more serious of the cases were the following:—

CASE II.—Pressure 48 lbs. G. L., æt. 30, American, had worked five months; was in the compressed air for two hours. Twenty-five minutes after coming out he had epigastric pain, paresis of both legs, and retention of urine; also shooting pains in the legs and back. In three and a half months he could walk by the aid of sticks. No note of his future condition is given.

CASE VII.—Pressure 50 lbs. L. B., æt. 24, had not worked in compressed air before. Half an hour after his first shift of two hours he was attacked with paresis of legs and epigastric pain. He was better in a few days, and was warned by Dr. Jaminet not to work in compressed air again. In spite of this advice he worked one more shift of two hours. He afterwards suffered from paraplegia, and paralysis of the bladder and rectum. Cystitis afterwards developed, from which he recovered in two and a half months.

Case XII.—Pressure 50 lbs. H. M., æt. 20, German, had worked for nine weeks. Immediately after finishing a shift of two hours he complained of pain at the epigastrium, paresis of the legs and of the left arm (the paresis was ascribed by Jaminet to a hot bath, which he considered always to be contra-indicated in these cases); there was also paralysis of the bladder and rectum, and bed-sores afterwards developed. In four months he was no better, but no future note of his condition was made.

Case XVII.—Pressure 40 lbs. J. A., æt. 28, a Dane, had not previously worked in compressed air. After his first shift of two hours he became unconscious; livid and swollen in the face; lips discoloured; pulse 110 per minute, and very feeble; both legs and left arm completely paralysed; cold and profuse perspiration. Paralysis of the bladder and rectum was present; cystitis and bed-sores followed, and death occurred in one month.

"Post-mortem examination held ten hours after death. Cranium: the vessels of the pia mater were full and distended. There were extensive adhesions of old standing; said adhesions between the fold of the dura mater, descending in the interlobular fissure, separating the two hemispheres of the brain. The brain, on inspection, was found healthy and firm to the touch, but two ounces of serum were found in the ventricles. The spinal column was not opened, but two ounces of serum were collected while escaping from the vertebral canal when removing the brain. The heart: the right ventricle contained a fibrinous clot extending to the pulmonary artery; the left ventricle contained fibrous clots and a bloody clot, and some two ounces of a dark liquid. The liver was of normal size, but of a slight nutmeg colour. The spleen was four times as large in all proportions as in the normal state, but of normal consistence. The lungs were normal, well inflated; but there were adhesions to the chest wall around the base of the right one. The kidneys were both larger than usual, the right one being the largest; both were soft, and the upper part of the parenchyma of each had a gangrenous patch of the size of a silver half dollar. The calyces contained no pus. The ureters of both sides were enlarged near their entrance to the bladder. The bladder was contracted, and contained some pus, and the walls were thicker than usual; there was no enlargement of the prostate gland. The stomach was apparently normal, but contained about a pint of greenish liquid. The ileum and jejunum were slightly congested."

CASE XXV.—Pressure 40 lbs. J. W. G., æt. 29, American, had worked for nearly three months; had suffered before from pains in the legs, but after a day's rest returned to work. Half an hour after a shift of two hours he had violent epigastric pain, paraplegia, and paralysis of the bladder. Cystitis followed, and he was well in three and a half months.

CASE XXXV.—Pressure 49 lbs. W. S., æt. 30, German, had worked for three months. After completing a shift of one hour's duration, and passing through the lock in four minutes, he became at once unconscious, and died in two hours and a quarter. Death in this case was attributed by Jaminet to the fact that the man had not had a meal for at least six hours.

"Post-mortem examination sixteen hours after death. Cranium: all the blood vessels of the scalp, as also all the membranes covering the brain, were highly congested, and about two ounces of serum escaped from the vertebral canal when the brain was removed. The brain was congested, and two ounces of serum found in the ventricles. The heart was of normal size; the right and left ventricles were normal. The lungs were inflated, and of normal appearance, but there were extensive adhesions around the base of the right, which seemed to be of long standing. The liver was normal, as well as the spleen. The kidneys and bladder were normal; the latter was empty. The stomach normal, and entirely empty. No traces of food were found," which confirmed Jaminet's opinion "that this man had not taken any dinner, and probably a very light breakfast, but had been drinking quite freely, as was afterwards ascertained."

CASE XL.—Pressure 50 lbs. M. H., æt. 24, Irishman, had worked for three and a half months. Half an hour after decompression complained of paralysis of the legs and of shooting pains in the chest. Some hæmoptysis (about three ounces); face flushed; pupils contracted; skin hot; pulse 110 per minute. The blood brought up was very red. Auscultation showed crepitations at the anterior and middle parts of right lung. During the following two weeks he had slight hæmoptysis and some purulent expectoration; the crepitations diminished, and he then left the hospital.

CASE LXXV.—Pressure 49 lbs. J. A. H., æt. 25, German, had worked for three and a half months; had been drinking freely, and neglecting his meals. Within a very short time after leaving the compressed air he vomited; a few minutes afterwards general paralysis supervened. There was paralysis of the bladder and rectum; cystitis and bed-sores followed, and he died in a fortnight. No autopsy appears to have been made.

Dr. Jaminet's opinion concerning the pathology of the illness we will examine later. His principal prophylactic rules were the following :—

1. Previous examination of men, rejecting especially those with heart disease or aneurism, chronic sore throat, blocked Eustachian tubes, or advanced lung disease. No lung disease at all would be permitted to a man working above 25 lbs. pressure.

2. Men of middle or low stature, and well built, would be preferred, as also single men of temperate habits.

3. No smoking to be allowed in the compressed air.

4. Three substantial meals should be taken daily, in which animal food should form the principal part ; alcohol in any form should be taken very sparingly.

5. Flannel clothes should be worn, especially on coming out of the air chambers.

6. Rest for at least one hour after coming out in a well-ventilated place, with a temperature between 65° F. and 75° F.

7. The process of "locking in" should last one minute for each 3 lbs. of pressure, and the "locking out" one minute for each 6 lbs. of pressure.

8. Short working hours as follows :—

For pressures from—

lbs.	hours' work.			hours' rest.		hours' work
15 to 20	2	thrice	a day, with	2	between each	2
20 ,, 25	2	,,	,,	3	,,	2
25 ,, 30	2	twice	,,	3	,,	2
30 ,, 35	2	,,	,,	4	,,	2
35 ,, 40	1	thrice	,,	2	,,	1
40 ,, 45	1	,,	,,	4	,,	1
45 ,, 50	1	twice	,,	6	,,	1
50 ,, 55	1	once	,,			

The chief engineer, J. B. Eads, considered that the use of galvanic bands, or armour, made of alternate scales of zinc and silver, and worn round the wrists, arms, ankles, and waist, and on the soles of the feet, was to be recommended, and at length all the men were provided with them. Jaminet was unable to agree that the men who wore these bands were less liable to suffer from illness than those who did not.

The curative treatment consisted in rest in bed; administration of stimulants, beef tea, and ice. No water or other drink was allowed for two hours, and baths were forbidden.

Regarding the prevention of the illness, two medical men, who had conducted the post-mortem examinations previously to the time when Jaminet commenced his observations, expressed the following two opposite opinions :—

1. "That the affection by which the labourers in the air chambers are attacked is chiefly to be attributed to the change from a very condensed to a comparatively rarefied atmosphere."

2. "I believe the greatest danger to persons entering the caissons is that they enter too rapidly; and that they should admit the pressure more moderately, so that the heart and internal organs accommodate themselves more gradually to this process of congestion. And as to the manner of coming out of the air lock, I should think it advisable to come out as rapidly as possible; for in every case, whether they suffer or not, there must take place a certain degree of reaction to the surface of the body, which is only accomplished by the removal of the atmospheric pressure in entering the open air."

Jaminet pointed out that the illness always followed the "locking-out" process; but, since he required the "locking in" to last twice as long as the "locking out," we are forced to conclude that he considered the former the more dangerous process.

Eads, relying on the fact that the air-lock tenders went backwards and forwards between the compressed air and the open air several times during a watch of two hours, and were never attacked with illness, considered both the "locking in" and "locking out" processes to be of little moment, and said that in the length of stay in the compressed air would be found the real source of danger.

There are five other accounts of autopsies on fatal cases at the St. Louis bridge, given by the late Dr. Jaminet; they did not come under his observation. As post-mortems on these cases are very scarce, and Jaminet's book is out of print, these are given *in extenso* here.

"J. Moran, æt. 35, Irish. Admitted to the hospital on March 10th, 1870; died on the 19th of the same month, nine days after his admission. When sent to the hospital he had only worked two hours in the caissons.

"The spinal column was first opened. In dissecting down through the dorsal muscles the veins were found to be very numerous, and distended with dark and tarry blood. The vascularity signally increased with the approach to the spine. On removing the vertebral arches, and exposing the dura mater, the cellular tissue exhibited great vascularity and reddish gelatinous infiltration. The dura mater was separated from the spinal cord by a copious collection of serum, fluctuating on pressure, and changing its level on altering the position of the body. The serum was not collected and measured, but was estimated at about two ounces. Leaving the spinal cord and its membranes *in situ* we proceeded to the cranial cavity, and removed brain and spinal cord together. The arachnoid membrane of both brain and cord was intensely vascular; its vessels of larger calibre; its structure succulent, and at various places of the brain changed in thickness and transparency, and covered with inflammatory products of a whitish-grey hue, besides being raised off by subarachnoid serous infiltration. In pressing on the spinal cord some elastic resistance was observed, which proved to be serum in its canal, so much accumulated in that space, that, being pressed from two opposite directions, it would distend the cord cylindrically. Near the cauda a moderate sized vein was completely thrombosed. The right side of the heart was filled with coagulated fibrine, which extended into the pulmonary artery; whereas the left side contained some blood of a dark appearance not coagulated. The lungs were well inflated: anteriorly, they were of normal colour; but, posteriorly, darkened from hypostasis. The kidneys, slightly enlarged, showed venous congestion. There was hæmorrhagic infiltration about the junction of the cortical and medullary substance. Ureters normal. About the bladder, and extending below the peritoneum, backwards and upwards, there was extravasation of blood without any mechanical lesion. The bladder itself, although containing a small quantity of urine mixed with blood, was collapsed, and, from previous distension, far larger than usual. The mucous membranes thickened, softened, and discoloured. Intestines, liver, and spleen were marked by hypostatic conditions, with extravasation of blood.

"G. S. Alt, æt. 22, German. Admitted to the hospital March 10th, 1870, after working two hours in the caissons; died March 22nd.

"The brain and spinal cord were found highly congested, the latter being softened in many places to a pulpy consistency. There was evident subarachnoid effusion, and probably more than a normal quantity of fluid in the dura mater of the cord. Small clots of extravasated blood were found at different points on the external surface of the latter membrane. All the abdominal viscera were surcharged with blood, the lungs suffering less in this respect than any of the other organs. There were clots of blood found in both kidneys; one of the ureters was very much enlarged.

"H. Krausman, æt. 27, German. Admitted to the hospital March 22nd; died next day.

"The whole contents of the cranium were found highly congested, with effusion beneath the arachnoid, the vessels of the latter membrane being highly injected. Blood oozed freely from the substance of the brain on section. The spinal cord presented pathological conditions precisely like those of the brain, with the addition of the existence of clots of extravasated blood at different points inside the dura mater; there was also a congested condition of the thoracic contents, less marked probably in the lungs than in the other organs. The abdominal viscera were very highly congested, with extravasation of blood in the kidneys. The mucous membrane of the bladder was healthy, and a small quantity of bloody urine was in the bladder.

"T. L. Baum, æt. 21, German. Admitted to the hospital March 22nd, 1870; died next day.

"On examining the contents of the cranium the substance of the brain was found surcharged with blood, oozing freely from minute points on section. The meninges were also highly congested, and considerable serous effusion was between them, mostly under the arachnoid. The spinal canal was also opened and examined, and about the same condition existed here as in the brain. The effusion under the dura mater was well marked. There were also found on the inside of the dura mater, at several points, small clots of extravasated blood. On examining the thorax the small capillaries of the pleura and pericardium were found highly injected. The lungs very highly congested, but much less than the other organs. All the abdominal viscera were intensely congested; clots of extravasated blood were found in the kidneys, and small dark patches on the mucous membrane of the bladder resembling ecchymosis.

"G. Barrows, æt. 22, American. Admitted to the hospital on April 1st, 1870; died on the 12th.

"The brain and spinal cord and its meninges were found congested, and with slight subarachnoid effusion. The thoracic viscera were found normal except for some slight adhesions of the pleura. On opening the abdomen the intestines and the peritoneum were found highly inflamed, with extensive adhesions between them. The bladder and the rectum were found gangrenous, the former having been perforated by ulcerations, discharging its contents of bloody urine into the peritoneum.

"J. Sayers,[1] æt. 21. Admitted to hospital after his first watch of two hours; died in twelve days.

"The brain and spinal cord were found highly congested, the latter being softened in many places to a pulpy consistence. There was evident subarachnoid effusion, and probably more than a normal quantity of fluid in the dura mater of the cord. Some clots of extravasated blood were found on the external surface of the latter membrane. All the abdominal viscera were surcharged with blood, the lungs suffering less in this respect than any of the other

[1] This case is recorded by Woodward in his "St. Louis bridge."

organs. There were clots of blood in both kidneys; one of the ureters was very much enlarged."

Dr. Bauer, of the City Hospital, St. Louis, wrote an article[1] concerning the illnesses that arose at the St. Louis bridge. Without detailing the cases he had an opportunity of watching, he sums up the symptoms as follows:—

"On coming out the workmen are pale and fatigued, and have often to lie down; some have involuntary muscular contractions, with hæmorrhage from the nose and lungs. In grave cases there is paralysis of different degrees, from a slight paresis to a complete loss of sensation and motion; often bladder troubles; often hæmaturia; respiration not troubled; fever rarely shows itself, and it leads to a fatal termination. Coma, with delirium, hiccough, stertorous breathing, and muscular cramps; pupils are dilated. Among the paralytics was found in a fatal case (post mortem) cerebral and spinal congestion; œdema of the arachnoid; softening of the brain and spinal cord, without a determined localisation. In one case (? at St. Louis) the softening occupied the anterior horns and the lateral columns in the whole length of the spinal cord. Baumgarten found in this focus abundant neuroglia cells fattily degenerated."

A French engineer (Malézieux) has given a similar account of the illnesses at St. Louis.[2]

In the years 1871 and 1872 the two caissons for the foundation of the piers for the Brooklyn Bridge, New York, were sunk by the aid of compressed air. A

[1] "Pathological effects upon the Brain and Spinal Cord of men exposed to the action of a largely increased atmospheric pressure"—*St. Louis Medical and Surgical Journal*, May 1870.

[2] "Report on the public works of America," 1870; translated into French, and published in Paris in 1875.

monograph on the medical aspect of the work was written by Dr. Andrew Smith.[1] The pressure varied from 18 to 36 lbs. to the square inch above the atmospheric pressure. Gas was employed for the lighting of the caissons. The number of men employed at one time in one caisson varied from 50 to 120 in the daytime and from 15 to 30 at night. Concerning the ventilation of the compressed air chamber, Dr. Smith says: "By increasing the number of compressors by which the air was supplied (the excess of air escaping beneath the edge of the caisson) the atmosphere was brought to such a degree of purity as to contain only one third of 1 per cent. of carbonic acid, as I determined by actual analysis. This amount of vitiation was not found to affect the men unfavourably. To maintain this standard, however, nearly 150,000 cubic feet of air were required per hour." At first the men worked two shifts of four hours, separated by a period of rest of two hours. As the depth increased the hours were reduced, until at last the two shifts comprised but four hours, divided by a four hours' interval.

During the four months that Dr. Smith was in charge of the men working in the caissons 110 cases of illness due to the compressed air arose, and of these 3 proved fatal. He puts on record 27 cases: of these a case of suppurative inflammation of the middle ear, a case of rupture of the tympanic membrane, and a case of pain in the frontal sinuses, although caused by the compressed air, are so obviously due to mechanical causes, and differ so materially from the bulk of compressed air illnesses, that we may

[1] "The physiological, pathological, and therapeutical effects of compressed air," by Andrew H. Smith, M.D. (Detroit, Mich., 1886); and "The effects of high atmospheric pressure, including the caisson disease," (a previous edition of the same book), 1873.

for the time exclude them from the category of true compressed air illness. Of the remaining 24 cases, 9 presented the symptoms known by workmen as "bends," or pains in various parts of the body, principally the extremities, and sometimes confined entirely to the joints: these pains all appeared soon after leaving the compressed air, and disappeared in the course of one or several days.

In CASE No. VII. there was swelling as well as pain of one knee, accompanied by heat and tenderness, which seems to suggest that this was a case of synovitis: subsequently to the disappearance of the pain and swelling a greenish yellow tinge of ecchymosis appeared over the front of the knee.

In CASE No. XII. pain in the left shoulder and arm was followed in twenty-four hours by the appearance of minute bright red points of extravasated blood where the pain had been most severe.

CASE No. XX.—Severe pain in right fore-arm. Into the middle of the palmar aspect of the fore-arm two minims of 100 per cent. solution of ergotine were injected. "The following day considerable swelling had taken place at the point of puncture. The original pain still continued, though less severe." Four days afterwards "the patient presented himself with a similar, though more extensive, swelling on the other side of the arm, the previous swelling having disappeared. This secondary swelling followed very closely upon the first. It subsided promptly under the use of cold applications; but on the 10th another similar swelling appeared on the part of the arm above the elbow. It was excessively hot and painful. By the continuous use of ice it was soon dissipated without suppuration."

CASE XXIV.—Pain in right knee, and considerable swelling above and internal to the patella. Slight elevation of temperature. Relieved by cold douche.

Except in the cases mentioned above no swelling or ecchymosis accompanied or followed the pain. In 9 cases some amount of paralysis existed.

CASE VIII.—Pain in arms and legs, chest and abdomen; vertigo; vomiting; paralysis of left leg, and paresis of right arm. The loss of power disappeared in two hours.

CASE X.—Pain in the epigastrium, arms, and legs; paraplegia, which was better in four hours; vertigo lasted at least five days.

CASE XIII.—Numbness and loss of power in right side; dizziness and vomiting. No note of the progress of the case.

CASE XVIII.—Paresis of legs; anæsthesia and partial paralysis of the bladder; pain in calves. Well in two days.

CASE XXI.—Pain in epigastrium; vomiting, followed by paralysis of legs and bladder. Sent to hospital. No further record.

CASE XXII.—Pain in right side; loss of feeling, and paralysis of the legs and "partly in arms" (according to the man). The paralysis passed off in four hours, and he was well in a few days.

CASE XXIII.—Numbness in left leg, and partial loss of motion. No further note.

CASE XXVI.—"Reardon, English, æt. 38, corpulent, began work on the morning of May 17th: was advised to work only one watch the first day, but nevertheless, feeling perfectly well after the first watch, went down again in the afternoon. The pressure at this time was about 35 lbs.; the duration of the morning shift $2\frac{1}{2}$ hours, that of the afternoon shift 2 hours. Immediately after coming out from the second watch Reardon was taken by very severe pain in the stomach, followed by vomiting. In a few minutes the pain seized upon the legs, which soon lost the power of motion, though they continued to be the seat of extreme pain, and were not entirely insensible to pinching or pricking. The vomiting continued all night; and toward morning he was removed to the hospital, where he gradually sank, and on the 18th died. The autopsy showed a slight engorgement of the lungs. All the other thoracic and abdominal viscera, as well as the brain, were healthy. The spinal cord was found to be intensely congested, and opposite the two lower dorsal vertebræ there was an extensive effusion of blood pressing upon the cord."

CASE IX. was one of swelling of the male mammary gland, similar to one recorded by François, and referred to previously. There was engorgement of the left mammary gland, recurring each day after coming out of the caisson, and especially after the second watch. There was marked swelling and tenderness, which disappeared during the afternoon and evening, to recur again on the following day. This continued for more than a week.

CASE V.—Vertigo. Recovered completely in a few hours.

CASE XIX.—Pains in limbs and epigastrium; vomiting and vertigo. Well in two days.

CASE XIV. was peculiar, in that severe pain in both arms "was followed by dimness of sight and partial unconsciousness." He remained in this condition for two hours; and had a feeling of oppression about the chest for one week afterwards.

There remain two other fatal cases, and as the number of these recorded are very limited they are given here *in extenso*.

CASE XXVII.—"Patrick McKay, Irish, æt. 50, had been four months at work in the caisson, and had not complained of ill health. On April 30th he remained in the caisson half an hour beyond the usual time at the second watch, the pressure being 34 lbs. Some other persons who were with him in the lock, when leaving found that he was sitting with his back against the wall of the lock, quite insensible. He was at once carried up to the surface, and removed to the Park Hospital, where I saw him directly afterwards. He was then in an unconscious condition; face pale and dusky; lips blue; pulse irregular and feeble. Under the administration of stimulants he recovered some degree of consciousness, and begged incessantly for water. The urine was drawn with a catheter, and found to be intensely albuminous. Paroxysms of convulsions soon set in, in one of which he died, nine hours after the attack. The autopsy showed that all the organs were healthy except the kidneys, which were the seat of Bright's Disease, and were very much altered in structure. In this case the effect of the compressed air was merely to hasten an event which at best could not have been very long delayed."

CASE XXX.—"John Meyers, æt. about 40, a native of Germany, of a stout, heavy build, commenced work in the caisson for the first time on April 22nd, 1872, the pressure then being about 34 lbs. to the square inch.

He worked during the morning shift of $2\frac{1}{2}$ hours without inconvenience, and remained about the yard for nearly an hour after coming up. He then complained of not feeling well, and started for his boarding-place, which was but a few rods distant. As he passed through the lower story of the house, on his way to his own room, which was on the second floor, he complained of pain in the abdomen. While ascending the stairs, and when nearly at the top, he sank down insensible, and was dead before he could be laid upon his bed. The autopsy showed that the brain, heart, kidneys, and larynx were perfectly normal. The only lesion discovered was in the lungs, which were congested to a very remarkable degree. The entire extent of both lungs presented an appearance closely resembling that of a highly congested spleen. The spinal cord was not opened; but nothing was found elsewhere to account for the sudden engorgement of the lungs."

Regarding the respiration, Dr. Smith said that it was increased in frequency. Roebling, an engineer at the bridge, noted that it was diminished in frequency, from 30 to 50 per cent.[1] The pulse he considered to be increased in frequency except under low pressures, when it might be diminished.

Ætiology.—Dr. Smith considered that the one essential cause of the illness was "the transition to the normal atmospheric pressure after a prolonged sojourn in a highly condensed atmosphere." But, inasmuch as some individuals suffer while others are free from all symptoms, he assumed a special predisposition to exist in some cases. To a too rapid "locking-out" process was attributed

[1] Malézieux: "Fondations à l'air comprimé"—*Ann. des Ponts et Chaussées*," 1874, vol. i., pp. 329-401.

blame in some cases. He thought that it was noticeable that men inured to the work were less liable to be attacked than those who were fresh, although some serious cases occurred among the old hands. He gave figures which appear to show positively that heavily-built men are more frequently and seriously affected than those who are sparely built. Exertion soon after leaving the compressed air, the abuse of alcohol, and the commencement of work without having previously had a meal, were accredited by Smith, as by Jaminet, with the causation of the illness in some cases.

Preventive treatment at the Brooklyn Bridge was attempted by the formulation of a set of rules based primarily on those previously drawn up by Jaminet, and two or three other recommendations on the general maintenance of good health.

Curative treatment.—Smith recommends very strongly the use of ergot either by the mouth or hypodermically. The use of this drug was suggested to him by his theory of the pathology of the illness, which we will consider later. Morphine or atropine for severe pain ; friction, with or without stimulating liniments ; local hot water baths ; an alcoholic stimulant, with ginger, for epigastric pain ; sinapisms to the epigastrium, and swallowing bits of ice for vomiting. In cases of paralysis cold douches and frictions to the spine, cups or leeches ; and possibly venesection for coma. With the view of carrying out Foley's suggestion of recompression Smith recommended that a compressed air chamber of a suitable size should be constructed above ground for the purpose. The plan was not carried out at the Brooklyn Bridge.

In 1884-89 compressed air was employed in the construction of the foundations of the bridge over the

Firth of Forth. A thesis on the medical aspect of the work was written by Dr. Hunter, and to his kindness I am indebted for the opportunity of obtaining access to this interesting essay.[1]

In comparing the symptoms of mountain sickness with those of compressed air illness Dr. Hunter narrates the case of a diver employed at the Forth Bridge, who, when half way down to a required depth of 40 fathoms, signalled to be drawn up. He was found to be in an exhausted condition; lips blue; face livid; pulse small. There was extensive extravasation of blood into the cellular and other tisses of the neck, forming a powerful mechanical impediment to respiration.

Dr. Hunter first deals with the physiological effects of compressed air.

Epistaxis sometimes occurs on leaving the compressed air even in healthy people. It is pointed out that some observers have found that the diaphragm descended lower and that the lungs covered a larger surface of the heart's area of dulness when in the compressed air. Dr. Hunter apparently was not able to substantiate this observation.

Concerning the reputed diminution of the frequency of respiration in compressed air, the average number per minute of many cases observed was from 12 to 14.

Dr. Hunter found that the "primary effect of compressed air is to accelerate the heart's action, but, after remaining in for a considerable period, the pulse becomes slower than normal"; further, that there is an increase in the arterial tension. He did not observe any difference in the appear-

[1] "Compressed air: its physiological and pathological effects." By James Hunter, M.B., C.M. Thesis for the degree of M.D.—Library of the University of Edinburgh, 1887.

ance of the vessels of the human fundus oculi, though in a rabbit it appeared to him that the vessels appeared more pale and thready than normally. The temperature of the body—taken in the axilla—was sometimes above and sometimes below the normal. The pressure varied from 15 to 34 lbs. above the normal. At first the men worked from four to six hours, with a like period of rest; but this seriously affected the men's health. "The most dangerous times for caisson workers were (1) whilst the soft silt was being removed, owing to the excessive dampness, as well as perhaps to the presence of decaying animal matter; and (2) when the process of concreting was being carried out after a caisson had reached its proper depth, this being due partly to a want of a renewed supply of fresh air, and partly to the development of an excessive amount of carbonic acid. The cases of illness met with during these two epochs were in number out of all proportion to those occurring during the excavation of the clay or of the rock."

Dr. Hunter does not give the number of cases of illness which occurred, though it would appear that a large amount of illness arose, and that there were no fatal cases. He narrates several typical cases, mostly of pains in the extremities, and says: "The joint pain is of all the symptoms the most constant, and almost invariably it attacks the knee alone, or with other joints, rendering its poor victims, from its severity, absolutely helpless. Five sixths of the cases affected were with joint pains alone or in combination with other symptoms; in some instances the pains were milder and of a character not unlike that of rheumatism. Another prominent symptom met with was epigastric pain, accompanied by vomiting. Frequently, soon after leaving the caisson, where he had felt well enough, a man would suddenly be seized with severe epigastric pain and vomiting, which might be associated or not with the articular pains referred to, or with other symptoms. *E.g.* :—R., a young Belgian, complained of sickness, vomiting, pain in the epigastrium, and giddiness after having come out of the caisson, had a meal, and changed his clothes. He became unsteady, and fell. Pulse normal ; no elevation of temperature ; frequent attacks of painful retching, and he continued completely unable to steady his movements or to walk. He had no joint pains, though a week before he had suffered from what he termed *la pression*—meaning thereby the articular pains described—along with slight retention of urine, which, however, the application of warmth had sufficed to relieve. He had rested for two days, after which, though feeling somewhat ill, he resumed work. He had had previous caisson experience. He was ordered to be perfectly still ; to take milk and ice, bismuth and dilute hydrocyanic acid being also prescribed. Next day his condition had improved, the pain in the epigastrium was less severe, the sickness had diminished, and he could walk a little, though unsteadily. In the course of a week the symptoms disappeared, and he returned to his home in Belgium, prudently fearing to resume caisson work."

Dr. Hunter narrates a case of severe hæmoptysis following exit from the compressed air. The hæmoptysis was succeeded by an attack of acute lobar pneumonia, from which the man nearly died. He had suffered from hæmoptysis some years before.

In this thesis is the only record I can find of cases of vertigo which are obviously auditory in character ; this is probably due to the fact that the reports of previous cases are too irregularly and incompletely described to allow of their identification at the present day. Since this result has occurred in several cases observed at the Blackwall tunnel, and is often very prolonged and insusceptible to treatment, I will venture to reproduce here Dr. Hunter's remarks.

"The next important symptom was giddiness frequently accompanied by headache. The subjoined note illustrates cases in which this was the most prominent feature.

"Fritz Imgovitz, a naturalised German, a tall, thin man of about 48 years of age, had been employed for some months as a labourer, but had had no previous caisson experience. Thinking to earn larger pay he volunteered, and was permitted to descend to the working chamber of Caisson No. 1., where he remained employed during one watch under a pressure of 20 lbs. above the normal atmosphere. He felt well enough at work, and continued so until he reached his lodging in Queensferry, about a mile distant from the caisson, when he was suddenly seized with giddiness and severe pain in the head. He reeled and staggered worse than a drunken man. He could not stand, or walk a step, without assistance, his invariable tendency being to stagger to the left. He was assisted to bed; but even there everything seemed to reel round, and the most uncomfortable sensation of painful giddiness continued. With the exception of the headache and the complete loss of the power of equilibration, he suffered from no joint pain or other disturbance. He was ordered perfect quiet; and large doses of bromide of potassium and ammonium were given several times a day. Under this influence he, to a certain extent, improved, and in the course of a few weeks was able by the aid of a stick to come to my consulting room, a distance of five hundred yards or so. I used to put him at one end of my consulting room, and, placing myself at the opposite end, ask him to walk straight towards me. His attempts to accomplish this task were interesting, for he always most unwillingly found himself separated from me by the breadth of the apartment, his tendency continuing to incline his movements to the left. There was no alteration in the structure of the membrana tympani, and, beyond some venous fulness, no altered appearance of the fundus oculi. The patient went to his home in December 1884, and remained there till the middle of the March following, suffering from vertigo and headache, for which he was blistered and otherwise ineffectually treated. On his return I found, on testing his progressive power, as already described, that he reached a point parallel to me about three feet to one side. I prescribed again bromide of potassium, and combined with it fluid extract of ergot in 20-minim doses, to be taken thrice daily. The effect of this treatment was extraordinary. His headache daily improved, he could walk much more steadily, and in three weeks he had recovered so completely as to be able to resume his former work of a labourer. I ordered these drugs on the assumption that there existed in this man a congested condition of the vessels at the base of the brain and of the upper part of the spinal cord which produced the distressing symptoms recorded. I hoped the ergot would contract the vessels of the congested parts, and, by partially emptying them, relieve the vascular pressure, the pain produced by which was, it was believed, allayed by the bromide in large doses. I was not until eighteen months afterwards aware of the fact that Dr. A. H. Smith of New York had on similar grounds also recommended and successfully used ergot in large doses and frequently repeated. Several other cases of giddiness occurred, in all of which, with one exception, the tendency was to turn to the left. I am not informed of any reason why this special tendency should have existed, and its frequent occurrence may have been merely a coincidence.

"None of my cases—one sixth or so of the men employed—proved fatal, and none of the illnesses are likely to lead to permanent disablement. One man, who suffered severely from joint pains, still complains of what seems to be a rheumatic affection of the muscles of his left thigh, which is half an inch less in girth than its fellow, and is, moreover, remarkably sensitive to barometric changes. Another person, who had vertigo, still complains of deafness in one ear—that to which his tendency was to turn."

In regard to treatment Dr. Hunter recommends the adoption of rules similar to those of Jaminet to prevent the occurrence of illness. As remedies he suggests re-compression, electricity, moist warmth to the joints, sedatives, ergot, possibly alcohol for epigastric pain, and ice for vomiting.

Paul Bert mentions two cases of severe illness due to compressed air—suppressing the name of the works where they occurred. Both had paralysis of the legs, and bladder troubles. The depth was 23 to 28 mètres; and decompression was effected in sixteen or seventeen minutes. One of these returned to his native country, and no further account is given; the other died. The autopsy showed the spinal cord to be softened in the dorsal region; for some inches it was converted into a soft, diffluent mass of a yellowish-grey colour, which lost itself above and below in healthy tissue. The cord and brain were congested generally. Nothing else was noted abnormal. A number of other severe cases of illness occurred at the same works.[1]

Compressed Air in Subaqueous Tunnelling.

The use of compressed air in tunnelling operations is of very recent development.

The compressed atmosphere, instead of being contained in a vertical cylinder (the caisson), closed above and open below, is in a horizontal cylinder (the tunnel), closed at one end by a temporary diaphragm fitted with air locks, and open at the working end (the face) to the soil which is being excavated. In the former case, however loose the ground, the caisson is free from water as soon as the pressure of air within is sufficient to balance the pressure of the surrounding water; when the pressure of air exceeds this amount the excess overflows beneath the edge of the caisson. In the latter case the water pressure at the bottom of the face is greater than that at the top by the weight of water corresponding to the height of the tunnel. In a loose and running soil, therefore, the air is always rapidly escaping at the top of the face, and the water is coming in below. Special precautions, in the form of a shield provided with shutters, are necessary in loose or gravelly soils to prevent the whole of the air escaping and the tunnel being flooded. By this pneumatic method of tunnelling it is possible to make tunnels through watery soils, which would have been quite impracticable by the aid simply of pumps. The first tunnel in which compressed air was used was that under the Hudson River, intended to connect Jersey City with New York; this was commenced in 1871; compressed air was not employed

[1] "La pression barométrique," p. 406. Paris, 1878.

until 1879. Different attempts have been made to finish it, but because of financial difficulties work has been suspended since 1891. Another effort is likely to be made shortly to complete it. At first no shield was used, but, instead, a large piece of canvas was hung at the face. On July 21st, 1880, the water broke in, and twenty men were drowned. A shield was afterwards employed. The highest air pressure used was 35 lbs. to the square inch above the normal. A large number of illnesses are said to have occurred.

No complete medical record of the Hudson tunnel appears to have been made. A few of the cases are related by Dr. Corning.[1]

CASE I. had worked in compressed air only four hours. On coming out had paralysis of legs, retention, and then incontinence, of urine. Anæsthesia. Pains like red-hot needles in skin. Girdle pains. On 6th day sensation and motion in legs began to return; on 10th day he could stand; on 15th could walk with a stick; on 22nd discharged well.

CASE II.—About half an hour after leaving work pain in knees and abdomen. Had been a worker in compressed air for some time. Present attack after a debauch. Hyperæsthesia of lower limbs. Retention, and afterwards incontinence, of urine. Discharged well on 12th day.

CASE III. had been working in tunnel several days previously. Soon after coming out he had peculiar pain in the region of the right deltoid muscle, then an aching sensation in the joints of the arms and legs, especially the

[1] *New York Medical Record*, 1890, vol. i., p. 515. An abstract of Dr. Corning's paper is given by Dr. Jas. B. Ball in *The London Medical Recorder*, 1890, p. 241.

knees and elbows. This increased in severity, and rapidly became excruciating. Pains gradually diminished, and he was discharged on the 23rd day.

CASE IV.—Like No. III., and also anæsthesia of lower extremities, culminating soon after in severe hyperæsthesia. Bladder symptoms. Some paresis of legs.

CASE V. had worked three days in the tunnel. Dull pain in knees, soon followed by violent cramps in the abdomen. Lost consciousness. Paresis and superficial anæsthesia of legs. Bladder and rectum symptoms. Discharged well at the end of the third week.

CASE VI.—At work for one week. Aching of knees. Hyperæsthesia of legs. Recovered in a few days.

CASE VII.—At work in compressed air for six weeks, one slight attack of "bends" during that time lasting twelve hours. Present attack came on half an hour after coming out. Great pain in chest, shoulders, back, and abdomen; slight pain also in knees. Then paraplegia suddenly came on, causing him to fall. Anæsthesia of legs extending to trunk, higher in front than behind. Vesical tenesmus and retention. Vomited solids. Incontinence of fæces. Remained under treatment "for a long time, and when discharged there was still great weakness in the legs, and the general health was far from satisfactory."

CASES VIII. and IX. resembled No. III.

One case from the Hudson tunnel is recorded by Dr. Gilman Thompson[1] of the New York Hospital:—

P. C., æt. 38, had worked for many years in caissons.

[1] "Notes on the Caisson Disease"—*New York Medical Record*, 1894, vol. xlv., p. 133.

Frequent previous "bends," but no previous paralysis. One day after working in the tunnel he suddenly lost the power of motion and sensation in the legs; this lasted a day or two, and slowly improved, when retention came on, and he was admitted to the hospital. No constitutional symptoms; pulse, respiration, and temperature normal; urine contained 5 per cent of albumen and a considerable quantity of pus. Could not walk because of paresis of legs; but could move feet and toes. Sensation impaired in both legs; patellar reflexes slightly exaggerated; no ankle clonus; no local tenderness over spine or principal nerves. There was no pain at any time such as had been present on previous occasions. Hands and arms not affected. Catheterisation necessary. Strychnine and ergot given. Bladder irrigated with boracic lotion, and galvanism to the legs. After three days considerable improvement and increase of power in the legs. At the end of one week micturition returned. After sixteen days he walked easily. At the end of three weeks he had completely recovered.

Besides these few cases, which appear to have been accidentally recorded, a very large amount of illness occurred at this tunnel through the use of compressed air. Indeed, in 1885 the deaths were taking place at the rate of one a month—*i.e.*, of 25 per cent. per annum of the actual men employed. Subsequently the conditions under which the men were working improved, but even then there were two deaths in fifteen months out of a hundred and twenty men employed. One case of permanent paraplegia is said to have resulted. In this case the man had worked for six months in the compressed air. The paralysis came on suddenly when walking home from his work. He fell down between some railway waggons, where he remained all night. When discovered he was again put under pressure, but with no good result.[1] He also had paralysis of the bladder and rectum.

A very similar case was under the care of Dr. Ball at the New York Hospital.[2] Two other similar cases are mentioned by Thompson in which the recovery was complete.

In 1886 to 1890, during the construction of the City and South London Railway in London, compressed air was first used in conjunction with a shield. The compressed air was not necessary under the Thames where the tunnel went through the London clay, but it was used in three lengths in South London where loose gravel and sand were met with. This work consisted of two separate tunnels, 11 feet 3 inches in external diameter. The pressure never exceeded 15 lbs. to the square inch, and no cases of illness occurred. The first tunnel on a large scale completed by means of a shield and compressed air was the St. Clair tunnel, under the St. Clair river in America. The highest pressure used was 32 lbs. per square inch above the atmospheric pressure. The external diameter was 21 feet.[3] I can find no medical account of this work, though a large amount of illness is said to have occurred. More recently tunnels under the Mersey,[4] the Clyde below Glasgow, and at several points in Glasgow in connection with the Glasgow District

[1] Remarks by Mr. E. W. Moir—*Minutes of Proceedings of Institution of Civil Engineers*, vol. cxxiii., session 1895-96, part i., p. 61.

[2] *New York Medical Record*, 1894, vol. xlv., p. 133.

[3] Paper read before the British Association on "Tunnel construction by means of shield and compressed air," by Mr. Maurice Fitzmaurice, 1894.

[4] Paper read before the British Association on "The Vyrnwy-Aqueduct tunnel under the Mersey," by Mr. G. F. Deacon, 1892.

Subway, have been constructed by means of a shield and compressed air.

In the Glasgow District Subway the pressure is said to have sometimes exceeded 30 lbs. to the square inch; one fatal result occurred within an hour after the man left the compressed air. No record of the case was apparently published, and no post-mortem examination made.

At the East River tunnel in New York, constructed for the conduct of gas pipes from Long Island to New York in 1893, four fatalities occurred,[1] the maximum pressure being 48 lbs. One of these men died half an hour after coming out of the compressed air; another expired in the air lock while coming out from his first shift of 2 hours in compressed air; and another on coming out "became paralysed from the shoulders down, and died shortly afterwards." No medical account of the accidents was published, but the following case is related by Dr. W. G. Thompson[2]:—

"J. H., æt. 33, moderate drinker, admitted to the Presbyterian Hospital August 8th, 1893. Had worked in compressed air for years; had only had slight attacks of anæsthesia and paresis in the extremities, coming on immediately after leaving the caisson, and lasting several hours at a time. The night before admission had been at work in the East River tunnel under a pressure of (?) 45 lbs. Took five minutes in coming out. Fifteen minutes afterwards he had pain of a tingling and lancinating character in the right leg, and was unable to walk.

[1] "Chief Engineer's General Report on the initiation and construction of the tunnel under the East River, New York," by Chas. M. Jacobs, M.I.C.E., 1894.

[2] *New York Medical Record*, 1894, vol. xlv., p. 133.

An hour later the left leg was similarly affected. Micturition and defæcation were unaltered; pulse, respiration, temperature, and urine normal. He retained some power in the legs, but was unable to stand; knee-jerks exaggerated, and there was some tenderness along the course of the nerves in both legs; hands and arms normal. Strychnine, ergot, and a cathartic were administered, and faradism to the legs. On the 4th day the paralysis had gone."

CHAPTER II.

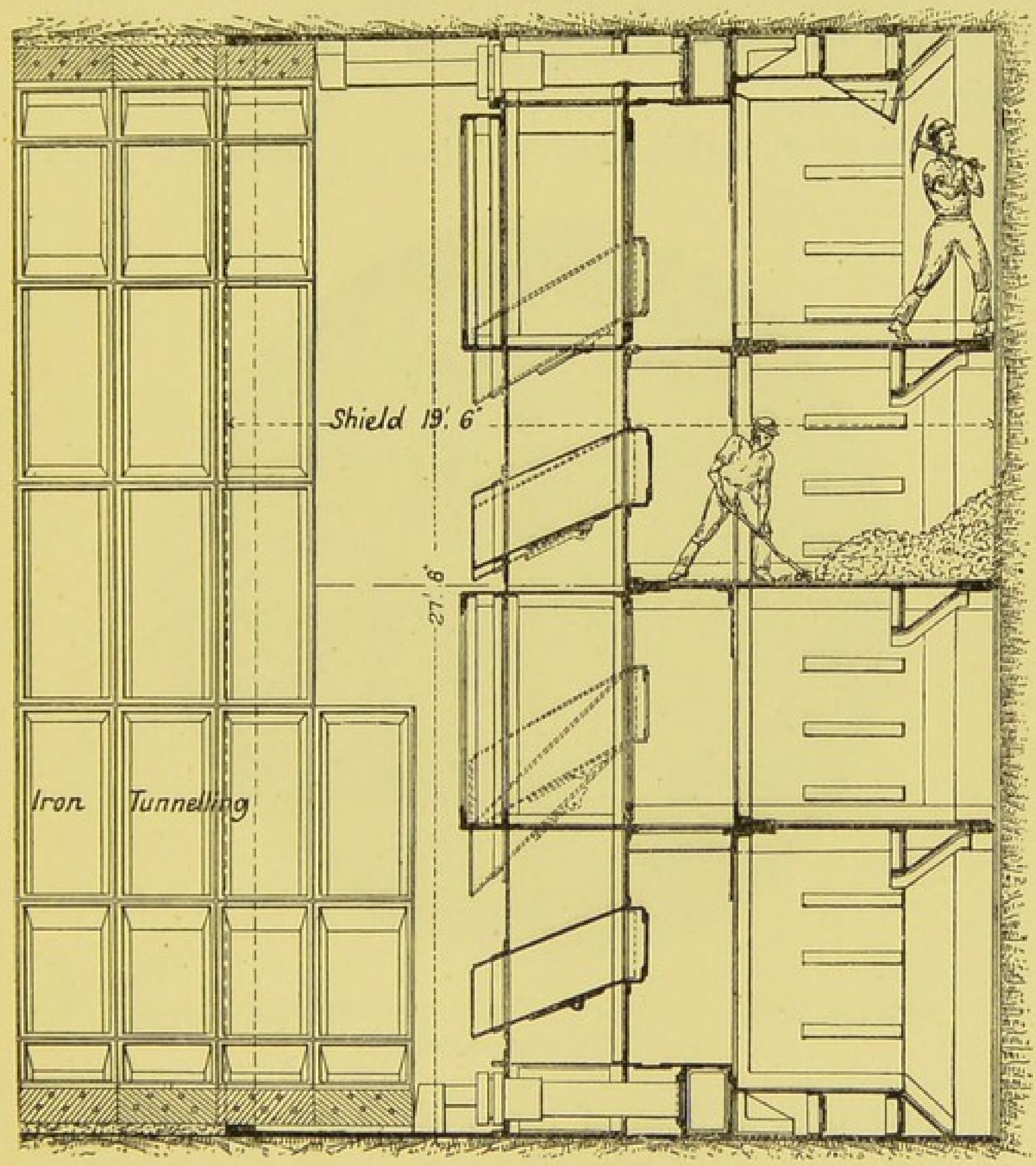
THE BLACKWALL TUNNEL.

IT would appear unnecessary in this place to enter in any detail into a description of this kind of work, but a very brief sketch may assist in rendering clear the conditions under which the men are placed.

The total length of the tunnel from entrance to entrance is 6,200 feet; that part under the river is 1,212 feet, and is horizontal; the remainder consists of the two inclined approaches—the one on the north side with a gradient of 1 in 34, that on the south side 1 in 36. The open approaches on the two sides account for a length of 1,735 feet. The first portions of the tunnel proper were constructed on the "cut and cover" plan, and the water was dealt with by pumping; in nearly the whole of the remaining portion compressed air was necessary. The depth of the floor of the river portion below high water is 80 feet. The maximum air pressure employed in this portion of the tunnel was 27 lbs. to the square inch, and the average pressure was a few pounds below this.

Four vertical shafts or caissons were sunk, two on each side of the river; through all of these the tunnel passes. The depth of these below the ground level is 75, 98, 98, and 76 feet from north to south respectively. The maximum air pressure employed was 36 lbs., and this was necessary in fitting an air-tight floor in one of the deepest caissons.

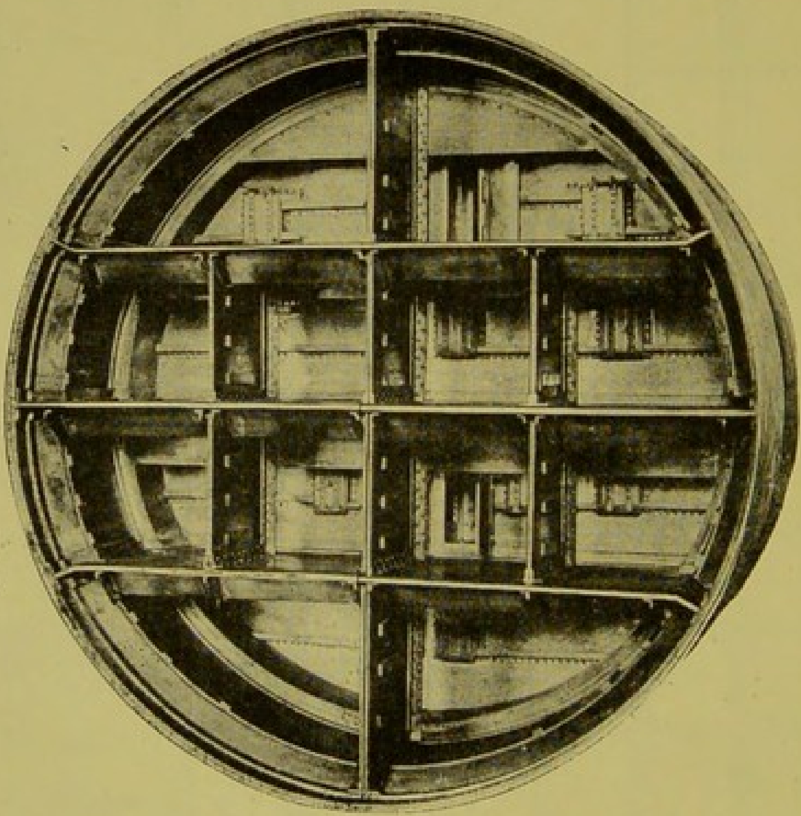
During the process of tunnelling the distal portion of



SECTION OF SHIELD. (FROM "ENGINEERING.")

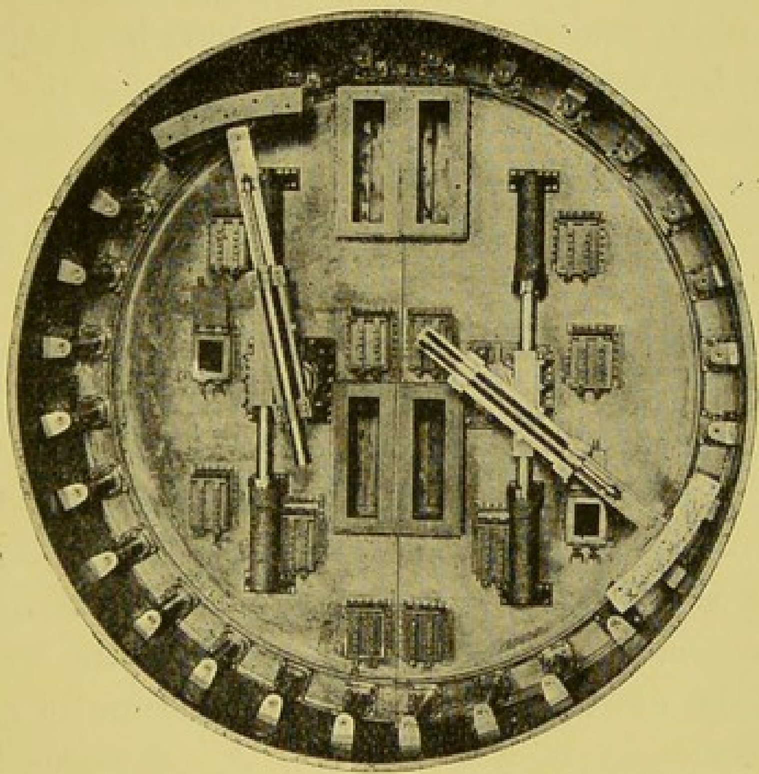
the tunnel, consisting of a variable length, is cut off from the proximal portion by an air-tight diaphragm consisting of a brick and concrete wall 12 feet thick. In this wall are built three air locks—two below, for the ordinary traffic of men and trucks; and one smaller one at the top, to be used as an emergency outlet in the event of a sudden inrush of water at the "face." Each air lock is provided with an inner and an outer air-tight door, both opening towards the portion being excavated, and also appropriate air cocks.

Since the tunnel is lined with iron, as progress is made



FRONT OF SHIELD USED AT BLACKWALL, SHOWING THE CUTTING EDGE AND COMPARTMENTS.

the part of it in front of the brick diaphragm or bulkhead may be filled with compressed air forced in by air compressors, and the only point of escape for the air is at the "face." Between the "face" and the excavated tunnel is the shield; at Blackwall this consists of a steel cylinder 19 feet 6 inches long, over-lapping the part last erected of the iron lining. The cylinder is strengthened by two steel diaphragms furnished with appropriate doors and material shoots; the front of the shield is divided by platforms into twelve cells, so that the whole of the face can be attacked at once. This, however, is only practicable when a comparatively impervious soil is being excavated; where the soil is loose running sand and gravel the escape of air is so free that no air compressors could replace



BACK OF SHIELD USED AT BLACKWALL, SHOWING THE HYDRAULIC ERECTORS, HYDRAULIC JACKS, DOORS, AND MATERIAL SHOOTS.

the loss rapidly enough, and the tunnel would at once be flooded with water. To overcome this difficulty at Blackwall the whole of the face has been closed with movable shutters, behind which the men work; by manipulating these shutters a portion only of the face is opened at one time. A large part of the tunnelling at Blackwall has been through loose running gravel. The danger of flooding was increased at the deepest portion of the river, where the river bed was only 5 feet 6 inches above the top of the tunnel. It was attempted to lessen this danger by dropping into the deepest portion of the river several thousand tons of clay. In spite of this the river broke in twice, though the pressure of the remaining air sufficed to prevent it rising in the tunnel to a greater height than 7 or 8 feet, and therefore fatal consequences were averted. Without this precaution the completion of this portion of the tunnel would appear to have been impossible; the clay had sunk into the cavity formed by the running ballast, so that for weeks a considerable portion of the face was occupied by it, and the tunnel was actually piercing through an artificial soil that had been dumped into the river.

The number of men employed at one time in the compressed air varied between 30 and 70 or 80. There were three shifts of 8 hours each during the 24: an interval of three quarters of an hour was allowed in the middle of each shift for the men to come out and have a meal; so that each man was in the compressed air for 7¼ hours per day. On leaving off work the men were allowed the use of a lift, so that the exertion of climbing an 80-feet staircase was avoided. A hot room, kept at a temperature of about 70° F., was provided for the men to change their clothes in and to rest in after leaving the compressed air. The resting was more imaginary than real, and could not be enforced, as the dwellings of the men were scattered over a very large area in the south and east of London; and the men, on leaving work, were anxious to get away rapidly. Hot coffee was provided for them on coming out of the air locks. A medical air lock, constructed out of a boiler, was placed near the hot room, so that in case of illness recompression could be effected without carrying the patient below, and thereby interfering with the traffic through the ordinary air locks. The contractors (Messrs. S. Pearson and Son) had a set of rules drawn up for the guidance of the men of a similar nature to those used at the Brooklyn Bridge.

CHAPTER III.

ILLUSTRATIVE CASES.

THE following cases are selected from a list of over two hundred similar ones of very varying degrees of severity that have occurred at the Blackwall Tunnel: a number of these are inserted, not because they present peculiar or rare features, but rather to illustrate the similarity of onset and course of the most common and most typical variety of compressed air illness. All of the cases of auditory vertigo are detailed because they have not previously been met with and recognised by writers on the subject; and a few others are recorded because they presented unusual objective signs.

CASE I.—"Bends." Recompression.

D. left off work at 6 a.m., Dec. 22nd, 1894, after working the usual shift of 8 hours. Pressure 20 to 24 lbs. Twenty minutes afterwards he had pain in both knees, most severe in the left knee; also slightly in thighs. No swelling. Battery used, and he was put into the medical air lock; the pain was then easier, but lasted for some hours afterwards. Seen at 11 a.m. No pain, no tenderness. Heart: apex, area, and sounds normal. Pulse 84; pulse pressure 7 ozs. (measured by Batten's clinical pulse manometer); no perspiration. Liver: the dulness in right nipple line was relative at the 5th rib, absolute at the 6th, and extended below to the costal margin. Has only been working in compressed air for two days. Returned to work Dec. 23rd at 2 p.m. He felt quite well on leaving at 10 p.m.; but when in bed, at 1 a.m., Dec. 24th, he had very severe pain in the right knee, and some pain in other parts of both legs; this was so severe that he returned to the works, went into the medical air lock to full pressure, but received no relief. He went in again, and came out very slowly; the pain was much easier, and he returned to bed. Seen at 11 a.m., Dec. 24th. No additional physical signs; no pain, no tenderness.

CASE II.—"Bends."

C. T., æt. 35. On Jan. 15th, 1895, left off work at 6 a.m. Pressure 20 to 25 lbs. Pain in legs, mostly in knees; came on at 6.15. This was slight at first, and he took little notice of it, but the pain gradually became worse until mid-day. He had gone to bed at 9.30 a.m.; rubbed the knees with lin. tereb. acet., and wrapped them up in flannel; but he was unable to sleep. Seen in the afternoon. No swelling of legs; no physical signs of disease.

Jan. 16th: Pain much easier, but not gone. Gets up, but feels weak on his legs.

Jan. 18th: Walked to the works. Complains of weakness in lower extremities. Has had slight giddiness. No alteration of reflexes.

Jan. 21st: Returns to work quite well.

CASE III.—"Bends." Recompression.

Jn. S., æt. 31, had worked nine shifts in compressed air. No ill effects until April 7th, 1895; he then worked from 6 a.m. to 2 p.m. Pressure 19 to 25 lbs. A few minutes after coming out of the locks, at 2 p.m., and before he reached the warm rooms, he had sudden pain in the left arm. Went into medical air lock; was better while in, but the pain came on again when he came out, and became worse after he arrived home. Seen at 5 p.m. Very severe pain in the left arm, mostly above the elbow; no swelling; no particular tenderness. Morphia (gr. $\frac{1}{4}$) and atropine (gr. $\frac{1}{140}$) injected into the arm, and lin. terebinth acet. rubbed in. He was better in ten minutes, and walked home. (He ascribes his illness to the warm rooms being cold, the steam being turned off on the two preceding days when he left work, and he had to return home in wet clothes.)

April 8th: Left arm better, but still painful.

April 10th: A heavy feeling in the arm remaining.

April 17th: Returns to work. The feeling of heaviness in the left arm has continued slightly until now. On re-entering the compressed air to-day this feeling entirely passed off, and did not reappear on coming out at the middle and end of the shift.

CASE IV.—"Bends." Recompression.

Geo. C., æt. 28, had worked in compressed air for about ten months; had "bends" once soon after commencing, and was away from work for three days. Active tunnelling operations were temporarily suspended on May 10th, 1895, and the "face" of the tunnel was more or less completely closed up. G. C., having finished his shift at 6 a.m., May 13th, pressure 19 to 23 lbs., had a pain in the right shoulder one hour after coming out, the pain occasionally radiating up to the right side of the neck. No swelling; tenderness in the anterior part of the left deltoid; pale complexion. The pain caused him to feel faint. Lin. terebinth acet. was rubbed in, but the pain did not become any easier during the course of the morning. At 1 p.m. the pain was severe, and he was put into the medical air lock and "leaked out." Morphia (gr. ¼) injected; ext. ergotæ liq. ♏xx and carbonate of ammonia given by the mouth. The pain was easier in ten minutes.

May 15th: Some pain in the right arm continues, though it is much better; a sort of dull, heavy feeling remains in the whole limb. Tenderness of the muscles of the arm; in the fore-arm this tenderness is localised along the middle of the front and back of the limb. ℞ liq. strychninæ ♏iii, ac. nitro-hydrochl. dil. ♏x ex aquā t. d. s.

May 18th: Occasional shooting pains in the elbow, lasting a minute or so.

(Two other men at work on the same shift suffered slighter attacks. These were the only three cases occurring during this month.)

CASE V.—"Bends." Recompression.

J. B. was working in Caisson No. 2 with J. W. (Case VI.) from 6. a.m to 5.30 p.m, with intermissions of half an hour for breakfast and one hour for dinner. At 6.15 p.m. he was seized with pain under the left knee-cap, "as if something was pinching inside"; it soon passed to the back of the knee, and it was difficult for him to stand; the pain also went upwards to the left hip; later, the right knee, thigh, and hip became affected. He returned home, but could get no sleep; so on July 30th he sought medical advice. He was then apparently in great pain, which came on in paroxysms, the legs becoming painfully rigid, and the body turned to the right side and drawn downwards. The "spasms" lasted from thirty seconds to two minutes, and occurred frequently. Knee-jerks absent; no paralysis; no head trouble; pupils equal; pulse low tension, irregular in volume and frequency 84 per minute.

He was carried to the medical lock, and the pressure raised; when this reached 5 or 6 lbs. the pain became much worse. After this, as the pressure rose, he gradually became easier. At 12 lbs. he was free from pain. The pressure was maintained at this height for thirty-five minutes, both inlet and outlet cocks being open, giving a current of fresh air. The pulse now became fuller and of a higher tension (96 per minute). The pressure was then gradually reduced. The patient could stand and move his legs without pain; the knee-jerks had returned. In thirty minutes more he left the lock, having been in sixty-five minutes. He was much better, and could walk unaided, although the pains had returned to a slight degree.

Aug. 1st: Much better. Walked to works from his home, a distance of over two miles.

Aug. 3rd: No pain. Returns to work Aug. 4th.

CASE VI.—" Bends."

J. W. had been working in Caisson No. 2 since the commencement of the use of compressed air there. On July 29th he was at work in that caisson with two other men at a pressure of 32 lbs.; this was before the whole of the water from the bottom had been forced out, and before active operations by larger gangs had commenced. He remained under pressure for eleven hours, from 6 a.m. to 5 p.m. *Three hours* after coming out he had a sharp pain in both knees, and, after a short time, in the right shoulder and right elbow. The pain was so intense that he was unable to stand. He was seen by a doctor, and on the morning of the next day came to the tunnel surgery. He had had scarcely any sleep. The pain was confined to the joints, and was of a sharp gnawing character. No swelling and no discoloration; tenderness on handling over the line of the articular surfaces. There was a tender spot on the outside of the right thigh 6 inches above the knee ; the knee-jerks were absent ; no pain in the head ; no deafness ; tongue slightly furred ; pulse 90, very small and rapid, almost "wiry" in character. The patient attributed the attack to getting his feet wet the day before, as he had never previously felt any bad effects of air work ; and he said that the pains were like "rheumatic" pains, which he had previously had. He walked very lamely, supported by a friend.

℞ : Phenazoni gr. xl
Sodii salicylatis ʒj
Tr. aurantii ʒj
Aquam ad ℥viii
M : Fiat mist. Sig. : ℥ss. tertiis horis.

July 31st: Pain has left shoulder. Knees are slightly better. Better night. Can now walk alone with a stick.

Aug. 1st: Much better.

Aug. 3rd: Slight occasional pain in the knee.

Aug. 7th: No pain. Feels all right.

CASE VII.—"Bends." Recompression.

H. C. had worked in the compressed air of the tunnel for the three weeks previous to July 30th, 1895, when the pressure varied from 15 to 25 lbs. On that day he was transferred to Caisson No 2, where the pressure was 32 lbs., and he worked from 10 p.m. to 5.30 a.m., July 31st. *Whilst in the compressed air* he felt a gnawing sensation in the right shin, then in the right arm, and finally it settled in the left shoulder. This was at 3 a.m. He remained in the compressed air till 5.30, and then came out to seek medical advice, as he could not hold his tools in his left hand. The pain became worse when in the open air. He had experienced similar pains two or three days previously, but had disregarded them. When seen there was considerable weakness of the left hand and arm, but not much pain. He was taken into the medical lock. When the pressure reached 12 lbs. the pain became worse: after this it gradually improved until a pressure of 19 lbs. was reached; pressure was then gradually reduced to nil. He was in the lock forty minutes. He could use his arm perfectly well, and only slight pain remained. During treatment in the medical lock he experienced formication of the left hand. [℞ lin. terebinth. acet.]

Aug. 1st: Better. Some numbness of left arm.

Aug. 9th: Feeling of numbness gone. Returns to work.

CASE VIII.—"Bends." Recompression.

G. B. had worked in compressed air for twelve months, and never suffered from its effects. On July 31st, 1895, he was transferred from the tunnel (pressure $16\frac{1}{4}$ to $23\frac{1}{2}$ lbs.) to Caisson No. 2 (pressure 31 lbs.), and worked from 10 p.m. to 6 a.m., Aug. 1st. Half an hour after coming up he felt a pain in the right knee. He had been wearing a leaky boot on that leg. He sought medical advice soon afterwards, and was at once taken to the medical lock. Pains slightly improved after half an hour in the lock. [Lin. tereb. acet.]

Aug. 2nd: Better. Has occasional attacks of pain only; these woke him up twice in the night.

Aug. 3rd: No pain. Can walk quite well, but has some stiffness in legs.

Aug. 10th: Returns to work, but elects not to again work in the caisson.

CASE IX.—"Bends."

Jn. G., æt. 47, generally works in the compressed air of the tunnel. He then worked two shifts in Caisson No. 2. He finished the last of these shifts at 10 p.m., Aug. 8th, 1895. Severe pain came on at 11.45 p.m. in both legs, mostly in the knees. Seen at 2.15 p.m., Aug. 9th. Had had no rest during the night. No physical signs. The left popliteal space is tender, and to a less extent the whole area of the left knee joint. Right knee less tender. Morphia and atropine injected subcutaneously, and lin. tereb. acet. rubbed in.

Aug. 10th: Pain a little easier, but still severe. Complains of weakness of his legs.

Aug. 12th: Better. Some stiffness in the left calf. Returns to work to-day in the lower pressure of the tunnel.

CASE X.—"Bends." Recompression.

Jas. G., æt. 30, has been working in the compressed air of the tunnel since the commencement. The last day or two he has been in Caisson No. 2. His last shift he finished at 6 a.m., Aug. 10th, 1895. At 6.30 a.m. pain came on in both legs and both shoulders—worse in the shoulders. Seen at 7 a.m. In great pain, which was not eased by rubbing with lin. terebinth. Put into medical lock, and pressure raised to 18 lbs.; pain had then gone, and he was allowed to "leak out" in forty-five minutes, at the end of which time there was no return of pain in the legs, though that in the shoulders was still present to some extent. There was no swelling over the seat of pain. Friction with lin. terebinth acet. was continued, and liquid extract of ergot (♏20) given every four hours.

Aug. 10th: Pain still severe; has had no sleep. Pil. opii (gr. i) at night.

Aug. 11th: Visited. He was out for a walk, but was said to be not much better, and to have had no sleep.

Aug. 12th: Better. Some pain continues in arm and leg. He describes the arm as being swollen ; no swelling can, however, be seen.

Aug. 14th : No pain. Returns to work.

CASE XI.—"Bends." Recompression.

E. H., inspector, has to be in compressed air frequently, but not necessarily for a long time together. On Aug. 10th, 1895, he was in Caisson No. 2 from 4 p.m. to 7 p.m ; pressure 32 to 35 lbs. At 7.40 p.m. pain came on in the lower portion of the back—he received a blow in the back, he explained, some months previously—and in legs, principally at a point which was also previously injured. Pain severe. Seen at 8 p.m. Put into medical air lock. Pressure raised to 18 lbs. Pain then gone at once. Allowed to "leak out" in forty minutes. Pain did not return.

CASE XII.—"Bends." Recompression.

J. B. After his last illness, on July 29th, 1895,[1] he returned to work on Aug. 4th, working generally in the compressed air of the tunnel. On Aug. 11th he worked his third shift in Caisson No. 2 ; pressure 32 to 35 lbs. Came out at 2 p.m. He then went home, and had dinner ; pain came on at 3.30 in legs, right arm, and abdomen ; vomited his dinner. Seen at 7.30 p.m. at the works. Put into medical lock ; better when pressure reached 18 lbs. ; no pain. Morph. sulph. (gr. $\frac{1}{4}$) and atropin. sulph. (gr. $\frac{1}{140}$) injected hypodermically. Allowed to "leak out" ; slight pain in right arm on reaching the open air. Felt giddy. No physical signs of disease.

Aug. 12th : Better. Slight pain about the knees still.

Aug. 17th : No pain. Returns to work Aug. 19th.

CASE XIII.—"Bends." Recompression.

T. R., æt. 26 (Aug. 11th, 1895), has been working in

[1] See page 77.

compressed air since the commencement, and for the last fortnight has been in the high pressure of Caisson No. 2, but has not until now suffered from any bad effects. Left work at 10 p.m. On his way home, at 10.45 p.m., slight pain came on in his legs; this became worse at 1 a.m., and continued throughout the night; and he "crawled" down to the works in the morning—a distance of two miles. He was seen at 6.30 a.m. The pain was said to be very severe, though he was able to engage in a long conversation, quite ignoring for a time the pain. He was put into the medical lock. No alteration in the pain. [℞ lin. terebinth acet. c̄ lin. aconit. āā.]

Aug. 13th: Better. No pain.

Aug. 21st: Is at work again in Caisson No. 2, and complains of loss of appetite.

CASE XIV.—"Bends." Recompression.

S. W., æt. 44, has worked for eleven months in compressed air. Works in the tunnel; left off at 6 a.m., Aug. 12th. Pain came on two hours after coming out, in both arms, neck, and chest. (He had a pain previously on coming out to supper at 4 a.m.; but went into medical lock, and was better, and returned to work.) Applies for advice at 5.30 p.m., Aug. 12th. Put into medical lock, and allowed to "leak out." No improvement. Pain said to be very severe; cannot walk well. No alteration of knee-jerks; no physical signs.

Aug. 15th: Pain better, but stiffness in legs remains. Right knee-jerk brisk; no ankle clonus. Complains of numbness of feet. No anæsthesia.

Aug. 17th: Better. No pain. Returns to work Aug. 19th.

CASE XV.—"Bends." Recompression.

W. P. finished an 8-hour shift in Caisson No. 2 at 10 p.m. Aug. 16, 1895; pressure 31 to 34 lbs. Pain came on at 10.30 in the right thigh and both groins. Applies for advice at 8 a.m. next morning. Rubbed with lin. terebinth. Put into medical lock. Morphia (gr. $\frac{1}{4}$) injected hypodermically. No noticeable difference in the pain.

Aug. 17th: Pain continues in right groin.

Aug. 24th: Only occasional pain.

Aug. 29th: Well. Returns to work in tunnel.

CASE XVI.—"Bends." Recompression. Ergotinin.

D. E., æt. 30 (Oct. 13th, 1895), has worked in compressed air about eight months. Came out of compressed air at 10 p.m. to-day; pain came on at 11 p.m. in left fore-arm; had no sleep during the night. He returned to the works the next morning, and went into the medical air lock by himself at 6.30 a.m.; let himself out in twenty minutes, and was no better. Applies for medical advice at 7.30 a.m. Pain then very severe. Ergotinin ($\frac{1}{50}$ gr.) injected hypodermically in left arm; within sixty seconds of the injection he states that he is "much better."

Oct. 15th: Some pain in left arm persists; it is worst now in the left shoulder and left side of neck. Says the skin feels tight. There is no swelling. A draught of bromide of potassium and chloral is given, to be taken occasionally.

Oct. 16th: After 15 grains of pot. brom. and $\frac{1}{2}$ a drachm of syr. chloral he slept from 2 p.m., Oct. 15th, to 12.15 p.m., Oct. 16th. Returned to work to-day quite well.

CASE XVII.—"Bends."

T. J., æt. 43. Not worked in compressed air before.

Examined for this work Oct. 15th, 1895, and passed. He was of robust build, but not stout. Had ague some years ago in Brazil, but has otherwise been healthy. Went to work at 2 p.m.; had pains in the ears and forehead on entering the compressed air: this became easier when in; came out for tea at 6 p.m. He then had pains in the legs; these disappeared on returning into the compressed air. Came out at 10 p.m.; pain came on at 11 p.m., first in the feet, and afterwards in the legs, affecting principally the knees. He had been wearing thin boots, and his feet had become wet. Sent for advice Oct. 16th at mid-day; he was then seen at his own home. Had had no sleep; the pain was not much easier, though he had been using turpentine liniment. No swelling of knees or other parts; no pain in ears, no deafness.

Ergotinin (gr. $\frac{1}{100}$) by mouth, followed by morphia (gr. $\frac{1}{4}$) after one hour. A liniment containing belladonna, aconite, and turpentine.

Oct. 17th: Pain much easier; slight pain in arms and legs. Slept well.

Oct. 18th: Better. Still some pain in arms, especially the right.

Oct. 19th: Returns to work on Oct. 21st—outside the compressed air.

CASE XVIII.—"Bends." Abdominal pain.

C. F., æt. 23 (Oct. 21st, 1895), has worked in compressed air for three months; has never had "bends," but has suffered from itching frequently after leaving the compressed air. Came out at 10 p.m.; felt well then. Had supper; went to bed; slept well until 6 a.m., Oct. 22nd, when he woke up with pain in the epigastrium. This was easier in two hours, after taking some ginger. Seen at 11.30 a.m.; pain not entirely gone. A carminative mixture given. Returned to work at 2 p.m.

CASE XIX.—"Bends."

M. C., æt. 21 (Oct. 23rd, 1895), has been working in compressed air for six months; has not suffered from it until now. Came out at 10 p.m.; went home and to bed; woke up at 3.30 a.m. with severe pain in both knees; this prevented him from having any further sleep, and he has been in great agony since. He "could not stand on his legs unsupported because of the pain." Came to works for advice at mid-day. Seen at 12.30 p.m. in medical air lock; had been helped there by two men. Considerable pain and tenderness in both knees and all round joints; no swelling. Pulse pressure 6 ozs. Raised pressure to 16 lbs.; pain a little easier; allowed to "leak out"; fell asleep while leaking out. This took forty-five minutes; he then had slight pain only. Pulse pressure 7 ozs. A liniment containing aconite and belladonna.

CASE XX.—"Bends."

W. J., æt. 45 (March 23rd, 1896), has worked in compressed air here for twelve months; has only had one slight attack of "bends." During the last three days he has worked three shifts in Caisson No. 1; came out at 6 a.m., March 24th. Pain came on at 7.15 a.m. severely in both legs, and to a less extent in the shoulders and arms; he could not get any sleep, and the pain was extremely severe. Sent for advice, and was seen at 2 p.m. Pain as before described, and of an excruciating character, causing him to writhe about in agony. No swelling; no physical signs of any sort, except tenderness all over the arms and legs on deep pressure.

℞: Pil. opii gr. ss. st. et rep. post tertias horas s. o. s.

℞ : Lin. terebinth c̄ lin. aconiti c̄ lin. camph. co. āā.

March 25th : Still considerable pain.

March 26th : Much better ; no pain, but considerable stiffness about legs.

March 28th : Returns to work.

CASE XXI.—" Bends." Recompression.

J. G., æt. 30 (March 25th, 1896), has worked in compressed air for nearly two years. Has worked in Caisson No. 1 since March 22nd. Came out to-day at 2 p.m. ; pain came on at 4 p.m. in the left shoulder and left arm. Seen at 6 p.m ; no physical signs. Put into medical air lock at 6.15 p.m., and pressure raised to 20 lbs. ; no improvement in the pain while under pressure, and he is allowed to " leak out " in half an hour. A rubefacient liniment.

March 26th : Not much easier. Liquid extract of ergot (♏20) given every four hours.

March 28th : Better. Going to work on the 29th.

CASE XXII.—" Bends." Severe abdominal pain.

J. J. M., æt. 38. Examined for compressed air Feb. 6th, 1895. The note made at the time of the examination was : " Never worked in compressed air. Has been a diver at Vera Cruz for seven months, at depths up to 60 feet. Heavily built man (14½ stones). Heart : apex, area, and sounds normal. Lungs clear. Urine : no albumen. Pulse 84 ; pulse pressure about 8 ozs. Warned that he is not a suitable man for compressed air work." As he was to be employed as a foreman, and his services were supposed to be valuable, he obtained my consent to go into the compressed air for a short time on trial. He went into the pressure for six hours (divided into two parts ; pressure 20 to 25 lbs.). Pain in the legs came on two hours after coming out. On the following day (Feb. 7th) he went into the "air" again for three hours. The pain in his legs was easier while in the "air," but came on worse afterwards, as well as pain in the abdomen; he then sought medical advice, and was again cautioned as to his unsuitability for the work. Seen again on Feb. 8th; the pain was then much easier. On Feb. 10th he commenced his first shift of 8 hours, and finished at 6 a.m., Feb. 11th. At 7 a.m. he had very violent abdominal pain. Seen at 7.20 a.m. in medical lock in very great pain. Pressure was turned on up to 20 lbs. Morphia ($\frac{1}{2}$ grn.) and atropine ($\frac{1}{100}$ grn.) were injected hypodermically, and some hot coffee given. When first seen no pulse at the wrist could be felt. Skin cold; face very pale. He vomited once, and his bowels were open while in the lock. The compressed air was allowed to "leak out," taking thirty minutes in the process. Pain was then easier. The pulse improved in about one hour. Pain returned slightly on movement. He was wrapped in hot blankets, and hot bricks were placed to the feet. At 10 a.m. beef tea given was at once returned; a small quantity given later was retained. At no time could any physical signs of any lesion be made out. At 1 p.m. he had much improved, and was sent in a cab to the Seamen's Hospital. Seen again at the hospital at 11 p.m. He felt well, but looked very pale. Temp. 99°.

Feb. 12th (evening): Practically well. Abdomen said by Dr. Windsor, the house physician, to be "a little distended. No pain or tenderness; no signs of organic disease; slight pain in right shoulder; no head symptoms." Left the hospital on Feb. 16th well, and did not again express a wish to attempt compressed air work.

CASE XXIII.—"Bends." Recompression.

J. G. A., æt. 29, has worked in compressed air for about two years; has never had "bends" before to the smallest extent. On March 25th, 1896, he was working his third shift in Caisson No 1; pressure 25 to 26 lbs. Came out for tea at 5.30 p.m. Just before emerging from the lock he felt a pain in the left knee, which became worse on getting out. Rubbed with turpentine liniment: no better. Applied for advice at 7.15 p.m.; put into medical air lock, and pressure raised to 20 lbs.: no better; allowed to "leak out." A rubefacient and anodyne liniment was given him, and he did not again report himself.

CASE XXIV.—"Bends." Recompression.

W. S., æt. 27, has worked in compressed air for six weeks, and for last three or four shifts in Caisson No. 1. Was quite well until the end of the 8-hour shift, finishing at 6 a.m., March 27th, 1896, pressure 26 to 27 lbs., when he went home and went to sleep, but woke up at 10 a.m. with a pain in the right thigh; there was no swelling. He was put into the medical lock at 12 noon; when the pressure was raised the pain was a little easier. After "leaking out" the improvement was maintained, and he was much more free from pain. Not seen again.

CASE XXV.—"Bends," following rapid decompression.

W. F., æt. 37 (April 2nd, 1896), has worked in compressed air about two years. Has had "bends" in the knees once or twice, but this has never caused him to leave off work; was recently working in Caisson No. 1 for ten days, and then was transferred to the tunnel two days ago (where no case of illness has occurred for over a fortnight). He worked from 10 p.m. till 6 a.m. (3rd); pressure 16 to 20 lbs. When coming out of the compressed air with several other men he had no sooner entered the lock and shut the inner door than one of these men signalled for the large cock (which should only be used during the passage of trolleys) to be opened by the lock-tender on the outside. This was done. W. F. very much objected at the time and afterwards. Soon after coming out he had pains in the knees, and he ascribes the illness to the before-mentioned circumstance. He was given a liniment, and did not again report himself.

CASE XXVI.—"Bends." Small, ill-defined area of anæsthesia.

G. C., æt. 30 (March 29th, 1896), has worked in the compressed air for about two years. Has worked in Caisson No. 1 the last week; no ill effects until to-day, when, one hour after finishing the night shift at 6 a.m. (30th), pressure 27 to 29 lbs., he had a pain in the right arm and right leg, and could get no sleep; he had also a feeling of numbness in these limbs. Applies for advice 12.30 p.m. (31st). He has slight anæsthesia over a part of the right fore-arm, wrist, and hand, not well defined. Pain principally in the right elbow now. Has a very pale and pasty complexion. Examination of blood by hæmacytometer shows 5,870,000 corpuscles in each cubic millimetre of blood; hæmoglobinometer shows 100 degrees of dilution—*i.e.*, $\frac{100}{117.4} = \cdot 84 =$ the value of a nominal corpuscle.

April 2nd: Anæsthesia gone; some aching of the fore-arm remains.

April 8th: Practically well. Returns to work.

CASE XXVII.—"Bends." (?) Crepitation in muscles.

T. J. had not previously worked in compressed air. He was examined for the work on April 8th, 1896, and rejected. In spite of his not being passed he worked in the compressed air of Caisson No. 1 from 10 p.m. until 6 a.m. on the 9th; pressure 26 lbs. Soon after leaving work he had severe pain in the shoulders and knees, and sent for advice in the afternoon. Seen at 3.30 p.m.: apparently in great agony. There was no swelling of the painful joints, though they were tender. During the examination a slight crepitation was felt in the substance of the muscles above the right knee; this could not be felt again, and did not arise from the knee joint or its bursæ.

April 11th: Better. Still has pain in thighs.

April 14th: Got out of bed for the first time yesterday. Much better, but still has pain in the left knee and left shoulder.

April 15th: Returns to work outside the compressed air.

CASE XXVIII.—"Bends." Pain in perineum, etc. Recompression.

G. C., æt. 28, has worked for months in the compressed air of the tunnel. Has been working the last two shifts in Caisson No. 2. He came out at 6 a.m., Aug. 9th, 1895; pressure 31 to 32 lbs. Pain came on in the abdomen and chest at 7 a.m.; also in both legs; afterwards it was most severe in the groins, especially the left, and in the perineum. No difficulty in micturition. Lives at Lewisham—a distance of four miles—and had returned home when the pain came on. Returned to the works later in the morning, as the pain did not cease. Seen at 2 p.m. in the medical air lock. The pain was most intense in the perineum. Air turned on, and pressure raised to 20 lbs., and lin. tereb. rubbed into painful parts. He was then allowed to "leak out," taking forty-five minutes in the process; the pain was then easier, and he left to walk home.

Aug. 12th: Returns to work quite well.

CASE XXIX.—"Bends," fourteen hours after leaving compressed air.

J. K., æt. 25, was getting out of bed on the morning of Nov. 20th, 1894—about fourteen hours after having left the compressed air—in order to return to work, when he had severe pain in the knees and calves. The calves were tender. Seen at 2 p.m., Nov. 20th. The pain was less severe; he was up, and otherwise feeling well. Has never had rheumatism. Heart: apex, 5th intercostal space, ½ inch internal to left nipple line; cardiac area of dulness normal, sounds normal. Pulse 96, regular; pulse pressure 10 ozs. Lungs healthy. No swelling or discoloration of knees or calves. He states that he had a precisely similar attack two or three months ago. This previous attack resembled the present one in coming on fourteen hours after leaving the compressed air, and in occurring in the knees and calves.

Nov. 21st: Much better; no pain.

Nov. 23rd: Returns to work.

CASE XXX.—"Bends." Swelling. Recompression.

J. A., æt. 38 (Aug. 16th, 1895), has worked in Caisson No. 2 for four shifts. Not worked in compressed air previously. Has had an attack of "bends" after every shift, but has not previously applied for advice. To-day he was in the caisson from 6 a.m. to 10 a.m., pressure 31 to 34 lbs., when he came out for breakfast; pain came on a few minutes afterwards in the left arm and left knee. Seen at 10.30 a.m. There is a diffused swelling of the left upper arm—tender to pressure. Put into the medical lock, and allowed to "leak out." He was considerably better after this, and was told to leave off work for a few days.

Aug. 19th: Left arm still painful. There is an ill-defined, hard swelling in the left arm about the insertion of the deltoid, 2½ inches in diameter in a lateral direction, deep in the muscles, and apparently situated between the deltoid just above its insertion and the bone ; tender on pressure. Temperature normal.

Aug. 22nd : Very much better. Occasional slight "catching" pain in the left arm. Swelling in arm is still present, but is smaller. General health good.

Aug. 24th : Slight pain still in left arm. Only a little thickening remains about the insertion of the deltoid.

Aug. 28th : Well.

CASE XXXI.—"Bends." Swelling near knee. Recompression.

J. H., æt. 39, has previously worked in compressed air for two weeks in Glasgow. Examined and passed for compressed air work at the Blackwall Tunnel Aug. 21st, 1895. It was noted that he had very grey hair (he states that the greyness came on before he was 20 years old ; his father was grey early, and his brother's children, under five, are beginning to have grey hairs!), and also that he smelt of spirits ; against the use of these while working in the air he was warned. He commenced his first shift at 10 p.m. ; came out at 4.30 for breakfast ; half an hour afterwards he had a pain in both knees. Seen at 5 a.m., and put into medical lock, and allowed to "leak out." [℞ lin. terebinth acet. c̄ lin. aconiti āā.] 1 p.m., pain worse again. [Pil. ipecac. co. gr. v. st.] 5 p.m., slightly easier, but has had no sleep. Has slight tumefaction on inner side of left knee. Sent to Seamen's Hospital.

Aug. 27th : Came out of hospital feeling nearly well. Was treated there by morphia injections. No swelling of left knee now. On the lower and inner side of this joint is a small blue (? ecchymotic) patch half an inch in diameter.

Aug. 31st : Slight stiffness in both knees.

CASE XXXII.—"Bends." (?) Swelling.

P. A., æt. 29. Not worked in compressed air. Examined and passed March 30th, 1896. Worked his first shift in Caisson No. 1, from 2 to 10 p.m; pressure 27 lbs. Immediately after coming out he had severe pains in his legs, and could not walk. He remained in the warm room on the north side rubbing his legs with some liniment until 2 a.m. (31st), when he was carried through the tunnel to see me. At 2.15 I put him in the medical lock; the pain in the legs was then extremely severe. No physical signs. The pressure was raised, and he improved a little. He had half a grain of morphia; was allowed to "leak out" in forty-five minutes, and was then driven home, and recommended to use a liniment containing equal parts of lin. tereb. acet., lin. acon., lin. sap., and lin. camph. co.

March 31st: Easier, but still has some pain. Has had no sleep.

April 2nd and 3rd: Better, though there is a great deal of deep tenderness about the lower part of the left thigh; the tenderness seems to be in the bone.

April 7th: Right leg free from pain. In the left leg, 4 inches above the external condyle of the femur, is a small, soft, ill-defined, tender swelling, quite subcutaneous, and not fluctuating, at the back of the ilio-tibial band; also tenderness at the insertions and origins of muscles about the knee. He has been taking an ergot mixture; he now has mist. fer. c̄ strych. He states that two years ago he had a vein blocked in the situation of the above-mentioned swelling, and he was ill in bed for a week afterwards. Throughout the remainder of the month he complains of stiffness in the legs; there is no pain. The swelling had remained as before, though the tenderness had gone; it was probably venous in origin and of long standing, though not noticed or drawn attention to at the commencement of the illness. He does not again work in compressed air.

CASE XXXIII.—Synovitis of right knee joint.

H. J. L., æt. 22, has been working in Caisson No. 2 for three shifts. Not previously worked in compressed air. Finished the third of these shifts at 2 p.m., Aug. 11th, 1895; pressure 32 to 35 lbs.; he then, in the afternoon, walked about Victoria Park and neighbourhood for several hours. At 5 p.m. he felt a pain in the right knee. He had not sustained any injury to the knee. Applied for advice Aug. 12th. There is excess of fluid in the right knee joint; tenderness around that joint. Is not accustomed to long walks. Wool and bandage to joint.

CASE XXXIV.—Paresis of the legs.

W. F., æt. 37 (March 26th, 1896), is a painter and decorator but through lack of employment has been working in the compressed air of the tunnel for ten weeks; he was then working in the open air for two weeks, and then for three shifts in the higher pressure of Caisson No. 1. The second day after beginning work in the compressed air he had pains in the legs after leaving work; these soon passed off, and he suffered no further ill effects while working in the tunnel. After the first two shifts in the caisson he was free from illness. The third shift was from 10 p.m., March 26th, to 6 a.m., March 27th; pressure 26 to 27 lbs. About five minutes after leaving the lock he had pain in the abdomen, followed by numbness and weakness in the legs. After walking a little way the weakness in the legs increased; he could not walk at all, and he was carried home, a distance of two and a half miles. In the evening of that day he sent for a neighbouring medical man, and the following day for me. I saw him at 3.45 p.m.; he then had a distended bladder and incontinence of urine; had had no voluntary micturition for thirty-three hours; there was great weakness in the legs, and he could only just stand on them; knee-jerks very brisk; no ankle clonus; no anæsthesia; constipation for two days. He was catheterised, and admitted to the Seamen's Hospital. The urine then contained a trace of blood and albumen, but this disappeared in two days. He left the hospital on April 2nd; he could then walk fairly well, but had little or no control over the bowels or bladder, and micturition was frequent. Mist. ferri. c̄ strych. was given and continued.

May 4th: Legs not quite so well as they were; has to "throw" the left leg forward in walking.

May 24th: Has frequently a sensation of pins and needles and numbness in left leg from knee downwards. No anæsthesia. Troubles with micturition, and defæcation slightly improved. Complains of loss of sexual power. No weakness of the legs remains.

CASE XXXV.—Paraplegia.

C. H. æt. 34 has worked in the compressed air at Blackwall all the time that it has been in use, and has never suffered from it. On Jan. 15th, 1896, he came out at 9 a.m. for breakfast (having been in a pressure of 20 to 22 lbs. for three hours). While walking to the cage he felt a pain in the situation of his belt, and, thinking the belt was too tight, he loosened it; the pain was not altered thereby, was like a tight band round the body, and very severe. He ascended in the lift. When at the top he found he could not walk, and was carried to the medical air lock, and his legs rubbed with turpentine liniment. When seen medically he was found to have total paralysis of the legs; could not make the slightest movement with either of them; both knee-jerks absolutely absent; also the cremasteric, abdominal, and epigastric reflexes. Severe pain in the abdomen; no anæsthesia. Morphia (gr. ½) given hypodermically. Compressed air turned on. When at about 19 lbs. pressure the pain was easier, and some voluntary movements of the legs could be effected. He was allowed to "leak out," the process taking forty-five minutes. The marked improvement was maintained: he could stand, but could not walk. Slight evidence of knee-jerks on both sides. No abdominal pain. Sent home in a cab.

Jan. 16th: Considerably better. Has more power of movement in the legs. Knee-jerks both present and more perceptible. Between 11 a.m. and 12 noon yesterday, when he had been put to bed, severe pain came on in the right leg throughout its whole length; this kept him awake; also yesterday, later in the day, he had considerable difficulty in micturition, which was, however, surmounted at length without medical assistance. Constipation lasted thirty-six hours. [Ext. ergotæ liq. ♏xv. every four hours.] A rubefacient and anodyne liniment and aperient pill recommended.

Jan. 18th: Can walk, but is weak on his legs. Right leg feels to him numb, but there is no anæsthesia. Thinks that the left leg is stronger than the right. Left knee-jerk is more marked than the right.

Jan. 22nd: Better. Walks well. Knee-jerks now not obtained even by Jendrassik's method. No trouble with bladder or rectum. A few days later he returns to work.

CASE XXXVI.—Retention of urine.

W. L. has been working in compressed air three or four months. Had "bends" once or twice in joints, but never sufficiently severely to prevent his returning to work the following shift. Was working Feb. 9th, 1895, from 6 a.m. to 2 p.m. Pressure 21 to 27 lbs. Applies for advice later in the day, complaining of retention of urine. No other symptoms. He is catheterised; $1\frac{1}{4}$ pints of urine drawn off; and no organic cause for the retention is discovered. Urine normal.

Feb. 11th: No further retention.

CASE XXXVII.—Auditory vertigo.

J. R., æt. 27, foreman, had worked in the compressed air at the Blackwall Tunnel since the commencement, and previously at the Hudson Tunnel. On Aug. 3rd, after working in Caisson No. 2 (pressure 30 to 32 lbs.), he was affected with pain in the "left side and front of the body" and in the limbs; also he noticed that he was deaf in the left ear, and heard noises in that ear. He went into the medical air lock; had the pressure raised, and came out slowly. The pain had gone in two hours. He did not seek medical advice until Aug. 5th, when he came, complaining of his deafness. Watch with the right ear was heard at a distance of 2 inches, and with the left not heard at all. Loud tuning-fork on the left mastoid not heard at all in the left ear. Nothing abnormal seen by speculum. The ringing noise in the left ear has continued until now. There is slight giddiness on rapidly moving the head to the right or the left—more, however, on moving the head rapidly backwards. Can walk perfectly straight. (He states that he had a similar, but worse, attack of giddiness while working at the Hudson Tunnel; he did not, however, then notice any deafness.) No history of previous illness of any sort. He undertook to report himself again in two days time: this he did not do. He was next seen on Sept. 9th at work in the compressed air, where he had been working since the previous note. He "thinks the deafness is somewhat better." He has no giddiness, but continues to have noises in the left ear.

CASE XXXVIII.—Auditory vertigo from too rapid compression.

R. L. works as a fitter, and is only occasionally in the compressed air. On Aug. 2nd, 1895, he was employed fitting smaller air cocks to the lock of Caisson No 2., the pressure at that time being 31 lbs. He had temporarily stopped up the hole, where the inner cock had been, by a plug of wood; the inner door was closed, the outer half open; he and a boy were together in the lock, and therefore under the normal atmospheric pressure only, when, either through accident or ignorance, a man on the inner side of the inner door knocked out the wooden plug. The lock was suddenly filled, through a comparatively large hole, with compressed air. He and the boy were knocked by the violence of the air against the outer door, which was thus closed, and the pressure was raised in a very few seconds to 31 lbs. above the normal. The boy is said to have felt no ill effects. The man was temporarily affected with pain and noises in the right ear and giddiness, which soon passed off; he became also suddenly deaf in the right ear, for which he did not seek advice until Aug. 9th. There was then no tinnitus, no vertigo, and no pain. He could not hear a watch at all with the right ear, and with the left only at a distance of 3 inches. A tuning-fork on the forehead was heard "equally distinctly in both ears." Both tympanic membranes seen clearly; cones of light normal. At the upper part of the right drum was a dark area (? congestion or hæmorrhage). No perforation.

Aug. 19th: Slight occasional pain the last week in the right ear. Watch: right ear, ½ inch; left ear, 5 inches.

Tuning-fork on forehead best heard on the left side. The dark patch on the right drum has disappeared. [Ext. ergotæ liq. ♏xx. ter die, 5 days.]

CASE XXXIX.—Auditory vertigo.

F. W., æt. 30, had worked in the compressed air at the Blackwall Tunnel since the commencement—that is, for twelve months. He had not suffered from its effects. He had had pneumonia two years before; no syphilis or other illness. On July 9th, 1895, he completed an eight-hour shift at 2 p.m. (pressure 16 to $19\frac{3}{4}$ lbs.), and had left the works to go home. He had gone about two hundred yards, when he felt suddenly giddy, and would have fallen if he had not been caught by two other men; this occurred at about 2.45. He was brought back to the works, and seen at 3 p.m. He could not walk at all by himself; if he attempted to do so he staggered to the right. He could not hear a watch with the right ear, even when touching, nor a loud tuning-fork on the right mastoid process, except with the left ear. Slight subjective noises in right ear. Nystagmus both lateral and rotatory. Surrounding objects appeared to him to be moving to the left, but irregularly so. [Ext. ergotæ liq. ʒj st.] He was at once taken to the medical air lock, and the pressure raised to 15 lbs. There was an immediate improvement in the vertigo, but none in the deafness. He could then stand by himself, and the nystagmus was not so pronounced. He was allowed to "leak out," taking about one hour in the process. There was no increase of the vertigo in consequence of coming out. He was then sent home in a cab. [Ext. ergotæ liq. ♏xx. quartis horis sumendum.] No disease of the viscera.

July 10th: Watch—left ear, 3 feet; right ear, 6 inches.

Tuning-fork on forehead best heard in left ear. Giddiness much less.

July 11th: No giddiness even on movement of the head in any direction. No nystagmus. The improvement was so complete that it seemed that he would soon be able to work. A relapse, however, occurred. The vertigo came on in short irregular attacks every few days or so. Slight rotatory nystagmus again appeared, and he suffered from continual frontal headache; the deafness in the right ear became also slightly worse, and he could only hear the watch at a distance of 2 inches. On account of the nystagmus, if he fixed his eyes on an object for a minute the sight became dim. The ergot was discontinued on July 19th, and bitter tonics given, followed afterwards by iron, arsenic, and strychnine. A blister behind the right ear had no effect. On Aug. 29th I noticed that the right pupil was larger than the left, and that there was slight external strabismus of the right eye. On further examining the eye I found that the vision on the right side was very defective, and that he could only just count fingers with that eye. He had not complained of this before, but stated that he thought the right eye had been dim for the last two days. There was no organic lesion of the fundus oculi, but there was a high degree of myopic astigmatism ($-6D$), which one would suppose must have been of old standing. The man had been a soldier, and had used the right eye for shooting, but had not noticed that the sight was defective.

In November the headache was more severe, and he was in a very nervous and tremulous condition. When writing he was troubled by severe trembling of the right arm. Syr. ferri, quininæ et strychninæ phosphatis was given, 1 drachm three times daily. The vertiginous attacks were diminishing in frequency, and in January 1896 he went to the seaside for two months.

September 18th, 1896: During the last eight months the vertigo has only been occasional, but his general health has been very much impaired, and he has suffered greatly from rheumatism. After several sojourns in the country and at the seaside, he is now fairly well. The defect in hearing on the right side continues; the giddiness is trifling and rare, and it is confidently anticipated that recovery will be complete.

CASE XL.—Auditory vertigo.

G. H., æt. 36, engineer, had been working in the compressed air at this tunnel since the commencement. From the nature of his work he was not usually called upon to be under pressure for longer than two or three hours at a time. On Feb. 11th, 1895, he remained in for four hours, a longer time than ever before; the pressure was also higher than on former occasions (26½ to 27 lbs.). He came out of the air at 3.30 p.m; he had then had no food for seven and a half hours. He thought that he came out quicker than usual. He then had a hurried meal. I saw him at 4.10 p.m.; he was then all right. Half an hour later he felt a "deafening sort of sensation" in both ears, lasting a few seconds, and most noticeable in the right ear. He heard some ringing noises in the ears, became giddy, and would have fallen. He was at once sent home in a cab. The deafness then had gone; the only symptom complained of was giddiness, which was worse on movement or turning round. He felt that the head was moving round to the right occasionally, when it was really stationary. By Feb. 14th the giddiness had much improved, though it had not then disappeared. The head still occasionally felt as though it were moving to the right, especially on excitement. The right pupil was smaller than the left: this was said to be always the case. The tendency to fall was always to the right. Hearing the same on both sides. From this time the vertigo rapidly disappeared, and in three weeks had practically gone. He was advised not to again enter the compressed air; this, however, he did on many subsequent occasions, making his sojourns as short as circumstances would permit, and he did not again suffer in consequence.

CASE XLI.—Auditory vertigo.

Joseph H., æt. 24, had worked in compressed air for some months. On Jan. 12th, 1895, at 2 p.m., he finished a shift of eight-hours (pressure 20 to $25\frac{3}{4}$ lbs.). He walked home—a distance of one mile; went up to his bedroom at 3 p.m. to change his clothes; he felt well at the time, but giddiness suddenly came on, and he fell down, and had to be put to bed; he felt quite helpless. There was no unconsciousness, and he was quite rational. If he sat up in bed he was giddy, and fell backwards. No malaise. Sent for medical advice on the 14th. He was seen on that day sitting up downstairs. The giddiness had lessened; there was no vertigo while remaining still; if standing erect and still, there was no vertigo and no ataxia; if the head was then moved forwards or backwards, there was no vertigo: this only came on when the head was rotated laterally either to the right or to the left, and more especially when the movement was to the right; and then the vertigo was so great that he collapsed at once into a chair behind him. The reflexes were normal. There was then no deafness, no tinnitus, and no nystagmus.

Jan. 15th to 18th: Vertigo gradually improving. Left pupil slightly larger than right; both pupils react to light and accommodation. Ophthalmoscopic examination reveals nothing abnormal.

Jan. 21st to 23rd: Can now walk any distance without assistance. Appetite has been good all the time. Advised not to work again in compressed air. He was seen by me so working on Jan. 30th: he had been so engaged for about five days, and had not suffered in consequence. His further working in the air was prevented.

CASE XLII.—Auditory vertigo.

John H., æt. 24. Examined for compressed air work March 26th, 1895. The note made at the time of examination ran thus:—"Never worked in compressed air. Heart area and sounds nil. Lungs normal. Liver, relative dulness at 6th rib, absolute at 7th rib in left nipple line, not extending below the costal margin; cutaneous veins over the ensiform cartilage enlarged. Urine, no albumen. Has just left the service, where he has been for seven years. Six years ago he had 'ulcers on the penis,' but no subsequent constitutional symptoms." He was passed for compressed air work, and completed his first shift of eight-hours at 10 p.m., March 27th, the pressure being $20\frac{1}{2}$ to $24\frac{1}{2}$ lbs. He had some slight inconvenience with the right ear while going through the lock, but no actual pain. On arriving in the compressed air he felt giddy; the giddiness lasted two or three minutes, but was only slight. He went to his "pocket," and proceeded with his work. His nose bled a little soon after getting in, and continued to do so slightly for some time. Instead of going out at half time for his meal, to avoid becoming giddy again he remained in the compressed air, having something to eat while there. He perspired profusely. On coming out through the lock he had noises in the right ear, but no inconvenience. He became very giddy soon after leaving the lock and before reaching the elevator. He was then assisted home by his brother; went to bed, and vomited blood (? less than a teacupful); giddiness, noises in the ear, and deafness remained. He did not send for medical advice before the morning of March 29th. He was then found in bed. The vertigo came on when sitting up or walking; there was a tendency to fall to the right. On waking on the morning of the 28th he had had pain in the right knee, which persisted more or less for twenty-four hours. Pulse 72; pulse pressure (measured by Batten's clinical pulse manometer) 9 ozs. Soft-ticking watch heard by the left ear at a distance of 1 inch; not at all with the right ear. Slight tenderness under the right external auditory meatus. Watch on right frontal eminence heard only in left ear. Only subjective noises heard in the right ear; right drum normal. By holding nose and blowing, air is forced into left tympanum, but not into right. Knee-jerks active. Constipation. [Pil. colocynthidis et hyoscyami gr. x. st.] The noises in the right ear began as soon as he came out of the lock; the giddiness commenced when he was half way towards the lift (*i.e.*, he had walked about 100 feet). No ataxy. Optic discs normal.

March 30th: There is a subjective feeling that the head is moving to the right. Loud-ticking watch just heard when touching the right ear and when 5 inches from the left ear.

March 31st: Loud-ticking watch—left ear, 1 yard; right ear, 1 inch. Gardiner Brown's tuning-fork on bridge of nose is heard for five seconds longer than the vibrations are felt by the finger, indicating middle or external ear disease on the left side. [Potass. brom. gr. vii. ter die.]

April 2nd: Soft-ticking watch—left ear, 1 yard; right ear, $\frac{1}{4}$ inch. Gardiner Brown's tuning-fork test of left ear $= 0''$. The giddiness is brought on by quick movements, and more by a sudden movement of the head backwards than by any other movement. There is a subjective feeling of oppression, as if a weight were hung at the back of the neck. A movement of the head suddenly to the right is more liable to bring on giddiness than a similar movement to the left.

April 11th: The giddiness is less; it only comes on when moving the head rapidly, especially backwards.

April 16th: Hearing normal in left ear; on right side it is the same as before. [Pot. brom. gr. x. ter die sum.]

April 23rd: Hearing on right side has improved; soft-ticking watch heard $\frac{3}{4}$ inch from ear. Slight improvement in giddiness.

May 2nd: Intervals between attacks of giddiness of longer duration.

May 8th: Tobacco smoking has brought on giddiness once or twice. Advised not to smoke. [Ext. ergotæ liq. ♏xx. ter die sum.]

May 15th: Says he is much better since the 8th. [Ext. ergotæ liq. ♏xv.; liq. strychninæ ♏iii.; liq. arsenicalis ♏ii. ex aquā ter die sum.]

June 1st: No giddiness for the last two weeks.

June 8th: The tinnitus on the right side continues, but not so loudly as at first. Hearing the same. If he stoops for any length of time the giddiness returns.

June 18th: Vertigo gone. Walks out every day. [Ergot stopped.] He now resumes work again—not in the compressed air.

Oct. 13th: Has had no return of the vertigo. The deafness in the right ear has not improved; he still has noises in that ear, but is able to disregard them.

CASE XLIII.—Auditory vertigo.

J. T., æt. 27, had worked in the Blackwall Tunnel about six months. He was on his way home after having worked in the compressed air at a mean pressure of $23\frac{1}{4}$ lbs. from 10 p.m., Oct. 18th, 1894, to 6 a.m., Oct. 19th. He had covered about two miles when he suddenly felt giddy, became faint, and would have fallen had it not been for others who were walking with him. He experienced a sudden noise in his left ear, and became quite deaf in that ear; surrounding objects appeared to him to be moving round. He had a slight aching pain in his left knee. He was then taken to the Seamen's Hospital. While he remained in the hospital he came under the care of Dr. Curnow, who published an account of the case in the *Lancet* of Nov. 10th, 1894, from which the following extract is made:—"On admission there was no sign of organic disease of heart, lungs, or abdominal viscera. He was in a very collapsed condition, with great pallor, and a cold sweat over the forehead. Pulse 66; temperature 96° F., and respiration hurried. He was in a tremulous condition, and unable to stand. He complained of intense giddiness, which was not influenced by position. He had loud, booming noises in his ears, particularly the left, uninfluenced by inflation of the tympanum. He vomited repeatedly when the attack came on, and the sickness lasted about twenty-four hours. There was horizontal nystagmus, especially when the eyes were directed to the right; also a small amount of vertical oscillation in both eyes. On the left side a loud-ticking watch could only be heard when touching the mastoid process; when held on the forehead it could be best heard with the right ear. Both tympanic membranes intact. No oculo-motor paralysis; pupils reacted well to light and accommodation. Ophthalmoscopic examination revealed nothing abnormal. Taste and smell unaffected; no headache. Reflexes normal; no paresis; gait uncertain and hesitating; no ataxia. When walking the patient evinced a tendency to reel and fall. This tendency was always to the right. With his eyes closed he stood alone, but was unsteady. He remained in the hospital a few weeks. His general condition improved, but the vertigo, nystagmus, tinnitus, and deafness, did not materially diminish; he remained unable to walk across a room without support. The giddiness was always increased by rapid lateral movements of the head." After leaving the hospital his condition remained stationary for months. He went into Norfolk to live.

Nov. 9th, 1895: Considerable improvement. Could walk easily across a room without help or support, but could not walk a distance out of doors in the same way. Complete deafness in the left ear continued, and some tinnitus on the same side.

March 5th, 1896: Considerably better. Could walk long distances—*e.g.*, ten miles—out of doors with the help of a stick.

June 30th: Has recently been acting as a night watchman at the Woolwich Ferry, but as the rocking of the pontoon frequently occasions a return of the vertigo he has been advised to discontinue the employment. (This he subsequently did and is now in receipt of a pension, being unable to obtain light work. Oct. 1886.)

CASE XLIV.—Auditory vertigo.

W. D., æt. 21, has worked in the compressed air of the tunnel for three weeks; he then worked in Caisson No. 1 for two shifts. Came out at 6.20 a.m., March 24th, 1896, pressure 20 to 22 lbs., and had a slight pain ten minutes afterwards in the right knee. He sat down in a chair on arriving home (close to the works), and thinks he went to sleep. He woke up at 7 a.m., stood up, became excessively giddy, fell down on the floor, and vomited. Sent for advice, and was seen at 2 p.m. The vomiting has persisted until now; the giddiness is slightly better, but becomes worse on moving the head backwards or to either side. No tinnitus aurium. Watch is heard in the right ear at 1 foot, and in the left at 2 feet; placed on the forehead it is best heard in the right ear. He states that he has had a difficulty with his ears on going into the "air" the last two shifts because of a "cold in the head." This difficulty was worse the last shift—*i.e.*, on going into the caisson at 10 p.m. (23rd)—and the pain in the right ear persisted to some extent while in the compressed air. The pain in the right knee is not severe, and there is no swelling. Pupils equal. There is slight nystagmus. No ataxy. Pulse 102; temperature normal. Digitalin (gr. $\frac{1}{100}$) given at once, and a rubefacient liniment applied to the knee.

March 25th: Vomiting has ceased, and the vertigo is not quite so severe. No appetite.

March 26th: Is now sitting up. The vertigo is less, but comes on when the head is moved rapidly in any direction. No tendency to fall in any particular direction. Watch: right ear, $1\frac{1}{2}$ feet; left, 2 feet.

March 28th: Much the same.

March 30th: Considerably better. Vertigo only occurs on moving the head rapidly to one side.

April 2nd: If after stooping he raises his head suddenly he is giddy for a moment; otherwise there is no vertigo.

April 9th: Yesterday he felt so well that he was returning to work, but the vertigo returned; he had also great pain in the back of the head. The nystagmus has now disappeared. Hearing normal. Has been taking an iron mixture for the last fortnight.

April 18th : No vertigo remains. Returns to work, but is not again allowed to work in the compressed air.

CASE XLV.—Vertigo : probably auditory.

C. W., æt. 29 (March 26th, 1896), has worked in compressed air of tunnel eight or nine months. Recently has worked three shifts in Caisson No. 1. After the first shift he had a slight attack of "bends," which kept him from work for one shift. After the third shift, which he completed at 10 p.m., March 26th, he had pain in the abdomen immediately on leaving the pressure (26 to 27 lbs.); also retching, but no vomiting. About one hour afterwards he had giddiness. Remained in bed until March 28th, not reporting his illness ; he then caused himself to be assisted to the works. When seen he complained of giddiness only. He could not walk or even stand unassisted. There was lateral and rotatory nystagmus. A watch was heard at a distance of 3 feet with both ears. No tinnitus aurium. No albumen in the urine. No other signs of disease found. An ergot mixture was prescribed.

March 30th : Not much difference in his condition. Vertigo is made worse on moving the head round to the right or the left, but not by moving it backwards. Nystagmus slightly less. No other eye symptom. Tuning-fork on forehead is heard equally in both ears.

April 2nd and 3rd : Better. Can walk by himself.

April 4th : An iron mixture ordered.

April 11th : Vertigo gone. Slight headache.

April 27th : Headache persists, but is otherwise well. He goes into the country, and after a rest obtains employment there. A subsequent report states that he has quite recovered.

CASE XLVI.—Vertigo: probably auditory.

J. J., æt. 24, has worked in compressed air for six months. Had an attack of "bends" after working in Caisson No. 1 on March 25th, 1896, which caused him to lose two days' work. On April 5th he had worked about ten shifts in this caisson, and he left work at 10 p.m. At 11 15 he felt "blind and giddy," and would have fallen if not held. He went home, and remained in bed until April 8th. The next day he sought medical advice. He has noticed no deafness and no noises in the ears; has had no trouble with his ears on going through the locks. Watch is now heard at 2 feet in right ear, and at 4 feet in left ear; on forehead it is best heard in right ear; no sign of disease in either ear. Vertigo is still present, and is especially brought on by lateral rotatory or vertical movements of the head. Mist. ac. sulph. dil. c̄ strych. given.

April 13th: Vertigo better; disappears entirely on lying down. Hearing the same, and good on both sides. No other symptom of any sort.

April 16th: Giddiness has quite disappeared.

CASE XLVII.—Temporary unconsciousness.

Jn. C., æt. 21, has worked in compressed air for nine months: recently in Caisson No. 2. Finished a seven-hour shift at 5 a.m., Aug. 24th, 1895 (pressure 32 to 34½ lbs.), and then went to do some work outside. At 5.45 he felt a pain in the forehead, and then he appears to have become unconscious, or partly so, and "to have torn his hair." He was brought over to the south side in a boat, and put into the medical lock, where he was seen medically at 7 a.m. during the process of recompression. Pressure had then reached 3 lbs. only. He was normal in every apparent way. Pressure was raised to the full extent—

about 20 lbs. He "leaked out," and then walked home. He is a teetotaler, and smokes very little.

Aug. 26th: Feels quite well, and has done so since he came out of the medical lock on Aug. 24th. Having come out of the "air" one hour earlier than usual on Aug. 24th he had had no coffee; but he had done precisely the same on the previous day, and had not then suffered in consequence. He states that he has occasionally had, after returning home from working in Caisson No. 2—*i.e.*, half an hour after coming through the locks—a slight blurring of the sight, and has seen stars; had no pain in the forehead on those occasions. Has never had any trouble with his ears.

Aug. 28th: Returns to work in the tunnel to-day, and not in the higher pressure of the caisson.

CASE XLVIII.—Œdema of scrotum and abdominal walls.

C. A., æt. 27, has worked for considerable time in compressed air both here and at the Hudson River tunnel. On Aug. 5th, 1895, he applied for advice concerning œdema of scrotum, front and sides of abdomen, and slightly of legs, which he noticed on the previous day after working in compressed air. The scrotal œdema is considerable. No disease of heart, kidneys, or liver. Nothing abnormal found in the abdomen. He had an attack of "bends" on Aug. 1st, for which he did not seek medical advice, but otherwise has felt no bad effects from the pressure. He has recently been working in the high pressure of Caisson No. 2, which has varied from 25 to 32 lbs. Recommended to cease work for a short time, and to lie in a horizontal position. A diuretic mixture given.

Aug. 7th: Œdema much less.

Aug. 9th: Without again reporting his condition he returns to work in Caisson No. 2 (6 a.m. to 2 p.m.). Afterwards he has pain in the left ankle, which lasts the whole day and the following night.

Aug. 10th: Again seeks advice. Recommended to give up working in the high pressure of Caisson No. 2, and to work in the lower pressure of the tunnel on the south side.

Aug. 15th: Since the above note he has worked two shifts in Caisson No. 2, and he to-day seeks advice because, after coming out and going to bed, he had a difficulty in breathing while lying down: better on sitting up. Slight hacking cough. No physical signs of disease. Promises to give up working in Caisson No. 2.

CASE XLIX.—Dysphagia, etc.

W. P. only occasionally works in compressed air. On the night of Jan. 10th, 1895, he was in for nine hours. On the morning of the 11th he felt a "sort of knot" in the middle and inside of the chest, which feeling extended back between the shoulders. No cough. Some dysphagia. No physical signs. Has often worked in compressed air before, but has never had the same experience. Applied for advice on Jan. 12th. Examined, and advised to report himself again if the feeling did not go off. Did not come again.

CASE L.—Fit (? epileptic) while in the compressed air.

J. B., æt. 28, has been working in compressed air for five months. On Feb. 26th, 1895, at 5.45 p.m., while working in the shield, he felt suddenly giddy; surrounding objects appeared to be moving towards the left. He fell down unconscious, and remained so for about twenty minutes. During this time he was carried out, and seen by me just outside the air lock; he was then sitting upon a truck, and rambling in his speech. Pupils equal. There had been no convulsions. He was brought up by the cage to the surface. He then became very excited and quarrelsome; stated that he had lost his belt; and said he wished to be left alone, that he had just left off work, and that it was 10 p.m. Then, again, he did not know how long he had been at work, or why he had left off; was quite unreasonable, and refused to lie down. There was no sign of organic disease, except that there was a trace of albumen in the urine, and he had had no previous fits; had had a "cold" for the preceding fortnight, but had never suffered from the compressed air in any way beyond sometimes having a difficulty with his ears on entering. Seen again Feb. 28th: quite well. Recommended not to work again in compressed air.

CHAPTER IV.

SUMMARY OF SYMPTOMS CAUSED BY COMPRESSED AIR.

THE whole of the foregoing series of cases, with three exceptions, comprises illnesses which follow *exit* from the compressed air. The injuries which may be sustained by the ear during the process of entry are so obviously mechanical in their origin that they may be at once separated into a class by themselves, not only on account of their time of onset, but also because of their distinctive pathology. From what has been already stated it will be understood that the entry to the compressed air is effected by means of an air lock, in which the pressure is raised gradually. The size of the cocks used for the men at Blackwall was so adjusted that the entry occupied from one to two minutes. In healthy people, with moderately patent Eustachian tubes, and who have acquired the knack of opening those tubes to allow the entrance of the additional air to the middle ear, no inconvenience is experienced even when the air is admitted as rapidly as the cocks will allow. If, however, the Eustachian tubes are not as patent as they should be—as may occur during the presence of a "cold in the head," or a sore throat, or other cause—more or less difficulty in entry is met with. The additional pressure outside the tympanic membrans pushes that structure inwards, causing more or less pain; and if this warning is neglected the pain may become excruciating, and rupture of the drum may occur: this event may happen even without any excessive pain if the drum is less resisting than normally. Short of actual rupture the relative vacuum in the middle ear acts as an effective cupping glass, and produces congestion of the lining walls of that cavity; and this may last some days, and be accompanied by some deafness on that side. Further, the congestion may be followed by actual inflammation, with or without suppuration. Several cases illustrative of these different stages have occurred at Blackwall, and many cases of more or less permanent deafness have resulted. Since, however, they exactly resemble similar cases produced by other causes, it is unnecessary to occupy space by detailing them. Also, many of the men who have worked in compressed air for a long period have not that acuteness of hearing which is normal; it is an amount of dulness of hearing which is not complained of, but which is only elicited on examination. It has appeared to me highly probable that the numerous entries into the compressed air are responsible for this. Although no trouble with the ears may be experienced, it must happen that the air pressure in the middle ear is frequently a little below that in the external ear. The process of "accommodation" of the ear—if the term may be so used—to the pressure, by swallowing or other means, even when effected frequently, is interrupted by intervals of seconds when the pressure outside the drum is gradually increasing and that within is stationary: in other words, the effect of a cupping glass to the middle ear is frequently present to a small, and in itself harmless, degree. Nothing appears more reasonable than to suppose that this must ultimately produce a thickening of the internal or mucous lining both of the membrana tympani and of the ossicles, which will necessitate some impairment in the hearing.

It very rarely happens that any pain is experienced in the ear on exit from the air. The narrow, funnel-shaped end of the Eustachian tube, directed towards the middle ear, more easily allows of the escape of the excess of air than the more trumpet-shaped opening towards the pharynx allows of the entry of air. On coming out from the compressed air the little bubbles of air can be felt leaving the middle ear, and no effort is required to open the tubes.

Allied to these cases are those of pain in the forehead. It appears to be never complained of except during the presence of a nasal catarrh, when the mucous membrane lining the openings into the frontal sinuses is swollen, and air cannot enter or leave these cavities readily. The pain is sometimes very severe, and may be followed by neuralgic pains for weeks afterwards. Similar pain may result from a cavity in a carious tooth temporarily cut off from the surrounding air either on entry to, or exit from, the compressed air.

One other class of case may be anticipated to accompany entry into the compressed air—namely, any ill consequence of the physiological rise of blood pressure which then occurs. In this class of case we might expect to meet with examples of cerebral hæmorrhage or of ruptured aneurism. Happily no such unfortunate incidents have occurred at Blackwall. By a systematic examination of all new employés I have attempted to eliminate those having an organic disease of such a nature that a sudden rise of blood pressure might be prejudicial.

Concerning the time spent in the compressed air it may be stated generally that no ill effects are then manifested. If the sojourn be prolonged for even twenty-four hours, as has occurred at some other works, no symptomatic consequences ensue *during* the stay. Cases are known where mules have been retained in the compressed air for months at a time, and have apparently been in perfect health. Among the cases that have been cited as occurring at the Blackwall Tunnel two have been especially inserted because they appear to be exceptions to this rule. In the one the man is stated to have become unconscious, or to have had a "fit," while under the pressure. If this condition was produced by the pressure, the man having already been working for some hours in the compressed air, the case is unique, not only among those at this tunnel, but also, I believe, at every other previous work where compressed air has been used. The man had never had any fits before, though he had been recently suffering some pain from his ears while entering the compressed air and afterwards, his ears having been "blocked"—the usual expression for the condition among the men. It is possible that this pain was more considerable than the man represented, and that, rather than leave off work, he had continued under great difficulties, and had at last fainted.

The other case, H. C. (Case VII.), where pain was experienced while in the caisson to an extent which prevented the use of tools by the left hand, stands quite by itself among some two hundred other cases. It is possible, on the one hand, that there was from some cause a more or less rapid fall of the pressure in the caisson, which might be followed by the pain; or it might be, on the other hand, that the account given by the man of the commencement of the pain has been misleading. The absence of symptoms during the sojourn in the compressed air is a feature which has been put on record by every observer.

True compressed air illness occurs during or after the decompression; it may commence immediately the exit air tap is turned, or may be postponed until some hours after coming out. The longest interval which I have recorded at Blackwall was that of fourteen hours in a case that has been cited. The usual interval is from a few minutes to one hour. Where this length of time is much exceeded it has usually occurred that the man has gone home, fallen asleep, and has been awakened some hours afterwards by a severe pain in one or more of the limbs.

By far the most common symptom is pain in the extremities, known by the men as "bends." The pain most usually affects the legs, and principally the parts about the knees—though it may affect the arms, especially the elbows and shoulders. It may be present in one or all of the limbs. Its onset is usually sudden, becoming more and more severe for a short time afterwards. It may be only slight, causing little or no inconvenience, or it may be of a most excruciating character, causing strong and robust men to writhe about in agony. The pain is differently described: sometimes as sharp and shooting, "like a knife"; or a dull, heavy, aching pain. It is sometimes located by the sufferer as deep down in the limb, or in the bone, and sometimes as affecting the more fleshy parts, and sometimes as in the joints; it certainly does not follow any anatomical distribution, such as that of the large nerves. There is generally more or less tenderness over the painful part, and this tenderness is not superficial. In the large majority of cases there is no objective sign accompanying the pain—such as swelling, or discoloration, or heat. Among the cases detailed previously, one presented a swelling in the situation of the insertion of the deltoid, one subsequent ecchymotic patches, and in one a doubtful crepitation in the muscles was made out. The case in which there was a small soft tumour on the outer side of the thigh may be excluded, as this was almost certainly of long standing. In most of these cases there is no other symptom whatever beyond the pains in the extremities. The pain may be so severe that it interferes with the use of the limb to such an extent that a casual bystander may describe the man as suffering from paralysis. It would seem very probable that the large percentage of paresis and paralysis cases recorded by some observers (*e.g.*, Jaminet) may be due to a number of these cases being so recorded.

A cold perspiration has been described as characteristic. I cannot corroborate the observation.

There is nothing constant about the pulse: sometimes it is more frequent than usual, sometimes less frequent; and its tension shows no constant change.

The pain may pass off, if slight, in one or two hours; if more severe, in as many days; in the worst cases it may persist for one or two weeks, or even more. Its disappearance may be hastened by appropriate treatment, especially by early recompression; but it tends to disappear by itself if left alone; and there is no relapse. There is no rise of temperature, and no albumen in the urine.

Jaminet described some epigastric pain as being present in 78 per cent. of his cases; Smith in 24 per cent.; my own experience gives a figure much below these. This is certainly accounted for partially by the fact of my being continually on the works, necessitating my recording a larger proportion of the cases occurring, and therefore including a number which would never have been seen by a medical attendant living at a distance from the works. The epigastric pain may occur by itself, or may be accompanied by pain in the limbs; it may be followed by vomiting or by merely nausea; it is usually easily relieved. In only one case was it really of an alarming character, and marked collapse was then present. It is not a pain of a girdle-like character, but is generally localised at the epigastrium.

Paralysis.—The cases of paralysis met with at the Blackwall Tunnel have been very few and trivial compared to those that have been recorded at such works as the St. Louis and the Brooklyn Bridges. Two cases only of paraplegia have been seen by me. Two other cases are said to have occurred before my appointment to the works: one of these was seen and treated (by the engineers on the works) by recompression, and he was said to have been cured in twenty-five minutes, and to have suffered from no after effects; it is possible that there was no paralysis properly so called. Of the two cases that came under my observation one was recompressed, and all after-effects had gone in a fortnight; in the other, four months after the attack there remained frequency of micturition and impotence. Besides these there has been one case of retention of the urine of a very temporary character.

A review of the cases of paralysis occurring elsewhere shows that the paralysis may or may not be accompanied by pain in the limbs, and sometimes an epigastric or a girdle pain; its time of onset is any time immediately after exit from the compressed air. There is generally involvement of the bladder and rectum, and frequently cystitis, which appears to be the most fatal of the complications. Omitting consideration of these latter, recovery is usually rapid and complete.

Auditory Vertigo.—It is curious that, although Menière published his cases of this affection in 1861, no description of cases due to compressed air appears in any records of the works where pressure has been used until the first of the series of cases occurring at the Blackwall Tunnel was published by Dr. Curnow :[1] yet vertigo has occasionally been mentioned as a possible effect of compressed air ; and at the Forth Bridge Dr. Hunter noted that it was occasionally accompanied by permanent deafness in one ear.

Among the nine cases of vertigo that I have before detailed as occurring after *exit* from the compressed air, the onset in all was sudden, and it came on in from a few minutes to one hour and a quarter after leaving the pressure. In six cases some amount of deafness was present : in one this was described as affecting both ears, and lasting only a few seconds ; in five others it was of longer or even permanent duration, affecting only one ear. In four of these cases the internal ear on one side was affected ; in the fifth it appeared to be the middle ear that was at fault ; in the three remaining cases, which were not seen until some days after onset, no deafness existed when seen, or had been noted previously by the men themselves. Tinnitus had been complained of in four of the patients as having occurred early ; in three this symptom was very persistent. In spite of the absence of tinnitus and deafness in the three cases seen late, the vertigo has been considered by me to have had an

[1] *Lancet*, November 1894.

auditory origin, because it was always increased by a movement of the head in one direction more than by movements in other directions: thus in some it was especially brought on or increased by backward movements, in others by lateral movements to the right or to the left. In the least severe case it lasted several days; in the more severe cases weeks, or even many months; in two, occasional attacks still occur. In four cases vomiting or retching occurred, never lasting more than twenty-four hours. In four cases lateral or rotatory nystagmus was present; in five the illness was accompanied by an attack of "bends."

Where the vertigo has been pronounced there has generally been a tendency to fall towards one side—that side on which the deafness has occurred, though in one the tendency was towards the opposite side.

There have been, in addition to these cases of sudden attacks of vertigo, several cases of middle-ear disease accompanied by some amount of giddiness; these attacks, however, have not been sudden, and have not occurred soon after exit from the air, and have improved at once with appropriate treatment directed to the local condition. The only exception to this statement in regard to the sudden onset was in the case of R. L. (Case XXXVIII.), who, through an accident with an air inlet in the air lock, sustained apparently a hæmorrhage into the tympanic membrane; here the vertigo came on suddenly, but rapidly disappeared.

Of the occurrence of attacks of unconsciousness after leaving the pressure I can say little. The only case which is said to have occurred here occasioned considerable excitement among the men. I attended at once, and found that he had been placed in the medical lock, and the pressure was being raised, but had only reached 3 lbs.; he was then normal in every way, and there was no subsequent symptom of illness. Dr. A. Smith states that a condition of profound coma is the usual forerunner of death, and the occurrence of this symptom leaves little hope of the patient's recovery.

Of the cases met with by me presenting symptoms not coming under any of the above headings may be mentioned the case of dysphagia accompanied by a feeling of a kind of "knot" inside the chest. A somewhat analogous experience is related by Mr. W. L. Saunders[1] concerning a visit of his to the Hudson River Tunnel. Mr. Saunders says that soon after coming out "severe pains, increasing in intensity, caught me at a point which seemed to be at the very bottom of my windpipe. At one time I thought it was in my back, but, as a matter of fact, the pains were *within* my body and not at any point on the surface; they seemed to be located about the centre of the trunk. Just before entering the hospital tank the pains were so severe that I was unable to breathe freely. It seemed a clear case of a man's breath being taken away with the cause of the trouble still acting. I felt just as I might had I received a blow squarely in the pit of the back. The relief was rapid and complete. No sooner had the pressure been turned on in the tank than I felt as well as ever."

The case of œdema of the scrotum and abdomen may not have been due to the compressed air but to some organic cause that I was unable to discover.

It sometimes happens that some itching of the skin is complained of after leaving the compressed air. My

[1] *Engineering and Mining Journal*, August 1st, 1891.

experience is that this is not so general as one would expect from the writings of Foley.

Epistaxis or hæmoptysis occasionally occurs after exit from the compressed air; or the blood may be swallowed, and hæmatemesis may follow. I have not seen any but very slight cases. I have accompanied phthisical individuals into compressed air, who, to my knowledge, have previously suffered from hæmoptysis, and none has occurred in consequence of the visit.

In the one or two slight cases that I have met with of hæmorrhage from the ear there existed an old or recent perforation of the tympanic membrane.

It may be asked whether work in compressed air may not, after a length of time, produce deleterious effects on the system. I am unable to say that it does. I have made careful examinations of many men who have worked for a long time in compressed air without finding that any ill effects could be attributed to this cause. In one case, where a man had in all worked about twelve years in compressed air, there was some hypertrophy of the heart without any other condition of the system to account for it; it is possible that this might be produced by the increased blood pressure which accompanies work under these circumstances. But further observations are desirable.

It has often been noted that men employed in compressed air have a pale, leaden appearance even when in the open air. This was so marked when I first came to the Blackwall Tunnel that I could single out men employed under pressure from this peculiarity; but later I was unable to do so. I do not think that this was because I became accustomed to the appearance, but because there was an actual improvement of the men in this respect, probably owing to improved ventilation of the compressed air chamber, as the impervious clay was left behind and the more porous ballast reached. Examination of the blood of these men showed no marked or constant deviation from the normal in the number of corpuscles or amount of hæmoglobin.

Nothing has here been said concerning the illnesses to which divers are subject. They are submitted to a pressure evenly distributed over the surface of their bodies and limbs by means of water, and around their heads by means of the air pumped into their helmets; this air is compressed to a tension corresponding to the depth of water; and their illnesses must be due to precisely similar causes as those associated with work in compressed air chambers. The scattered literature dealing with the subject would give one the general impression that few symptoms are met with beyond paralysis of the legs or death; a systematic inquiry into all the illnesses occurring in a given time at any extensive diving station would probably dispel this general impression.

CHAPTER V.

PROGNOSIS.

CONCERNING the progress of those cases of ear disease due to the mechanical action of the compressed air nothing need be said here, since this is better treated of in works on diseases of the ear. Of the symptoms of true compressed air illness fortunately the most common—the pains in the limbs—are of the least serious import. In duration they vary from trivial pains, lasting one or two hours, to more severe ones, lasting several days or even one or two weeks; there may remain some stiffness in the affected limbs for a few days after the pain has gone. Of the most severe cases—and leaving a wide margin, since one is here dependent on the statement of the sufferer, there being no objective signs—I have seen no case of pains in the limbs (which could certainly be ascribed to the compressed air) lasting longer than five or six weeks, or being followed by any sequelæ. In suggesting this limit as the maximum duration I am exceeding the period which has been laid down by previous observers. There is only one case which I can discover recorded which would appear to be contrary to this generalisation: this case is described by Mr. G. E. Twynam,[1] of the Prince

[1] *British Medical Journal*, 1888, vol. i., p. 190.

Alfred Hospital, Sydney, New South Wales. In this case a man, weighing 14 stones 3 lbs., having been for four hours under a pressure of 60 lbs. (probably inclusive of the atmospheric pressure), and having suffered subsequently from pain in the right elbow and right knee, developed a popliteal abscess, and, later, some abscesses in the thigh, with necrosis of bone, which, after one or two years, ended in amputation through the hip. It is difficult to believe, without further evidence than that afforded by the *post hoc, ergo propter hoc* method of reasoning, that the necrosis of bone and consequent abscesses were results of the action of compressed air. My own experience furnishes me with equally valid reasons for assigning the formation of a stone in the kidney to the action of compressed air!

The itching of the skin which sometimes follows exit from the compressed air soon passes off.

Pain in the epigastrium rarely lasts more than a few hours, and is generally relieved by some carminative. The only case of an alarming character which has occurred to me I have already detailed.

Paralysis usually passes off in from one to a few weeks, unless accompanied by bladder troubles. The fatal cases have usually died from cystitis and bed-sores. With the strictest precautions as to cleanliness of catheters and good nursing the prognosis would on the whole appear good. When the bladder is involved some chronic trouble with micturition may remain; and impotence of a more or less lasting character may result from such an illness.

In the cases of auditory vertigo associated with affection of the internal ear the prognosis may be said to be generally good, though partial or complete deafness may be permanent. Concerning the most severe forms of this illness it is necessary at the present time to speak with caution, though *a priori* one would anticipate that the vertigo would gradually lessen in the amount and the frequency of the attacks, and probably ultimately disappear —possibly, however, leaving an incurable internal ear deafness.

CHAPTER VI.

DIAGNOSIS.

THE diagnosis of compressed air illness from other conditions has assumed considerable importance at the Blackwall Tunnel owing to a compensation scheme whereby the London County Council had acquired parliamentary powers to grant relief to any men who might be injured by the action of the compressed air, or to their representatives in case of death. These powers were obtained because it appeared possible that the Employers' Liability Act might not cover such accidents. Illnesses of a temporary nature were met by the Sick Fund of the Works, whatever might be their cause; those of longer duration, if due to the compressed air, were relieved by the Council. Under any circumstances it is quite natural for a working man who contracts some illness while employed in compressed air to ascribe the illness to the nature of his employment: the liability is even greater where such a compensation scheme is in existence; and in addition to carefully separating illnesses due to the compressed air from other maladies, the possibility of malingering has always to be borne in mind.

The first important point to be determined is the patient's account of the time and manner of onset; in the absence of physical signs of disease this becomes the only criterion of the nature of the illness. In one case I was consulted with a view to receiving compensation nine months after the commencement of an alleged illness presenting only pains in the limbs, which were said to have commenced six weeks after working in the compressed air, and to have incapacitated the man from work until he first consulted me. The knowledge which we have of the onset and length of duration of "bends" enabled me to negative the possibility of this case being due to compressed air even apart from inconsistencies in the man's own statement. Several other cases of a like nature have been similarly negatived.

It occurred that two cases of rheumatoid arthritis presented themselves as having commenced soon after working in Caisson No. 2; the mode and time of onset, the progress of the cases, and the presence of physical signs in the affected joints months after the inception of the pains, were opposed to all past experience of compressed air illness; and they could both be amply accounted for by the fact that just before the onset both men had been engaged for hours at a time lying on very wet ground while making some attachments to the foot of the caisson. In both cases the large joints on the side on which the men were accustomed to lie were affected. Some chronic degenerative nervous diseases, including locomotor ataxy and progressive muscular atrophy, with their gradually increasing symptoms and absence of sudden onset, could not, in the present state of our knowledge, be admitted by me to be due to the compressed air.

A number of other illnesses, such as renal calculus, pyelitis, pleurisy, jaundice, etc., were readily excluded as not being caused or accelerated by compressed air.

Cases of malingering presenting tremors, proved to be of voluntary origin, were dealt with on general principles.

It is possible that in the future the inclusion or exclusion of symptoms from the category of those caused by compressed air may undergo some modification ; but meanwhile the records of compressed air illness, when gathered together, furnish us with a mass of evidence which justifies us in speaking somewhat dogmatically on the possible forms which the illness may assume.

CHAPTER VII.

ÆTIOLOGY.

It is unfortunate that the accidents resulting from working in compressed air should have been indiscriminately grouped together and christened "Caisson Disease." The name of an illness should at least recall either some characteristic feature of the symptoms, or some common factor in its causation. The term "caisson disease" does neither; and, moreover, it is something of a misnomer to designate these accidents as a "disease." A caisson is a cylinder, and is used for the formation of the piers of bridges, etc., and may be employed for convenience' sake in making tunnels; it, however, forms no essential part of a tunnel, and need not necessarily be used at all. Even when used, the compressed air is not necessarily in the caisson: it may be only in the tunnel itself. The caisson has nothing more to do with the production of the illness than has the lift by which it may be approached. It would be quite as well, and equally as misleading, to talk of a "tunnel disease." Such a term, in addition to being meaningless, is not coextensive with compressed air illness. The illnesses of divers due to pressure should be included; and it is possible that in the future some new industrial or other occupation may be associated with similar conditions and similar mishaps.

The causation of this illness is by no means as simple and uncomplicated as we might anticipate that it would be. Among the factors which influence its incidence the following three must be placed foremost :—

1. *The pressure itself.*—The higher the pressure the larger the amount of illness caused. This is not only what has always been observed, but what we should expect to be the case ; it is so much of a truism that it is unnecessary to give figures in support of this relationship.

2. *The length of stay in the compressed air.*—It was by no means at first appreciated that this was a matter of primary consequence. The illness so immediately followed the exit from the pressure that attention has invariably been directed principally to the length of the "locking out" process. Although Jaminet recommended, at the St. Louis Bridge, the adoption of short shifts, he yet considered the exit as the most essential cause. Mr. Eads, the chief engineer of that bridge, was the first, and, as far as I am able to ascertain, the only one who distinctly recognised and stated that the length of stay in the compressed air was more important than the shortness of the exit in determining illness. He was led to this conclusion by observing that the lock-tenders entered and left a pressure of 50 lbs. to the square inch many times during a shift of two hours ; and, although their time of entry and exit was the same as that of the other men—they, indeed, accompanying the other men in and out of the pressure—they were never the subjects of this illness ; whereas the other men, remaining in for a shift of two hours or so, were severely and often fatally affected. The clearness and precision of this observation failed to attract the attention it deserved, and many times since it has been categorically stated that the length of the "lock out" is the matter requiring most attention.

At the Blackwall Tunnel the shifts have been of eight hours' duration, and no comparison can therefore be instituted between the results of longer and shorter shifts; though in exceptional cases where a foreman or another has remained in for the supervision of some important work longer than his usual time he has often suffered in consequence. In connection with some recent compressed air work at Glasgow a foreman on leaving the compressed air was so severely affected with pains in the limbs that he at once returned. Being relieved when in, and fearful of making the experiment again, he remained in, I am informed, for several shifts; when ultimately he did come out he died within an hour of his exit. I cannot learn that any inquiry concerning the cause of death was held, and no account of the case has been published.

3. *Ventilation.*—In this connection I feel compelled to lay claim to whatever credit may attach to first pointing out the close relationship which exists between the amount of illness and the ventilation of the compressed air space; and my observations have led me to enunciate this in the form of a law, that the amount of illness varies inversely with the amount of fresh air supplied to the compressed air chamber. Dr. A. H. Smith appeared to specifically deny such a possibility when he said: "By increasing the number of compressors by which the air was supplied (the excess of air escaping beneath the edge of the caisson) the atmosphere was brought to such a degree of purity as to contain only one-third of 1 per cent. of carbonic acid, as I determined by actual analysis. This amount of vitiation was found not to affect the men unfavourably. To maintain this standard, however, nearly 150,000 cubic feet of air were required per hour. The number of men

employed at one time in the caisson varied from 50 to 125 in the daytime, and from 15 to 30 during the night."

It is thus seen that during the daytime each man was supplied with from 1000 to 3000 cubic feet of air per hour; and an atmosphere so vilely foul as to contain ·3 per cent. of carbonic acid—·06 per cent. is the maximum which a well-ventilated space should contain—was spoken of as reaching "a degree of purity"!

Bucquoy analysed the air of the caissons used at the building of the bridge at Kehl, and found 2·37 per cent. of carbonic acid. The statement of the analysis is followed by what would appear to be a platitude. He says: "Those who had to work for a long time in the compressed air became emaciated; many labourers lost their appetite, and looked as if they were just recovering from a severe illness," and then he proceeds to relate the more definite symptoms of compressed air illness.

The only writer who appears to have even hinted at the lack of ventilation as possibly being concerned in the causation of the illness is Dr. Hunter, whose thesis concerning the Forth Bridge was unfortunately not published. Dr. Hunter remarks that "the most dangerous time for caisson workers was (1) while the soft silt was being removed, owing to the excessive dampness, as well as, perhaps, to the presence of decaying animal matter; (2) when the process of concreting was being carried on after a caisson had reached its proper depth, this being due partly to the want of a renewed supply of fresh air and partly to the development of an excessive amount of carbonic acid. The cases of illness met with during these two epochs were in number out of all proportion to those occurring during the excavation of the clay or of the rock."

I recorded my opinion concerning the probability of this relationship in my first monthly report to the Bridges Committee of the London County Council, dated December 5th, 1894. That report, after reviewing the precautions taken at this and other works against illness from the compressed air, goes on to say: "I can find no stress laid on the ventilation of the compressed air chamber; but at the same time it has seemed to me that in those works where no record has been made of the ventilation, and where, therefore, the ventilation was probably neglected, the number of cases of illness has been exceptionally high. This observation has led me to direct my attention to the ventilation of the tunnel. I have calculated the amount of fresh air supplied per minute during the five months in which the compressed air has been in use. These amounts are shown in the following table, which also gives the range of average daily temperature, the range of average daily pressure, and also the number of cases of illness occurring each month:—

Month.	Range of average daily temperature.	Range of average daily pressure.	Average number of cubic feet of air per man.	Number of cases of illness.
	Fahr.	lbs.		
April	82 to 85°	17 to 19	1700	8
May	80½ to 83⅓°	12 to 17½	1800	8
September	64 to 71¾°	15 to 22¾	1400	16
October	68½ to 71½°	21¾ to 23¼	2000	12
November	67¾ to 69°	19¼ to 25	2500	2

"These observations are extended over so short a period of time, and so many other factors need consideration, that it would not be justifiable to draw any general conclusions

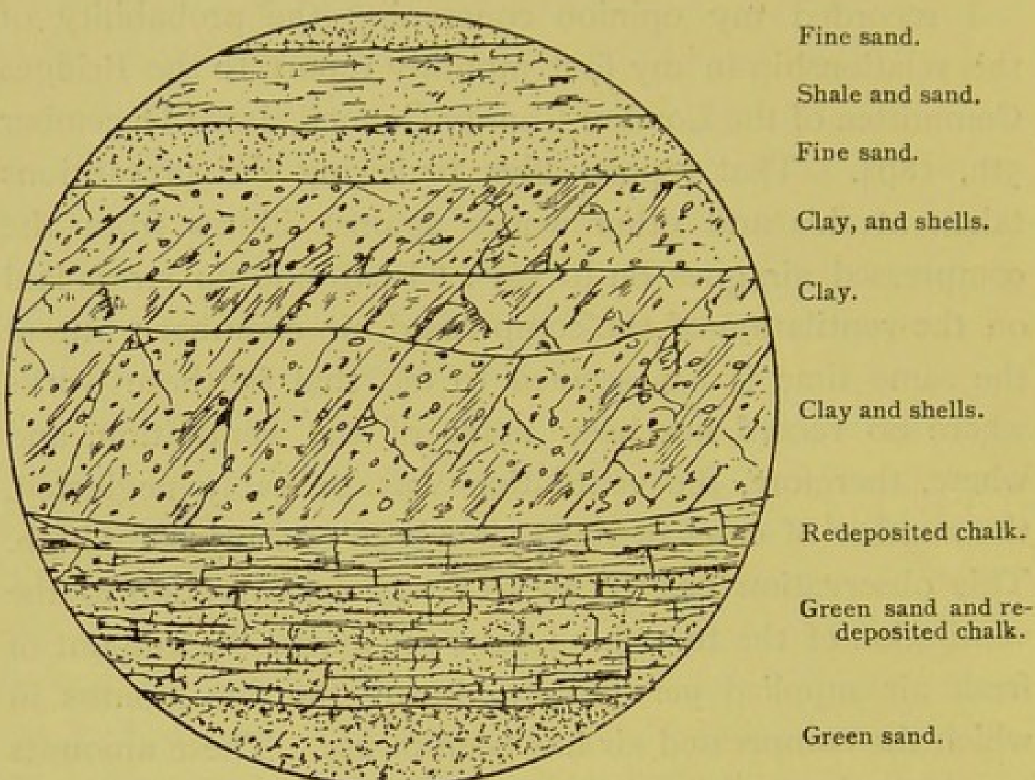

Fine sand.
Shale and sand.
Fine sand.
Clay, and shells.
Clay.
Clay and shells.
Redeposited chalk.
Green sand and re-deposited chalk.
Green sand.

FIG. A.

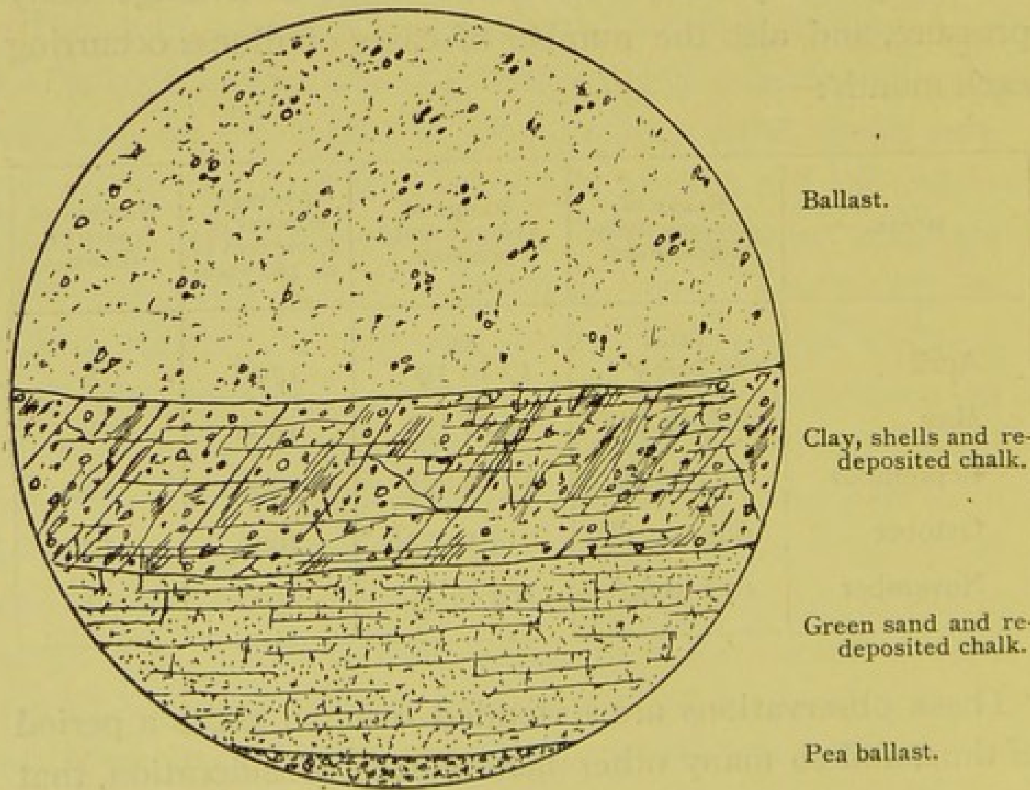

Ballast.
Clay, shells and re-deposited chalk.
Green sand and re-deposited chalk.
Pea ballast.

FIG. B.

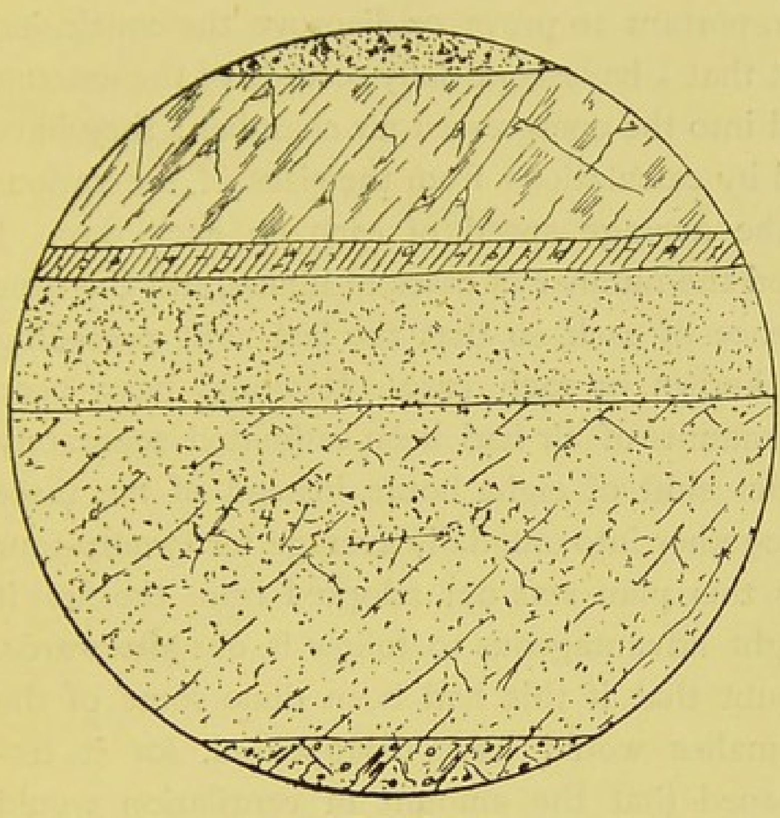


FIG. C.

[These three diagrams, representing the "face" of the tunnel on December 11th, 1894, January 15th, 1896, and May 30th, 1896, respectively, show how the geological characters of the "face" vary from time to time; the escape of the compressed air through these different strata varies in rapidity according to the nature of the soil. Thus through loose ballast the escape is very free, while through the clay only a relatively small quantity of air can find its way; it follows, therefore, that the natural ventilation of the compressed air chamber will vary largely from time to time, if a certain standard of air pressure is to be maintained.]

at present. But it cannot escape attention that in the month of September, when the supply of fresh air was the least, the largest number of cases of illness occurred; whereas in November, when the supply of fresh air was larger than it ever had been before, only two cases of illness arose, in spite of the fact that the pressure was higher than in any previous month."

It was so important to prove or disprove the conclusion here hinted at that I have kept daily records of the amount of air pumped into the compressed air chamber; they have been obtained by calculations from the sizes of the various engines and the average speed of each on each day. I have also noted the number of cases of illness, and the time of the occurrence of each, so that the last shift preceding the illness is known in each case. It would have been better if the amounts of air had been estimated separately for each distinct shift of eight hours, instead of the three being united together into one daily average for twenty-four hours; but as this plan was not adopted from the first it was not thought advantageous to follow it out afterwards. I have no doubt that if this had been done some of the apparent anomalies would have disappeared, for it frequently happened that the amount of ventilation would vary considerably from one shift to another; and of the three shifts in one day the cases of illness would sometimes only appear after one. The days are reckoned to begin at 6 a.m. one day and end at 6 a.m. the next day; an illness then occurring (say) at 7 a.m. on the latter day would be ascribed in the table to the preceding day.

In spite of the likely source of error in estimating the amount of air supplied in one minute out of the twenty-four hours the conclusion before enunciated in my first report has been proved over and over again from observations extending over a period of two years.

The pressure varied from day to day and from hour to hour, the changes being determined by the engineering necessity of dealing with a varying "hydraulic head" brought about by the rise and fall of the tide. In order as far as possible to eliminate the pressure as a determining factor in the causation of illness I have, in compiling the following tables, selected days which could be fairly classed together as having practically the same pressure.

Thus the first table deals with 215 days during a period of nine months when the pressure reached and exceeded 20 lbs., varying in the course of each day from a few pounds below 20 to a few pounds above 20. These days are divided into four sections, according to the average amount of fresh air supplied each hour to each man on the average shift for each day. During these 215 days thirty-three cases of illness were reported, and they were distributed among the days as shown below:—

Cubic feet of fresh air per man per hour in average daily shift.	No. of days.	Cases of illness.	Estimated cases of illness for 100 days.
Below 4000	56	16	28·5
From 4000 to 8000	47	9	19·1
From 8000 to 12,000	71	8	11·2
Above 12,000	41	0	0

The table demonstrates conclusively, I think, the direct relationship between the ventilation and the prevention of illness at the pressure considered.

Since the size of the three daily shifts sometimes varied considerably it appeared to me that it would be preferable to estimate the amount of fresh air supplied per hour for each man in the largest daily shift. The following table is so constructed from all the days, presenting conditions of pressure similar to those of the previous table, occurring during a period of seven months subsequent to the nine months previously considered :—

Cubic feet of fresh air per man per hour in largest daily shift.	No. of days.	Cases of illness.	Estimated cases of illness for 100 days.
Below 4000	21	17	80·9
From 4000 to 8000	80	18	22·5
From 8000 to 12,000	70	6	8·5
Above 12,000	19	0	0

Thus, during a period of sixteen months, in which over four hundred days may be grouped together as presenting nearly similar conditions of pressure, the figures obtained by comparing the amount of compressed air illness with the amount of ventilation afford us very noteworthy results: and this notwithstanding such errors of calculation as those already suggested, and in spite of numerous minor determining factors of the illness which remain to be considered later.

It would appear probable that similar results would attend a corresponding analysis of the days when the pressure exceeded 25 or even 30 lbs.; unfortunately for this purpose the pressure in the tunnel only occasionally reached 27 or 28 lbs., and it never averaged this pressure throughout a day. We are obliged therefore for this purpose to have recourse to the sinking of the caissons. Compressed air was used in the sinking of Caissons Nos. 1 and 2, whose depths below the ground level were 75 and 98 feet respectively. The "hydraulic head" of water pressure to be dealt with was therefore greater than that in the tunnel, and the pressure of air sometimes went up to 35 lbs. per square inch. But as the length of time occupied in the sinking of these was comparatively small it is only possible to tabulate a small number of days. For this purpose I have grouped together all those days when the pressure rose above 25 lbs. (including all pressures up to 35 lbs.). There were 61 such days in all, and they group themselves as follows :—

Cubic feet of fresh air per man per hour.	No. of days.	Cases of illness.	Estimated cases of illness for 100 days.
Below 4000	13	41	315·5
From 4000 to 8000	26	78	300
From 8000 to 12,000	10	8	80
Above 12,000	12	4	33·3

It is seen that the same relationship holds as at lower pressures, but that the percentage of cases occurring is in each case larger than with a corresponding condition as regards fresh air supply at lower pressures. It will also be noticed that four cases occurred when the amount of fresh air supplied was very large, when, if there is any truth in the proposition now being advanced, it might have been hoped that at least a smaller number than this would have been met with. On reference to the days when these four cases occurred it is seen that they occurred on two days when active work was not in progress and when only two or three men were in the compressed air at one time, that actually a smaller amount of air was being supplied than was usual when work was in progress, but that the small number of men caused the amount per head to be large.

One such case occurred in the tunnel, when work was once suspended : the pressure that day varied from

$21\frac{1}{4}$ to 25 lbs; only two men were in the compressed air, and the amount of fresh air per man per hour being pumped in was as much as 40,000 cubic feet. It appears obvious that there must be some explanation for this apparent anomaly. I believe it is to be found in the inadequate distribution of the fresh air supplied. The conditions that appertain when work is suspended are just those which will not tend to help a proper diffusion of the fresh air. The escape of the contained air is as far as possible minimised by claying-up apertures (to avoid the expense of an air supply uncalled for by the engineering necessities); the constant movements of a large number of men and waggons of material are absent, and there is no incessant movement of the locks backwards and forwards as men and material enter or leave. Also, it has to be borne in mind that the velocity of diffusion of a gas at a greater density is smaller than at a less density, varying as it does inversely with the square-root of that density. At a pressure of (say) 35 lbs. the density of the air is four times more than normally—its tendency to diffusion is consequently half as great as usual. This physical fact would appear to be the reason why candles smoke in compressed air; although they are in an atmosphere richer in oxygen, volume for volume, they invariably smoke. This is not the case, however, if we cause the surrounding air to reach the flame sufficiently rapidly—as when a glass chimney is held over the flame. In that case combustion goes on as it would in a more richly oxygenated atmosphere; the flame is brighter, and there is no smoke. The two men employed as watchers, when work for some reason is suspended, are not generally moving about; and, unless situated near an inlet or an outlet of air, may be very badly circumstanced so far as fresh air is concerned. Suppose they are at the bottom of a huge caisson 50 feet in diameter and 60 feet deep, suppose the supply pipe or pipes end 20 feet from the top, and suppose that the superfluous air is escaping at the top, nothing is more certain than that the air in the vicinity of the men will be more impure than that at the top. That this explanation of these circumstances is not imaginary was amply demonstrated at the time when the men were working in Caisson No. 1, from March 23rd to April 10th, 1896. The men were practically all working at the bottom; the supply pipe entered the "air-tight floor" (*i.e.*, the roof of the chamber), and then ended; the air was nearly all escaping through the "air-tight floor," which was imperfectly caulked in order that ventilation might be assisted. Men were affected with compressed air illness at the rate of seven a day. On March 30th the supply pipe was lengthened in order to better ventilate the lower portion of the chamber. During the remaining ten days only one case of illness occurred every two days. It might be urged that the amount of air supply per man was also increased. That was so: but the improvement was maintained even on those days when the air supply was considerably below what it had been before the supply pipe was lengthened; and with this improved distribution of the fresh air no case of illness occurred on any day when the supply was above 9000 cubic feet per man per hour.

I believe that I have said sufficient on this point to have proved my contention that the amount of illness varies directly with the lack of ventilation of the compressed air chamber. Minor causes of compressed air illness remain to be considered.

4. Among these I place a too rapid "locking out" process or decompression. In so doing I am fully aware that I am according to this process a less important position than

that which has almost invariably been assigned to it. Nearly all of my predecessors in the observation of compressed air illness place it foremost among its causes. The considerations already advanced under the three previous headings will, I think, have justified me in assigning to them the greatest influence in the production of the illness. On the other hand, however, Foley was distinctly in error in recommending the reduction in length of the decompression, and in blaming the stay in the cold misty atmosphere of the lock during a few minutes for all the accidents that might afterwards result. That a just appreciation of the value of this factor may be arrived at, it will be well to review a few facts having reference to this point.

Jaminet, Smith, and many others, have drawn up dogmatic rules defining the appropriate duration of decompression. The first decided that one minute should be allowed for each additional 6 lbs. of pressure; Smith, that five minutes should be spent in the lock for each additional atmosphere; others advised lengths of time so considerable that the time occupied by the exit of the men from the compressed air would form a very formidable item in the financial estimate of an engineering undertaking. All reasonable suggestions in this respect have at different times been adopted, but whether the amount of illness has been diminished to any extent thereby remains still a matter of conjecture.

It has been already related how Mr. Eads, the chief engineer of the St. Louis Bridge, noted that the lock-tenders who entered and left the compressed air many times in the course of a two-hour shift did not suffer from illness, whilst those that had remained under pressure for the whole period of two hours were very largely taken ill, often with fatal results. The time of exit was the same for the lock tenders as the other men.

At the Blackwall Tunnel each air lock was provided with two pairs of air cocks, the larger for material, the smaller for men: they were of such a size that the air of the lock with a pressure of 28 lbs. could escape in about four minutes with the smaller cock turned on fully; while by the larger one exit could take place in about thirty seconds. There was a regulation thoroughly understood by the men that the larger cocks were to be used only for material. It has come to my knowledge that the regulation was often disobeyed. By giving the requisite signal from the inside, men coming out have induced the outside lock-tender to turn on the material cock—the tap of which was not accessible from the interior of the lock—and have thus come out in half a minute. One man has, I am given to understand, made a practice and a boast of this. He has not, to my knowledge, suffered in consequence from compressed air illness, though during the progress of the work he has on two occasions suffered severely from other illnesses. Neither has any other case, where the rules laid down on this point have been infringed, come under my notice, with the single exception which I have recorded among the selected cases, where a man against his will and in spite of his objection was compelled by others to come out with the large air cock. This man did not leave off work, and the pain, if present, was very trivial—in fact, he appeared at the time to come to me in order to air a grievance rather than to complain of his pain.

Again, where men suffering from "bends" have been *immediately* recompressed in the medical air lock, the pain has invariably left; when allowed to "leak out" in forty-five minutes some slight pain usually returned ; where the men, without seeking medical advice, have recompressed themselves, and come out moderately slowly (say) in twenty minutes, they have been rarely much improved by the process. This case is not precisely analogous to those we have been considering, but it appears to show that while there may be considerable difference in the results of decompression in four and forty-five minutes respectively, this is not so much marked when the difference in time is that between four and twenty minutes.

We have also to consider carefully the unexpected results of the inquiry into those fearful accidents which have occurred when a caisson filled with compressed air has burst. They have been already referred to in dealing with the history of the subject. In all those cases that terminated fatally, where full investigation has been possible, there had been mechanical injuries from the explosion sufficient to account for death. An absence of cases which could be directly assigned to the compressed air is a fit subject for contemplation, bearing in mind always that our accounts of these accidents were derived from subsequent investigation and from secondhand sources.

This would appear to be the most convenient place to refer to some experiments made in 1893 and 1894 at Bordeaux by M. Hersent, a French engineer. They were intended principally to determine whether men could exist without risk at very much greater pressures than those hitherto attempted in compressed air working. Arguing from the fact that sponge divers descend to depths of from 50 to 60 mètres (164 feet to 196 feet), M. Hersent saw no reason why similar pressures should not be supported by caisson workers. These experiments were not designed to prove anything beyond the possibility of existing without inconvenience under these high pressures; yet, as the times of decompression varied, it may be possible to utilise them in making further inductions.

Having arranged a chamber capable of withstanding pressures of 7 kilogrammes to the square centimètre (99·5 lbs. to the square inch), and having had it fitted with a steam coil for warming it during decompression, the experiments were proceeded with, first on animals and afterwards on men. We will review those that appear most instructive.

Animals employed.	Pressure.	Length of time.
A dog. Dec. 3rd, 1893.	3·1 kilos. to sq. centimètre.	Compression, 2′ Stay under pressure, 11′ Decompression, 45″

Observation.—No accidents.

Same dog. Dec. 9th, 1893.	3·250 kilos.	Compression, 15′ 30″ Stay, 14′ 30″ Decompression, 32″

Observation.—Weakness of right leg, especially on mounting stairs, which lasted a few days.

Four dogs. Feb. 7th, 1894.	3·5 kilos.	Compression, 6′ Stay, 1 hr. 54′ Decompression, 50″

Observation.—Nothing noticed abnormal with the dogs on coming out; but on the following day one of them had a difficulty in walking, and the posterior half of the body became paralysed. He was moved to the Faculty of Medicine, and there died. Autopsy showed that "the vessels along the side of the spinal cord contained globules of air, and had the appearance of a string of beads (alternate globules of blood and air)." The three other dogs were normal.

Three dogs. Feb. 13th, 1894.	3·8 kilos.	Compression, 9′ Stay, 4 hrs. 11′ Decompression, 40″

Observation.—All dogs quite well on coming out. Five minutes afterwards one of them had a commencing paralysis, which very rapidly became complete and general; whilst another had paralysis of the right leg. The third dog was quite well. On the same day all three dogs were recompressed :—

	3·5 kilos.	Compression, 14′ Stay, 25′ Decompression, 23′

Observation.—The first dog was not thereby improved. He was moved to the Faculty of Medicine, and died the next day. The autopsy showed that "the vessels were filled with air, which had hindered the circulation of the blood." The second dog was improved by the recompression, and the effects had disappeared the following day.

A cat. Feb. 24th, 1894.	5·0 kilos.	Compression, 5′ Stay, 52′ Decompression, 2′

Observation.—No change.

In all of these experiments the pressures varied from 47 to 71 lbs. to the square inch. The decompression in each case was very rapid. It will be noted that although bad results followed sometimes, yet they were not a necessary consequence.

The following twelve experiments were made at the same pressure—viz., 5 kilogrammes to the square centimètre (71 lbs. to the square inch). In all, seven dogs were employed.

One dog. Feb. 27th, 1894.	5 kilos.	Compression, 30′ Stay, 4 hrs. Decompression, 35′

Observation.—No accident.

Two dogs. March 1st, 1894.	5 kilos.	Compression, 16′ Stay, 4 hrs. Decompression, 30′

Observation.—One dog had "temporary paralysis of right leg" five minutes after coming out.

Two dogs. March 2nd and 3rd, 1894.	5 kilos.	Compression, 15′ Stay, 6 hrs. Decompression, 17′

Observation.—On coming out both dogs refused nourishment, and lay down. One was said to be paralysed in the lower half of the body, the other in the left side; both were recompressed to the same pressure as before, taking ten minutes going in, remaining in for one hour, and then taking one hour for decompression. The former dog died soon after coming out. (M. Hersent makes no remark concerning the recovery of the other dog, but as it was subsequently used in further experiments it may be presumed that the dog completely recovered.)

Three dogs. March 16th, 1894.	5 kilos.	Compression, 30′ Stay, 3 hrs. 25′ Decompression, 1 hr.

Observation.—One dog was "affected in the left leg for twenty minutes." The others were normal.

Three dogs. March 20th, 1894.	5 kilos.	Compression, 30′ Stay, 4 hrs. Decompression, 1 hr.

Observation.—Ten minutes after coming out one dog was paralysed in the left leg, the paralysis lasting fifteen minutes. The others were unaffected.

The same three dogs. March 21st, 1894.	5 kilos.	Compression, 30′ Stay, 4 hrs. Decompression, 1 hr. 10′

Observation.—The dog affected on the previous day again had paralysis of the left leg, lasting ten minutes. The others were unaffected.

The same three dogs. March 22nd, 1894.	5 kilos.	Compression, 30′ Stay, 4 hrs. Decompression, 1 hr. 15′

Observation.—One dog coughed considerably.

One of these dogs.	5 kilos.	Compression, 1 hr. 30′ Stay, 1 hr. 30′ Decompression, 50″

Observation.—General paralysis a short time after coming out, and died same day. The chamber had not been warmed during decompression, and the temperature had fallen to $-7°$ C. No note of autopsy.

Three dogs.	5 kilos.	Compression, 30′
March 13th, 1894.		Stay, 4′
		Decompression, 1 hr.

Observation.—The first dog seemed quite well on coming out, but a few seconds afterwards it returned into the chamber and appeared inanimate. Recompression was followed by no change, and death occurred. The "autopsy showed that death was due to a disengagement of gas in the respiratory apparatus and its accumulation at the heart."[1] The second dog had paralysis of the posterior half of the body, and recovered in five days. The third dog was unaffected.

Three dogs.	5 kilos.	Compression, 30′
March 23th, 1894.		Stay, 4 hrs.
		Decompression, 1 hr. 15′

Observation.—Two dogs normal. The third was "affected in the right leg, but without paralysis."

Three dogs.	5 kilos.	Compression, 30′
March 28th, 1894.		Stay, 4 hrs.
		Decompression, 1 hr.

Observation.—No accidents.

Three dogs.	5 kilos.	Compression, 30′
March 29th, 1894.		Stay, 4 hrs.
		Decompression, 1 hr.

Observation.—No accidents.

These experiments would have been more instructive had the duration of entry and stay in the pressure been the same. We are not, however, prevented from noting

[1] Three medical men—professors of hygiene, medicine and physiology respectively—at Bordeaux are said to have assisted M. Hersent in these experiments. From the description of this autopsy it would not appear probable that they assisted in the post-mortem examinations.

that fatal results followed not only a rapid decompression of fifty seconds, but also a slow decompression of one hour and that when the exit was prolonged to one hour and a quarter symptoms were not certainly prevented.

M. Hersent then made a series of experiments with three men, the pressure gradually increasing throughout the series from 2 to 5·4 kilogrammes to the square centimètre, (28 to 76 lbs. to the square inch). The length of stay in no case exceeded one hour, and the duration of decompression, which at the beginning of the experiments was thirteen minutes, was gradually increased to three hours and three minutes. The one man who had suffered least discomfort from the lowest pressures was alone employed in the highest pressures. Even with a stay never exceeding one hour, and with an exit lasting for three hours, attacks of troublesome formication and "bends" were not prevented.

Although I have no wish to under-estimate the influence of a rapid decompression in producing illness I believe that I have said sufficient to make it clear that it is not the primary factor in its causation; that in too exclusively directing our attention to this point, as has been done in the past, we have lost sight of other considerations of greater significance; that a few minutes more or less in the duration of exit are of little moment; and that to effectively prevent illness by a long "lock out" this must be prolonged to an extent never yet practically attempted, and very inconvenient and expensive from an engineering point of view.

5. There are certain personal idiosyncrasies, etc., which appear to influence the incidence of this illness.

(*a*) *Fulness of habit.*—This has been noted by most observers. On this account, at the Blackwall Tunnel, I have as far as possible excluded men of very heavy build. On two occasions my advice to men of this type was disregarded, and their first sojourn in compressed air was followed in either case by an attack of "bends" which was effective in enforcing my advice. Because a man is stout it does not follow that he necessarily suffers: it can only be stated that in many cases the liability to illness is increased to a remarkable degree.

(*b*) *Age.*—It has been frequently stated that younger men are less apt to suffer than older men. It would be satisfactory to test the accuracy of this by comparing the ages of those who suffered with the ages of those employed. I am not able to do this, as no account of the ages of men employed has been kept on the works; and as it was a voluntary matter for men who had been employed in the compressed air before my arrival to submit themselves to examination by me, I have only an account of the ages of those men whom I had an opportunity of examining: as these, however, were very numerous the figures will give an approximate idea of the proportionate ages of men employed.

Ages.	No. of men examined and passed.	No. of men taken ill whose ages are recorded.	Proportion of illnesses to every 100 men passed.
15 to 20	55	0	0
20 ,, 25	145	15	10·3
25 ,, 30	152	37	24·3
30 ,, 35	91	19	20·9
35 ,, 40	61	14	22·9
40 ,, 45	38	10	26·3
45 ,, 50	3	5	166

These figures are, I think, sufficiently large to justify very valuable conclusions—namely, that below the age of 20, men are remarkably free from illness; that between the ages of 25 and 45 the liability to illness does not vary much; that between these latter ages the chances of illness are about twice as great as between the ages of 20 and 25; and that above the age of 45 the liability to illness is very largely increased. It has been said that men with grey hair or with commencing degenerative changes in the arteries are especially likely to be attacked. These causes are probably intimately associated with the influence of age. It has appeared to me that men with grey hair are frequently attacked, though a record of the colour of the hair in all cases would be necessary to give a more accurate conclusion than that of a general impression. In the matter of the degenerative changes in the arteries I have sedulously rejected men having any sign of such changes, so that my personal experience teaches nothing.

(*c*) *Organic disease.*—Also concerning men having any organic disease I am unable to state that they are especially liable to illness, for the reason that I have always rejected them, with the exception of some lung diseases, such as emphysema or an early stage of phthisis. Two cases of early phthisis I have allowed to work under pressure, and they have not again come under my notice. One case of emphysema was always better in health while working in compressed air.

(*d*) It has frequently been remarked, both by engineers and by medical men, that men who have been drinking heavily, and then work in compressed air, are especially liable to be taken ill. There is every reason to believe that this is the case. Immediately after a holiday, for instance, it has frequently happened, especially when the higher pressures were reached, that a number of cases of illness occurred. Dr. Lehwess[1] of St. Petersburg, on the other hand, denies that the use of alcohol gives rise to any obvious mischief.

(*e*) It has been more than once observed that men who walk long distances, or who undergo any severe exertion immediately after leaving the compressed air, are on that account more prone to suffer from compressed air illness. At the St. Louis Bridge the use of a lift instead of ladders for ascending from the caissons was followed by a diminution in the amount of sickness.

(*f*) It is frequently stated that men new to the work are more liable to suffer than old hands. It is very difficult to either substantiate or to disprove a statement of this sort, which, when once enunciated, so easily gains credence. It is certain that some men are more suitable than others: those very unsuitable will often suffer after their first shift, and in consequence discontinue the employment; and this may readily give rise to the belief. Yet one sees that it is of frequent occurrence that an old hand may work for twelve months without bad effects and then suffer from a severe illness. I have seen this occur so often that I hesitate to give credit to the proposition.

Among other conditions which might have been of importance, and of which I have taken note, are the temperature and the hygrometric conditions of the compressed air chamber. Of the former I have kept a daily record. During the first two months the air forced in was not artificially cooled. In the process of compression the mechanical work performed on it, to press it into a smaller space, was partly converted into heat, and the resulting

[1] *Petersburg Med. Woch.*, September 1st, 1877.

temperature was uncomfortably high, being generally over 80° F. The air was, after that time, cooled by means of cold water pipes, and the temperature was reduced to below 70°. Both in summer and in winter the usual temperature was between 60° and 70°, varying little from day to day, but on a few occasions going down as low as 55° and 56°. No connection between the occurrence of illness and the rise or fall of temperature can be traced.

The "rheumatoid" nature of the pains in the joints might very easily suggest the possibility of the aqueous vapour in the chamber being of some moment, and I caused daily readings of a wet and dry bulb thermometer to be taken for some months. I found that the air of the chamber was always fully saturated with moisture; the floor of the tunnel was usually wet, and a stream of water was generally coming in at the lower portion of the "face," so that there was ample opportunity for this confined air to become saturated. The only occasions when the reading of the wet bulb thermometer was a very small fraction of a degree below that of the dry bulb thermometer were when the pressure was being raised, when the temperature therefore was rising slightly, and the point of saturation was in consequence slightly below the actual temperature. Any small decrease in the pressure, leading always to a small decrease of temperature, was followed by the formation of a mist in the atmosphere, showing again that the air was always completely saturated with water. This being the case the hygrometric condition of the compressed air chamber fails to account for the occurrence of illnesses at one time and not at another, and therefore probably has nothing to do with the causation of accidents.

CHAPTER VIII.

MORBID ANATOMY.

No fatal cases having occurred at the Blackwall Tunnel I am unable to add anything to our knowledge of the morbid anatomy of these accidents. I have already related several accounts of autopsies made elsewhere. A perusal of these gives rise to the regret that more of them were not conducted by experienced pathologists.

Pol and Watelle described congestion of different viscera, and in one case a general subcutaneous emphysema.

François, described congestion of the bases of the lungs and of the brain.

Several of the cases mentioned in Jaminet's monograph are said to have shown extravasations of blood in the kidneys, congestion of various other viscera, and one case small extravasations of blood within the dura mater of the spinal cord pressing upon the cord.

Disseminated patches of softening of the brain and cord are described by Bauer.

Baumgarten found softening of the anterior horns and lateral columns in the whole extent of the spinal cord, and discovered fatty degeneration of the neuroglia cells in this situation.

Smith found an extensive effusion of blood pressing upon the spinal cord opposite the two lower dorsal vertebræ. In another case there was found engorgement of the lungs, but the brain and spinal cord do not appear to have been opened. In a third there was advanced Bright's Disease of old standing.

Leyden [1] described an autopsy where death took place fifteen days after leaving the compressed air. He found small irregular fissures in the mid-dorsal region of the cord, chiefly within the posterior parts of the lateral columns. The fissures were filled with round cells, but contained no red blood corpuscles, and from their well-defined edge they were certainly not produced by the infiltration of cells within them. The most probable explanation appeared to be that by the escape of gas the spaces were formed, and afterwards these became filled by round cells.

A post-mortem examination related by Schultze was made on a case where death took place two and a half days after leaving the compressed air. There was a disseminated myelitis in the dorsal region, combined with fissures, and appearances, suggesting that the tissue had been lacerated.

It will have been noted that examinations were made on some of the animals which died from M. Hersent's experiments, and that bubbles of free gas were usually found within the blood vessels.

[1] *Archiv f. Psychiatrie* ix., vol. ii.

CHAPTER IX.

PATHOLOGY: RÉSUMÉ OF THEORIES.

VERY numerous indeed have been the theories that have from time to time been advanced to attempt to account for the effects of compressed air on the animal economy. It will have been already seen that the records of the actual effects produced are frequently at variance in material particulars. It is possible that these differences are due in some cases to the different conditions under which the effects arose; it is probable that they are oftener due to a difference in the care with which they have been recorded, and to the personal preconceived opinions of the various observers. We should anticipate, therefore, that the differences will be considerably magnified and multiplied when we approach the pathological aspect of the subject—an aspect into which must enter the consideration of highly intricate physiological problems, and assisted scarcely at all by evidence derived from morbid anatomy. This is the precise condition which we find. We have theories advanced from all sides: by clinicians, who have not troubled to review such facts as have been proved in the physiological laboratory, and whose theories are often counter to the most elementary physical laws; by therapeutists in the possession of a compressed air bath capable of sustaining a pressure of a few pounds to the square inch, quite incomparable in amount to the pressure under which engineering works are often undertaken, and whose object is to show for how many ills their compressed air bath is beneficial; by physiologists, with an experience limited to the laboratory and the effects of compressed air on animals; and, lastly, by engineers, who appear to ground their hypotheses on the supposition that the body is a variety of furnace, and that arteries, veins, and capillaries are a simple piece of hydraulic machinery.

To review everything that has been written in this connection during the latter part of this century would be a very heavy and a very useless task; it is necessary, however, to glance at the writings of those who have been the most entitled to speak on the matter.

As long ago as the eighteenth century experiments on animals were made by Musschenbroeck and Haller,[1] and later by Achard.[2] They appear to show little beyond the fact that animals subjected to a compressed atmosphere that is not renewed, will, after a varying length of time, die.

Brizé-Fradin[3] attempted to explain the illnesses of divers. His physiological explanations are, however, so obviously erroneous that his conclusions lack interest.

Poiseuille[4] made some experiments on frogs, tadpoles, very young rats, mice, etc. By an ingenious contrivance

[1] "Elementæ physiologiæ corporis humani," 1761, vol. iii.

[2] "Extrait d'une lettre de M. Achard au citoyen Van Mons."—*Ann. de Chimie*, 1801, vol. xxxvii.

[3] "La chimie pneumatique appliquée aux travaux sous l'eau." Paris, 1808.

[4] "Recherches sur les causes du mouvement du sang dans les vaisseaux capillaires."—*C. R. Acad. des Sciences*, 1835, vol. i., pp. 554-560. Also, "Mémoires des savants étrangers," vol. vii.

he could microscopically watch the capillary circulation whilst the pressure was increased to from 2 to 8 atmospheres, and, on the other hand, diminished below the normal pressure. He was unable to detect any change in the capillary circulation.

Hervier and St. Lager,[1] at the suggestion of Pravaz, carried out some experiments to show whether the organic combustion is increased by the compressed air or not. They did not measure the absolute amount of carbonic acid expired, but only its relative amount in the expired air ; they also give no figures. But they state that at first the carbonic acid is increased in amount ; afterwards, when the pressure is still further increased, the lungs give out less carbonic acid. They find it difficult to explain this paradox ; but they put down the primary increase to a chemical effect, and the subsequent decrease to a mechanical effect (the hindering of the escape of carbonic acid from the blood) predominating over the chemical effect. The resulting accumulation of carbonic acid in the blood explains, say the authors, why the carbonic acid exhaled two or three hours after the compressed air bath is in excess of that exhaled immediately after the bath.

Pravaz[2] says that compressed air (1) increases the amplitude of inspiration ; (2) augments or assists the interchange of gases between the blood and the air ; (3) facilitates the return of venous blood to the heart. He studies the subject from a therapeutic point of view, and does not assist us in forming a conclusion concerning the pathology of compressed air illness.

[1] "Note sur la carbonométrie pulmonaire dans l'air comprimé."—*Gaz. Méd. de Lyon*, 1849, p. 148.

[2] "Essai sur l'emploi de l'air comprimé." Lyon, 1850.

Pol and Watelle[1] were the first to attempt to explain compressed air illness; they were the first to determine positively its time of onset. "Payment is only made on coming out," say they. With the exception of cases of muscular pains where there is no evidence of the nervous centres being affected these cases were probably produced, in their opinion, by the circulation of hyperoxygenated blood through the capillaries of the nervous system. Excepting, also, the gastric pains, which appear often to be of a sympathetic character, the illnesses would appear to suggest a congested state of the brain and lungs. In order to explain why the symptoms only supervene after the decompression, they state that the compression itself exercises a corrective influence over the possibly bad results of the congestion it produces.

Guérard[2] points out that there must be an increase of oxygen and nitrogen dissolved in the blood, and consequently, he says, there must be an increase of the amount of interstitial combustion, from which emaciation will result. He considers that the pains in the extremities are rheumatic in nature, and due to the rapid cooling of the air lock during the locking-out process.

Milliet[3] denies that any chemical change takes place in the normal functions of respiration. "The only result," says he, "of the increase of the amount of air with which the lungs come into contact is an increased facility of respiration. The reduction of the frequency of the rhythm

[1] "Mémoire sur les effets de la compression de l'air appliquée au creusements des puits à houille."—*Ann. d'Hygiène Publique et de Médecine Légale*, 1854, 2nd series, vol. i., pp. 241-279.

[2] "Note sur les effets physiologiques et pathologiques de l'air comprimé."—*Ann. d'Hygiène Publique et de Médicine Légale*, 1854.—2nd Series, pp. 279-304.

[3] "De l'air comprimé," etc. Lyon, 1854.

of the respiration is a purely physical result; the air has not been modified in its chemical constitution, and the laws which regulate our organism have not ceased their natural action." He points out an increase in the secretions caused by the compressed air.

In 1855 Eugène Bertin[1] pointed to the slowing of the respiration in compressed air. He did not admit that there was also at once a diminished frequency of the pulse, though this appeared in the course of a short time, and lasted even after leaving the compressed air.

Hoppe,[2] in a remarkable work on the causes of death of animals killed suddenly by a rarefied atmosphere, found in their blood vessels bubbles of free air, to which, according to him, death was due. He applies the same explanation to the result of decompression from a compressed atmosphere. He says the lungs have not time to get rid of the excess of free gases in the large vessels. His reasoning is, however, only from analogy, and he had not made direct experiments on this point.

Dr. François[3] rejects at once the suggestion made by Guérard, that the pain is rheumatic in nature, by pointing out that it at once disappears on recompression. He explains the pathological symptoms by saying that the compressed air during compression insinuates itself in the cellular tissues of the body, and hence on decompression attempts to establish equilibrium with the outside pressure by escaping from the tissues, thus producing muscular pain. The respiratory and cerebral accidents he puts down to pulmonary and cerebral congestions.

1 "Étude clinique de l'emploi et des effets du bain d'air comprimé dans le traitement des diverses maladies." Paris, 1855.

2 "Ueber den Einfluss," etc.—*Müller's Archiv*, 1857.

3 "Des effets de l'air comprimé," etc., 1860.

Professor Rameaux of Strasbourg supports this theory.

Bucquoy[1] states that although the amount of oxygen dissolved in the blood may be increased during compression, that absorbed by the corpuscles cannot be so increased. From the fact that venous blood in compressed air is of a bright red colour, and also from the fact that respiratory combustion cannot be less free in compressed air than in the open air, Bucquoy infers that either the oxygen given up for combustion partly comes from the corpuscles and partly from that dissolved in the serum, or that the corpuscles re-take more oxygen from the serum. Bucquoy considers that the peripheral blood is driven towards the interior of the body, producing congestion of the viscera. He shows theoretically how, by the law of Dalton, the amount of gases dissolved in the blood will increase in accordance with physical laws; and he considers that on decompression gas must escape and may in some cases cause emphysema and hæmorrhages, and articular and muscular pains. He goes on to relate how, in a case of "bends" at Douchy, he was watching the application of cupping glasses to a painful knee by a skilful hospital attendant; and they one after the other fell off—due, he says, to the escape of air through the skin into the glasses.

Foleÿ,[2] as we have previously seen, ascribes the swellings of the limbs to "arterial congestions." He has practically nothing to add to the pathology of the illness.

Babington[3] only attempts to explain the cerebral and spinal cases. "The brain and spinal cord, encased as they are in bony cavities, and having their vascular supply con-

[1] "Des effets de l'air comprimé," etc., 1861.

[2] "Du travail dans l'air comprimé," 1863.

[3] "Paralysis caused by working under compressed air," etc.—*Dublin Journal of Medical Science*, 1863, vol. xxxvi., pp. 312-318.

veyed through vessels similarly encased, cannot yield to alternating rates of pressure with the same facility as parts of a more elastic and pliant nature. Hence the brain, working together with the other parts of the body under excessive pressure, cannot, when the pressure is removed from the surface, accommodate itself to the altered circumstances so rapidly as other organs; the excess of pressure on the brain and spinal cord must pass off by the narrow passages in which the blood is carried to and returned from the brain and nervous system generally." He goes on to say that "the idea of any noxious element in the condensed air, which has been broached by some, must be abandoned, as the workers suffered no inconvenience during their stay (of three or four hours) in the cylinder; all the cases of serious illness occurred on the removal from the air." Further, "that there was no excess of carbonic acid was evident from the fact that the candles in the cylinders burned with increased brilliancy. Hens, dogs and rabbits were kept at the bottom of the cylinder for many hours (*sic*) without any symptoms of suffering or injury."

Sandahl[1] says that the principal effect of compressed air is on the relative amounts of gases dissolved in the blood, and that on the increase of the oxygen dissolved in the blood depend the effects on the system. He maintains that if more oxygen were, however, used by the system in a given time, it is most probable that the temperature of the body would rise, and he points out that the most careful experiments have failed to show a rise of temperature.

Tutschek[2] similarly ascribes the symptoms to the increased amount of oxygen absorbed by the blood in compressed air.

1 "Ueber die Wirkungen," etc., 1862.
2 "Die comprimirte Luft," etc., 1863.

Rudolph Ritter von Vivenot[1] produced one of the most important works on this subject; his experiments were mostly conducted at the baths of Johannesburg. The pressure was a little less than half an atmosphere above the normal; twenty minutes were allowed for entry, the stay usually one hour, and the exit forty minutes.

Respiration.—Vivenot says that the effect of the pressure on different parts of the body varies with the consistence and situation of different organs, that the lungs are the most delicate and elastic organs, and that their bases are less supported, and more movable, than their surfaces exposed to the ribs, and in consequence we get a displacement downwards of the diaphragm. He finds by percussion that in compressed air the diaphragm and the liver are situated lower by $1\frac{1}{2}$ to 2 centimètres; the dulness of the heart is less extended, and has altered in form, having taken the shape of a reaping hook with the convexity towards the sternum; the cardiac impulse is less vigorous, sounds of the heart more feebly heard, and apparently more distant. These signs are explained by the mechanical dilatation of the lungs, which Vivenot considers demonstrated by these facts, and again by the records of the spirometer, which shows an increase in volume of the expiratory capacity of from $\frac{1}{29}$th to $\frac{1}{25}$th of the whole expired air, or about 3·3 per cent. Vivenot also gives figures from which he concludes the surprising fact that this increase in respiratory capacity is not transitory, but with successive séances in the compressed air bath increases from day to day. In this way he increased his own

[1] "Zur Kenntniss der physiologischen Wirkungen und der therapeutischen Anwendung der verdichteten Luft. Eine physiologisch—therapeutische Untersuchung." Erlangen, 1868. For other works by Vivenot on this subject, see "Bibliography."

respiratory capacity, as shown by the spirometer, by 24 per cent., and obtained a corresponding increase in three other persons; moreover, at the end of three weeks after the last compressed air bath, this increase was maintained, and the alteration in the position of the diaphragm and liver, and the diminished dulness of the heart, were also unaltered.

Vivenot finds the number of inspirations diminished; the diminution varies in different individuals. It is in general from three, two, one, or one-half a respiration per minute. In two emphysematous patients Vivenot found that the respirations, which normally were 33 per minute, diminished by 16 and 11 respirations. On returning to the open air, the diminution only partially disappeared. A repetition of the compressed air baths has an increasing effect on the diminution of the frequency of the respirations. Vivenot's own respiration, normally 16 to 20 per minute, fell, after three months' daily use of compressed air baths of two hours' duration each, to 4 or 5 in the normal air, and 3 or 4 in the compressed air. Similar, but less striking, results were noted by Vivenot in three other people; in one of these, an emphysematous person with normal respiration of 33, the respiration fell to 18, and then, after five days, to 10·4. Vivenot remarks that the frequency of the inspirations are inversely proportional to their amplitude, and that the former is the effect of the latter.

Vivenot also measured the amplitude of the respirations by a sort of cyrtometer. He found that the increase of the chest circumference during inspiration, after a sojourn of an hour in the compressed air, was 18·14 centimètres, that under the normal pressure being 12·39 centimètres. This applies to an *ordinary* inspiration. Vivenot found a similar increase to obtain in the case of a forced expiration and a maximum inspiration, though in a very much less degree. In his own case (the only one he mentions) the increase in circumference, over that obtained under normal pressure, after a maximum inspiration, was 1·5 centimètres, and after a maximum expiration 1 centimètre; from which he concludes that there was an increase in the pulmonary capacity equivalent to an increase of the chest circumference of ·5 centimètres, a result very different from that which would appear to be indicated by the previous experiments on ordinary inspirations.

He states that inspiration in compressed air is more easy on account of the extensibility of the pulmonary tissue and the compressibility of the intestines; whilst, on the other hand, expiration requires greater force to contract the distended lungs and to force out the larger quantity of air: consequently expiration is longer than normally. The relation of inspiration to expiration, then, instead of being 4 : 3 is 4 : 6 or 4 : 7, or even 4 : 8 and 4 : 11.

Vivenot's pulse sphygmograms show a smaller height of the wave, a less rapid up-stroke, a more rounded summit, and a less rapid line of descent. These characteristics increase with the height of the pressure of the compressed air, and also with the length of stay in the pressure; they disappear on the return to the normal pressure. There is an increase of arterial tension in the compressed air.

Concerning the pulse frequency, out of 423 observations Vivenot found a lessened frequency 375 times, an acceleration 30 times, and no change 18 times. The slowing of the frequency he found to persist to some extent after return to the normal pressure.

Conjunctivitis is temporarily improved by the compressed air, and the vessels of the fundus oculi become less full of blood. Vivenot concluded from this, and from observations on the ears of a rabbit, that under compressed air the amount of blood diminishes in the vessels of the periphery of the body.

Vivenot explains the increase in the capacity of the lungs in this way: "The pulmonary tissue, which is delicate and elastic, and yields easily, will resist less the increase of pressure on the side of the base of the lungs, where it is only supported by the intestines, which are very compressible, than on the side of the thoracic parietes, which are formed by harder and more compact tissues. This accounts for the increase in the vertical diameter of the lungs and their displacement downwards."

Concerning the modifications in the chemical changes of respiration produced by compressed air, he says: "It is necessary as a basis of observations to determine the quantity of carbonic acid exhaled by respiration, in order to see if the quantity of oxygen absorbed, and the quantity of oxygen consumed, are altered as a result of the action of compressed air. *A priori*, we should expect an increase in the absolute and relative quantities of oxygen absorbed: in the absolute quantity on account of the increase of the pressure exercised on the lungs, as also on account of the increase, previously stated, in the pulmonary capacity; in the relative quantity, since the number of respirations is diminished, and since it is a fact that the carbonic acid exhaled, sometimes also the oxygen absorbed, are in an inverse proportion to the frequency of respiration" (Vierordt). Vivenot, in order to arrive at conclusions on this point, used a spirometer, into which one deep expiration was expired. In his own case the volume of air expired averaged 3700 c.c., and the duration of respiration from fifteen to eighteen seconds. The first experiment was made one hour before going into the compressed air;

the second experiment was made one hour afterwards—*i.e.*, immediately before entering the compressed air chamber; the third one hour afterwards, while in the compressed air; the fourth one hour afterwards, under normal pressure, immediately after exit from the compressed air; and two others subsequently, at intervals of one hour. These experiments were made daily for nineteen days, with the following results. The quantities of carbonic acid are expressed in grammes contained in each expiration, and the corresponding quantity of carbon exhaled.

Observer, VIVENOT.	Under normal pressure.		Under increased pressure.	Under normal pressure.		
	8 a.m.	9 a.m.	10 a.m.	11 a.m.	12 noon.	1 p.m.
Quantity of CO_2 contained in one expiration, in grammes.	·1983	·2236	·2676	·2183	·2177	·2106
Corresponding quantity of Carbon, in grammes.	·05408	·06098	·07298	·05954	·05937	·05744

"This result proves evidently that an expiration in compressed air contains ·0440 to ·0570 or a mean of ·050 grammes carbonic acid more than under normal pressure." In Vivenot's experiments on himself the maximum carbonic acid found under normal pressure was ·2890 grammes, and in compressed air ·3215 grammes.

Experiments on other persons gave similar results. In the case of M. H——t a normal expiration of 3000 c.c. contained in the open air ·1305 grammes of carbonic acid, but in compressed air ·1735 grammes, or an excess of ·0430 grammes—*i.e.*, one-quarter of the total and normal quantity of carbonic acid. In the case of Mdlle. B—— (one experiment only), under normal pressure an expiration of 3000 c.c. contained ·138 grammes of carbonic acid, and in compressed air ·170 grammes. Dr. Lange, working with Vivenot, made similar experiments, as represented in the following table :—

Observer, LANGE.	Under normal pressure.	Under increased pressure.	
		Immediately after entry (entry occupying half an hour).	After one hour's stay under maximum pressure.
Quantity of CO_2 in one expiration, in grammes.	·2506	·2959	·2211
Corresponding quantity of Carbon, in grammes.	·06827	·08070	·06300

The maximum amount of carbonic acid expired by Lange under normal pressure was ·3770 grammes ; under compressed air the maximum was ·4345 grammes. The fact is to be noted that Lange found a diminution in the amount of carbonic acid after a sojourn of one hour under the maximum pressure. Vivenot doubts these figures, and quotes another experiment of Lange's :—

Observer, Lange.	Under normal pressure.	Under increased pressure.	
		Immediately after entry (entry occupying half an hour).	After one hour's stay under maximum pressure.
	gram.	gram.	gram.
Carbonic Acid . .	·2460	·2910	·2920
Carbon	·06709	·07936	·07964

Vivenot then gives the amount of excess of carbonic acid in several persons under compressed air, compared to the total quantity :—

Vivenot	$\frac{1}{4\cdot35}$	= 22·99 per cent.
M. H——t	$\frac{1}{4\cdot04}$	= 24·75 " "
Mdlle. B——	$\frac{1}{4\cdot31}$	= 23·20 " "
Dr. Lange	$\frac{1}{5\cdot53}$	= 18·08 " "
Average	$\frac{1}{4\cdot50}$	= 22·26 " "

In order to show that this excess of carbonic acid is not due to an actual excess of carbonic acid contained in the air of the pneumatic chamber, Vivenot analysed this air and also the air in the waiting room adjoining, and found that 3500 c.c. of the former contained ·0391 grammes of carbonic acid, and a similar quantity of the latter contained ·0392 grammes—*i.e.*, that the two amounts of carbonic acid were the same. (It may be pointed out here that this amount represents a percentage of carbonic acid in the air which is very large and which shows that the air of the waiting room and the pneumatic chamber was very foul indeed ; again, according to Vivenot's previous experiments the respiratory capacity in the compressed air is augmented ; is it that the excess of carbonic acid in an expiration in compressed air is due to the increased respiratory capacity ? Vivenot proceeds to answer this question.)

"If we compare the relations of the quantity of carbonic acid exhaled under the normal pressure and in the compressed air with the relations of the pulmonary capacity in these respective conditions, we find :—

	Respiratory Capacity.		Quantities of CO_2 produced.	
	In normal air.	In compressed air.	In normal air.	In compressed air.
	c.c.	c.c.	gram.	gram.
Vivenot . .	3425	3533	·2176	·2676
Lange . . .	3950	4083	·2505	·2959
Average	3687·5	3809·5	·23410	·28175

—*i.e.*, an increase of 122 c.c., ·04765 gramme.

"Taking a unit to represent the normal amounts, we have the following relations :—

Vivenot	$1 : 1 + \frac{1}{31·7}$	$1 : 1 + \frac{1}{4·35}$
Lange	$1 : 1 + \frac{1}{29·7}$	$1 : 1 + \frac{1}{5·53}$
Average ...	$1 : 1 + \frac{1}{30·80}$	$1 : 1 + \frac{1}{4·91}$

"Thus, while the increase in the pulmonary capacity in the compressed air was $\frac{1}{30·8}$ of the normal capacity, the quantity of carbonic acid exhaled increased by $\frac{1}{4·9}$; the relative proportion of these increases is 1 : 6. If we calculate what should be the quantity of carbonic acid exhaled, if its increase in the compressed air is proportional to the increase in the pulmonary capacity, we find the proportion thus: 3687·5 c.c.: 3809·5 = ·2341 gramme: x. Whence x = ·24197 gramme. The calculated increase in this case is ·00787 gramme, instead of ·04765 gramme found by experiment."

Vivenot is here making minute calculations about matters which as yet are not susceptible of such mathematical treatment. Without pausing to inquire by what means he was enabled to so accurately determine the amount of carbonic acid contained in one expiration, we may point out that it is futile to trouble to compare any figures with the increase of pulmonary capacity, for this latter by no means represents or corresponds with the accompanying increase of surface of pulmonary vesicles exposed to the inspired air; and even this latter unknown quantity would be far from giving us any information concerning the processes of transfer of gases into and from the blood, which goes on under the extraordinary conditions which prevail in compressed air. Would it not be more to the point to compare the increase of carbonic acid in one expiration in compressed air with the reduction of the number of respirations? If, as Vivenot has already pointed out, the respirations are so remarkably reduced in frequency as to be only six, five, or even four per minute, must we not expect to find an increase of carbonic acid in one expiration, and that even in a much larger proportion than that which has been found above by Vivenot?

From such figures as those above given, carried sometimes to six decimal places, concerning the weight in grammes of the carbonic acid contained in *one* expiration and estimated by actual experiment (!), Vivenot calculates the amount of carbonic acid expired per day, both in the normal state and in compressed air; he finds that normally in twenty-four hours 1300·37760 grammes of carbonic acid are expired, and that in the same time, under a pressure of half an atmosphere, the quantity would become 1449·49350 grammes. Regarding the former figure it is not surprising that it is entirely in opposition to the estimate obtained by all other observers, and this fact lessens our faith in the latter figure. Paul Bert, in commenting on these results, says: "How have these figures been obtained? By analysing the product of *one* expiration "*as strong as possible, yet made without great efforts,*" under the normal pressure, which gave ·2176 gramme of carbonic acid, and of *one* expiration under pressure, which gave ·2676 gramme; and at the same time taking account of the mean number of respiratory movements per minute, which was 4·15 in the first case and 3·76 in the latter; lastly, by multiplying the resulting number by 60 and then by 24. For myself I refuse to accord any kind of value to figures obtained by a method so absolutely contrary to that which true physiological precision requires."

Vivenot points out two facts which accord with his experiments above mentioned:—

1. The increase of appetite noticed after the compressed air bath.

2. The notable increase of urinary secretion. Both of these were noticed by himself and his colleagues. He refers to the increase of weight noted by himself and his co-experimenters, and points to the opposite result the diminution of weight noted by Sandahl and others in men who work under such greatly increased pressures as 3 or 4 atmospheres. This he explains by supposing that the supply of food is insufficient to keep up with the greatly increased demand on the system.

G. Lange,[1] a co-worker with Vivenot, follows very closely the latter's line of argument. He, however, explains the slowing of the respiration in the compressed air by supposing that, on account of the increase of expiration of carbonic acid, there is less of this gas in the blood, which would necessarily produce less need of respiration. This explanation obviously explains nothing, for if there is more carbonic acid being exhaled there must be a corresponding increase of carbonic acid in the blood to produce this result; moreover, it cannot explain the permanent slowing of the respiration by a course of compressed air baths. He then further attempts to explain the same phenomenon, by supposing an increase of the force of the respiratory muscles which, together with an increase of the pulmonary capacity, causes a diminished frequency of respiration to meet the necessities of the system; and he quotes some remarks of J. Lange[2] to prove this increase of respiratory muscular force.

G. Lange explains the cerebral symptoms by repeating the statements of various previous authors, notably Junod, that the brain, being contained in a bony cavity, is less exposed to the increase of the atmospheric pressure, and consequently more blood is driven into the cranial cavity from the periphery of the body.

Elsässer[3] enunciates the opinion that the action of compressed air depends on two principal factors:—

1. The increase of pressure.

 (*a*) On the external surface of the body.

 (*b*) On the respiratory cavities.

[1] "Mittheilung über die physiologischen Wirkungen und therapeutische Bedeutung der comprimirten Luft." Wiesbaden, 1865.

[2] "Ueber comprimirten Luft, ihre physiologischen Wirkungen und ihre therapeutische Bedeutung." Göttingen, 1864.

[3] "Zur Theorie," etc., 1866.

2. The larger quantity of oxygen and nitrogen respired in a given volume of air.

He appears to take it for granted that from the platitude contained in the second of these factors will follow an increase in the absorption of oxygen into the blood, and from this will follow an increase in the actual consumption of oxygen.

Panum,[1] in criticising Vivenot's results, says that the enormous quantity of carbonic acid found by him indicates that his expirations were very much forced. Taking Vivenot's figures, Panum calculates that the pulmonary ventilation in twenty-four hours would amount, under a normal pressure, to 21,111·2 litres, and in compressed air to 19745·5 litres. (Panum himself, under a normal pressure, only obtained 1152 litres.) By an expiration so enormously forced it results that Vivenot finds a production of carbonic acid to the extent of 1300 grammes under a normal pressure, and 1449·5 grammes in compressed air. (Panum in his own case found 816·2 grammes.)

Panum then gives the conclusions he draws from his own experiments, without going into much detail as to the methods employed; his analyses, unlike those of Vivenot, were made on 60 or even 120 litres of air expired into a spirometer at different moments of the experiment; the pressure was only increased by 24 centimètres of mercury. He says: "I have found no trace, in my experiments, of this increase in the production of carbonic acid after the compressed air baths of which Vivenot speaks. I consider Vivenot's opinion erroneous, because his method is fallacious and could not serve to estimate the quantity of air which regularly traverses the lungs in a given time with a natural and easy respiration, his respiratory

1 "Untersuchungen," etc., 1868.

rhythm being forced and unnatural. If we compare in my tables the cases in which equal volumes of compressed air and of normal air have been respired, we find that the quantity of carbonic acid exhaled has been increased absolutely and relatively in the compressed air. But if we compare the cases in which there has been an equal volume of air measured at the same pressure, respired either in the free air or in the compressed air, we see that there has been in the compressed air a little less carbonic acid produced than at the normal pressure. In other words, the quantity of carbonic acid expired during respiration in compressed air increases by the augmentation of the mass of the air which traverses the lungs in virtue of the pressure, but in a proportion a little less than this.

"The experiments of Regnault and Reiset, in which the respiration of an atmosphere rich in oxygen had not led to a greater excretion of carbonic acid, appeared *a priori* to prove that we should have no increased excretion of carbonic acid in compressed air. However, I have obtained a result which Vivenot had seen, and, in spite of my expectation, which is much more convincing.

"On what can depend such a difference between respiration in an atmosphere rich in oxygen under a normal pressure, and respiration in a normal atmosphere under an elevated pressure? We can only ask ourselves if it is the oxygen chemically combined to the corpuscles of the blood, or that which is simply dissolved, which in the one case oxidises more energetically than in the other? If we respire hyper-oxygenated air at the normal pressure, then the increased partial pressure increases also the proportion of oxygen simply dissolved in the blood, whilst that which is in a state of chemical combination very probably does not vary. This shows that it is not the oxygen simply dissolved, but the oxygen combined, which produces the carbonic acid, since, in the experiments of Regnault, this production does not increase. We can similarly see that the increase of oxidation and of carbonic acid produced, which we have stated occurs in compressed air, depends on the combined oxygen of the blood."

Panum, in discussing the increase in the pulmonary capacity in compressed air, mentions the following beautifully illustrative experiment: "I submerge under water in a bottle a bladder containing air; a second bladder, provided with a tube, is placed in the top of the bottle; the tube passes through a cork which hermetically closes the bottle. The whole is arranged so that the vessel is full of water, except for the space occupied by the bladders. The lower bladder represents the intestinal canal and its gases, the upper the lung with the trachea, the bottle and the water representing the closed thoracic cavity. If we carry this very simple apparatus into the compressed air, we see that the lower bladder diminishes in size and the upper increases. This result does not absolutely change if we employ a bottle in which the bottom is replaced by an elastic membrane. The closed bladder behaves in the same way, but a part only of the space, which its diminution sets free, is filled by the upper bladder; the membrane at the bottom rises. This shows that it is the compression of the air contained in the intestines which is the cause of the increase in the capacity of the lung, and the lowering of the diaphragm."

Concerning the accidents following decompression Panum says: "The morbid phenomena result largely from the air, becoming suddenly free in the blood vessels, being forced on by the circulating current and forming embolic obstructions in different vascular areas."

G. von Liebig[1] made some experiments on the relative amounts of carbonic acid expired in normal air and in compressed air. His experiments were made in each case on the air expired in fifteen minutes. His results were as follows: two experiments in normal air gave in fifteen minutes 8·442 and 7·955 grammes of carbonic acid respectively, and in the compressed air the results of four experiments were 7·614, 7·784, 7·747 and 7·136 grammes of carbonic acid; and on the return to the open air 7·701 and 7·287 grammes;—*i.e.*, the average before compression was 8·198 grammes; during compression 7·570; and after, 7·539. The experiments were made on one individual, and since they all appear to have been made on one occasion, Paul Bert's criticism, that Liebig does not give details concerning the diet and exercise of the individual, does not appear to detract from the value of the results.

M. Gavarret[2] concerns himself with the pathological and not the physiological consequences of the compressed air.

"The return to the free air often produces buccal and nasal hæmorrhages which are not generally accompanied by any pain. In our opinion these hæmorrhages are the result of the rupture of the capillaries, determined by the tension of the gas with which the blood is supersaturated. The modifications determined in the cutaneous circulation at the moment of decompression appear to us sufficient to explain these accidents. The blood, supersaturated with

[1] "Ueber das Othmen unter erhöhten Luftdruck."—*Zeitschrift f. Biologie*, vol. v., pp. 1-27. Munich, 1869.

[2] "Atmosphere."—*Dictionn. encyclopédique des sciences médicales*, pp. 111-164. Paris, 1867.

free gases at a high tension, is flowing through the capillaries, distends them, stretches the innumerable nerves and filaments which enlace them, and leads to, according to the rapidity and intensity of the vascular congestion, sometimes a simple feeling of heat, and sometimes actual pain."

M. Leroy de Mericourt,[1] after having described divers' paralysis, explains it by saying: "We believe that it is possible to admit that in these cases there is produced a lesion of the spinal cord, and that this lesion is a hæmorrhage. According to the seat and intensity of this hæmorrhage, death supervenes quickly or after some time." He explains the hæmorrhage by comparing the position of a diver, who has remained a long time under water, to a bottle of water supersaturated with dissolved gas under pressure, which, when the pressure is reduced, effervesces; he points out that if, in injecting a solution into a vein of a horse, we inject a bubble of air, the horse falls down as if struck by lightning: the effect is only momentary. If a number of bubbles of air are introduced, then death supervenes. In this way Leroy de Mericourt assumes that hæmorrhage may be produced, and he supposes that they will appear in the cerebro-spinal system rather than elsewhere, because of the congestion consequent on the blood from the softer parts of the body being forced within these encased cavities; and rather in the spinal cord than in the brain, because of the greater vascularity of the former.

M. Bouchard[2] considers the accidents of compression and decompression as due to abdominal, spinal, and

[1] "Considerations sur l'hygiène des pècheurs d'éponges."—*Ann. d'hygiène publique et de médecine légale*, 2nd Series, vol. xxxi., pp. 274-286. 1869.

[2] "De la pathogénie des hémorrhagies." Paris, 1869.

cerebral congestions and hæmorrhages; he explains the abdominal congestion by showing that during compression the intestinal gases are diminished in volume; the abdomen is thus largely diminished in volume, the abdominal wall presenting a concavity; the elasticity or tonicity of the abdominal muscles, he says, tends to reduce this concavity, and thus the abominal wall acts as a sort of large cupping glass on the contents of that cavity, and draws the blood from the rest of the body, producing a general anæmia. Thus we get an abdominal congestion during compression. During decompression the reverse takes place: the excess of blood in the abdomen is forced into the other parts of the body, where possibly the vessels may have meanwhile lost their "tone," and do not accommodate themselves immediately to this sudden irruption. Thus hæmorrhages may take place, epistaxis, hæmoptysis, transient or fatal apoplexy, accompanied in certain cases by temporary or permanent hemiplegia or paraplegia.

M. Bouchard, however, does not appear to think that this explanation is the universal one, and he says that the hæmorrhages are possibly sometimes due to the excess of gases dissolved in the blood. In discussing the gases held in solution in the blood, he discusses only, without saying why, the carbonic acid, which, in a man who has remained for several hours in a pressure of 4 atmospheres, will be four times that normally contained in the blood. On decompression this will return to the gaseous state. If the decompression is made slowly the blood, in passing through the lungs, will get rid of its excess of carbonic acid, and no accident will occur, but if the decompression is rapid the carbonic acid will tend to come to the gaseous state even in the blood-vessels, and by its rapid expansion and by the obliteration of small vessels in which it cannot circulate, will tend to cause ruptures and extravasations. He applies this explanation to the formation of painful muscular swellings. "These swellings are not inflammatory, they are not exudations nor extravasations; they disappear immediately on recompression and are never followed by ecchymotic patches; the swelling is accompanied neither by pulsation nor redness, so that they can scarcely be attributed, as by Foleÿ, to an exaggerated arterial dilatation. If it be true that muscular work is an important source of carbonic acid, could we not suppose that the muscles which have done the most work are charged with carbonic acid dissolved in the muscular substance, and that at the moment of the decompression this carbonic acid acquires the free state, to be redissolved by a new compression?

M. Gal[1] appears to oscillate between different theories in explaining cases; appealing at one time to Foleÿ's explanation of exhaustion of nervous force, to arterial congestion, active or passive, to a reaction of the circulation too violent or ill-directed, to actual hæmorrhages, and sometimes to the escape of the gaseous contents of the blood; the only determining factor in fixing on the appropriate cause in each case being apparently the violence and rapidity of the illness and its duration. He advises a slow decompression, and when great pressures are reached he recommends that the length of stay should be shortened.

Jaminet, at the St. Louis Bridge, made a number of observations on the pulse rate. His conclusion was that the passage from a normal pressure to an increased pressure quickened the pulse rate; a stay of any duration

[1] "Des dangers du travail dans l'air comprimé et des moyens de les prévenir."—*Thèses de Montpeleer*, 1872.

in the compressed air caused the frequency to be less than the normal; and that on the return to the outside air the rate again increased. The following is a fair example of one of his series of figures, obtained after noting the pulse rate in six individuals :—

Normal pulse rate.	On arrival in compressed air.	After two hours' stay in compressed air.	After coming out.
81	97	64	104
75	77	70	90
76	77	67	90
80	92	69	100
76	88	68	94
82	90	68	96

It must be remembered in connection with these figures that there was a considerable flight of steps to be descended before arrival at the air locks, and afterwards to be ascended. The fourth column of figures was admittedly obtained after the ascent. This will account for the increase of those rates, apart from any influence of the compressed air. It is not stated whether the first column of figures was obtained at the top of the caisson or on arrival at the air locks; these rates are described as the "normal" pulse rates of those individuals, and so we must suppose that they were taken before a flight of steps was descended—and here again the slight increase in frequency on arrival in the compressed air may be expected, apart from any action of the compressed air. The only one fact that can be properly inferred is that after a stay in the compressed air, with little or no muscular exertion during that stay, the pulse rate is certainly below the normal. All of Dr. Jaminet's other figures on the pulse rate are open to the same objection.

Jaminet found generally that the respiration was slightly increased in frequency, but found no alteration in the measurement of the chest on arrival in the compressed air. He made a number of experiments on the boiling points of different liquids under pressure; these had been before amply determined by physicists, and are of no interest in the present connection.

Jaminet's theory concerning the causation of compressed air illness was that it is due to exhaustion of the system. He considered it unnecessary to prove that a greater waste of tissue or consumption of oxygen took place in compressed than in normal air; this appeared to him a necessary consequence. In support of this idea he took samples of urine passed after coming out of the compressed air, and recorded the specific gravity of these samples; figures so obtained he regarded as showing relatively the amount of urea contained in the samples. The specific gravity he found generally to be high; the specimens were not twenty-four-hours specimens. From these premises he concluded that the amount of urea was increased by a stay in the compressed air.

On account of these pathological reasons, basing the causation of the illness on the exhaustion of the system, Jaminet drew up his rules for the regulation of work in compressed air. When the pressure rose he recommended shorter working hours and longer intervals of rest; a meal before entering the air, and coffee immediately on coming out; and a rest of half an hour or so before going home. Regarding the changes found at the autopsies in the fatal cases Jaminet says: "We do believe that those pathological changes were not caused by the *immediate* effect of exposure to a condensed atmosphere, but the result of a reaction produced too suddenly on those taken sick, by the means used to bring on the reaction; among which we may name such as the administration of alcoholic stimulants in too large doses for the nature of the cases, the hot bath administered immediately after being taken sick, and which was followed in some cases by immediate paresis, and even paralysis, from which the patients recovered very slowly, if at all—a fact which induced us to forbid the use of the bath entirely in the treatment of such cases. We may also mention, as a means of bringing on reaction, the injudicious use of magneto-electricity, and the removal of the patients from the piers too soon after they were taken sick, and when they were not in a condition to support such removal."

This explanation would hardly affect those fatal cases occurring rapidly after leaving the compressed air, before any means to bring on this supposed "reaction" could have been attempted, and before any possible "reaction" could have asserted itself.

Dr. E. A. Clark, who observed a number of the cases at St. Louis and made some of the autopsies, referred the causation of the illness to "congestion of the organs."

"Another eminent physician"[1] of St. Louis ascribed the symptoms to carbonic acid poisoning, by the carbonic acid being abnormally retained within the body.

Mr. C. M. Woodward, Professor of Mathematics and Applied Mechanics at the Polytechnic School of the Washington University, who produced a large and technical volume on the construction of the bridge at St. Louis says: "My opinion is that the vital energies of the men taken sick are to a great extent paralysed by loss

[1] *Vide* "The St. Louis Bridge," by C. M. Woodward. St. Louis, 1881.

of heat." The reasons given in support of this opinion are, however, difficult to follow, inasmuch as the writer has physiological notions and a medical nomenclature entirely his own.

Dr. Gilman Thompson[1] thinks that although it may be easier for the blood to obtain its due amount of oxygen in compressed air, yet it is more difficult to get rid of the carbonic acid from the lungs, as a consequence of the pressure. As a result, with very high pressures, animals die with convulsions, asphyxiated by their own carbonic acid.

He made a number of experiments on animals.[2] A monkey withstood a pressure of 4½ atmospheres in pure oxygen for three-quarters of an hour, the only effect being a slight convulsion from too suddenly lowering the pressure. Monkeys, cats, dogs and pigeons were placed in a pressure of 4 atmospheres of oxygen and air respectively for one and a half hours; there were no symptoms except when the pressure was too suddenly lowered, when there might be a slight convulsion. A dog of 22½ lbs. weight withstood a pressure of 8 atmospheres "for some time," before evincing any discomfort; he then had a slight convulsion, but was quite well on coming out. From these experiments, Thompson felt justified in blaming entirely the "locking out" process, and said that there should be three air-locks instead of one, with a "graded air pressure," and "fully three-quarters of an hour should be consumed in entering or leaving the caisson, instead of five or ten minutes. The progressive character of the symptoms should be a warning to those who have had a first attack,

[1] "Notes on caisson disease."—*New York Med. Record*, 1894.

[2] "A paper read before the New York Academy of Medicine."—*Medical Record*, July 6th, 1889, vol. xxxvi., No. 1, p. 1.

that they cannot with safety continue to work under the same conditions."

Professor L. Bauer[1] suggests that hyperoxygenation and increased waste of the organic structures take place in the body while it is in the compressed air, and that at the same time the blood necessarily carries more carbonic acid and other effete materials. So long as the person continues in the compressed air the hyperoxygenation goes on and no ill effects are experienced; but when the pressure is removed the hyperoxygenation immediately ceases, and the accumulation of waste materials acts as a poison to the system.

Dr. A. H. Smith,[2] who was in charge of the men working in compressed air at the Brooklyn Bridge, favours the congestion theory. As he is more precise than most of his predecessors, it will be best to quote his remarks in detail:—

"It is probable that the pathology of this disease is not entirely uniform in all cases. Doubtless, the chief element in it is the congestions already described, and especially of the brain and spinal cord. The mechanism, therefore, of these congestions becomes a subject of paramount importance.

"It is obvious that if the blood were exposed to an equal pressure in all parts of the body, there would be no change in its distribution. It is equally clear that the blood, if free to move, will pass from a place where the

[1] "Pathological effects upon the brain and spinal cord of men exposed to the action of a largely increased atmospheric pressure."—*St. Louis Med. and Surg. Journal*, May 1870, New Series, vol. vii., pp. 234-245.

[2] "The physiological, pathological, and therapeutical effects of compressed air." Detroit, Michigan 1886.

pressure is greater to one where it is less. The body is made up of structures of different densities, and presenting a varying resistance to compression. But permeating these structures in every direction are vessels in perfect communication throughout the entire system, and filled with a mobile fluid, which is free to change its locality in obedience to any force which is brought to act upon it. Now when the surface of the body is subjected to an even pressure on all sides, the tendency is to a distribution of this pressure towards the centre. If the body were composed entirely of solids, this could be effected only by the compression of these solids, and a point would very soon be reached where the resistance would balance the compressing force, and the parts lying more toward the centre would remain unaffected. But the presence of a fluid in the structures, with free channels in which to move, changes all this. While the solid tissues resist compression, the fluid blood retreats from the surface to the centre, and accumulates there until an equilibrium of pressure is produced.

"Hence we deduce the law that under high atmospheric pressure the centres will be congested at the expense of the periphery. But, aside from location, vessels coursing through dense and resisting organs will be less exposed to external pressure than those passing through soft and resisting structures. Hence a second law, that firm and compact structures will be congested, at the expense of those more compressible.

"But there are structures very soft and yielding in themselves, yet enveloped in a rigid casing of bone which entirly shuts off the influence of external pressure. Hence the establishment of equilibrium in them is wholly dependent upon the afflux of blood. This gives us the third law, that structures within closed bony cavities are congested at the expense of all others.

"In accordance with these laws, we shall find that, while in the caisson, the condition of the different parts in regard to the supply of blood will be as follows:—

"The skin and the superficial structures will be anæmic. The central portion of the limbs and the interior organs of the body will be congested. The solid viscera of the abdomen will be especially engorged, on account of both situation and structure. The brain and spinal cord, and the interior of the shaft of the long bones, will be congested to a high degree, from the operation of the third law.

"These changes are not perfected until a considerable time has been passed in the compressed air. The circulation up to this point goes on everywhere with vigour, the change being in the relative calibre of the vessels, not in their tension. The counter-pressure becomes uniform throughout the whole vascular system, but this counter-pressure supersedes the natural muscular resistance or *tone* of the vessels, which have become passive tubes. The blood is distributed, not in accordance with the physiological demands of the different parts, but in obedience to overpowering physical force.

"This is the condition of the circulation at the moment that the process of locking out begins. Yet the changes which have taken place up to this point are not the cause of the morbid phenomena which constitute the caisson disease, else the attack would take place while *in* the compressed air, instead of after leaving it. It is evident that the *removal of the pressure*, and not the pressure itself, is the immediate cause of the seizure.

"This removal is effected in the few minutes which are occupied in locking out. But it is not to be supposed that the vessels will instantly assume their normal condition. They are in a state of relaxation, not only in the congested, but also in the anæmic parts; in the former because of over-distension—in the latter because the muscular coat cannot at once recover its inaction. The aggregate capacity of the vascular system will, therefore, be in excess, compared to the volume of blood to be conveyed; or, in other words, there will be a lowering of vascular tension. Hence, the circulation will be languid, and the congested parts will not readily empty themselves of the excess of blood which they contain. Especially will this be the case in the brain and spinal cord, where the conditions are most favourable for the production of congestion. The capillaries being clogged with effete blood, the nutrition of the part must suffer, and disturbance of function will result.

"It is to this, I think, that the delirium, and the transient loss of consciousness, which occasionally occur, are to be attributed. When the spinal cord is the seat of this condition, pain in the parts deriving their nerves from that section of the cord may result, or paralysis more or less complete may follow.

"This appears to me to account for the phenomena in those cases in which the local symptom is paralysis or pain of a transient or shifting character. These cases may, I think, be considered as entirely spinal in their origin. But in many cases there are evident local changes, such as tumefaction, rise of temperature, etc., which indicate local irritation, and which are probably due to obstruction of the vessels of the part as a sequel to the local congestion. This explanation is applicable also to those cases in which the pain is fixed in one locality, which may be very much circumscribed, and when it persists for days without intermission, feeling, as the patient expresses it, "as if it were in the bone," where it very likely is. Such a pain presents a marked contrast to those shifting pains which have been described, and if considered of spinal origin, would indicate a serious lesion confined to a minute portion of the cord. That such a circumscribed lesion might occur as a very rare exception, must be admitted; but that it should be present in a considerable proportion of cases is in the last degree improbable.

"The testimony of all observers is that the liability to attack is directly as the duration of the stay in the caisson. This admits of an easy explanation, on the theory which I have advanced. The more thoroughly the system has become adapted to the change in the circulation, the less readily it will resume its normal condition when the pressure is removed. The congested vessels, especially, will lose their contractibility in proportion to the time their muscular fibres have been upon the stretch."

Among the causes, immediate and remote, of the illness, Dr. Smith enumerates the following:—

1. Too rapid locking out. He recommends that at least five minutes should be allowed for each atmosphere of pressure.

2. Newness to the work. In regard to this matter he alleges that the new hands are more liable to be affected than the old ones, the system becoming adapted to the changed conditions, and protected in a measure from their effects. Nevertheless, he admits that some serious cases occurred among the old hands.

3. Fulness of habit. In order to put this point to a numerical test, as it had been remarked previously as a general impression, Dr. Smith divided those men who

were ill into three classes, spare, medium, and heavy, and obtained the following result :—

	Spare.	Medium.	Heavy.	Total.
Lost little or no time from sickness . .	25	14	3	42
Taken sick . . .	28	22	36	86
Paralysed . . .	2	3	8	13
Died			3	3

and he adds : " Considering that among labourers below the age of forty-five (and none of the cases were above that age), the class described as *heavy* are very much in the minority, these figures are sufficiently striking."

4. Severe exertion after leaving the caisson.
5. The abuse of alcohol.
6. Entering the caisson fasting.

These last possible predisposing causes have been previously discussed by earlier writers.

Dr. A. V. Meigs,[1] in a clinical lecture on a case of illness due to compressed air, summarises the theories of Bauer, Smith, Jaminet, François, Bert, and Woodward, and then adds : " It would seem likely that the real state of the case is that the effects are due, not to any one of the causes suggested alone, but to all of them acting together, or to varying combinations of two or more of them acting together." These unfounded generalisations do not assist us in elucidating the pathology of the illness. Meigs illustrates his lecture by one case of " bends " that came under his notice, and says that " the prognosis must be guarded " —an evidence of discretion which, under the circumstances, we are compelled to admire.

[1] *Medical News*, 1885, vol. xlvii., pp. 589-592. Philadelphia.

Dr. James Hunter,[1] after his observations made at the Forth Bridge, says: "I think with Professor Meigs that the real explanation is not contained in any one of these theories alone, but that it is to be found in a combination of parts of all of them, different theories being accountable for different sets of symptoms. All the alarming symptoms are produced by decompression, nothing in the least degree detrimental to health occurring while one remains in the working chamber even under a pressure of 4 atmospheres. There is therefore in this stage (compression) a degree of increased vital activity proportionate to the degree of increase of pressure.

"There is further, for mechanical reasons, an intropulsive effect on the cutaneous circulation, with an absorption of gases by the liquids of the body. Were decompression to be effected sufficiently slowly, and with proper precautions, probably little would be heard of caisson symptoms. But by existing methods it takes place by considerable rapidity; there is a great giving-out of heat, producing an extremely devitalising effect on the workers. There is a loss in the balance between oxygenation and tissue waste, which held during the increased vitality of compression, and there is a sudden liberation of the gases, which had been absorbed, and which now tend to interrupt the circulation, causing severe pain in the neighbourhood of the vascular fringes of joint surfaces.

"But to me it seems also that there is a nerve element in the production of this severe pain. Sir Joseph Fayrer has pointed out that in cases of sciatica he has obtained relief by incising the nerve sheath, releasing thereby a varying quantity of fluid, which has accumulated within the

[1] "Compressed air, its physiological and pathological effects."—*Thesis for M.D. Univ. Edin.*: Edinburgh University Library.

sheath, and, by its painful pressure on the nerve substance proper, has given rise to a condition whose name indicates the locality of that special neuralgia.

"It is quite a possibility, then, that there occurs in certain areas richly supplied with nerve filaments, an absorption of nitrogen during compression by the infra-perineurial fluid, and that the excessive pain referred to these areas is produced by attempts at release of bubbles of the gas when decompression has begun to take place."

Corning,[1] having detailed some of the cases that came under his notice from the Hudson Tunnel, recites an account of Glaisher's famous balloon ascent from Wolverhampton in 1862, regarding the symptoms that Glaisher suffered from —loss of the use of the hands and limbs, and unconsciousness—as precisely analogous to the symptoms of compressed air illness ; he attributes both, without proof, to anæmia of the spinal cord, and adds : "At one time it was believed that, on leaving the condensed atmosphere, there was a development of gas from the blood which caused a rupture of the neighbouring tissue. What added plausibility to this theory was the fact that Bert and Hoppe-Seyler had been able to produce analogous phenomena experimentally. It has been urged, however, in rebuttal, that the limitation to the dorsal portion of the cord and the infrequency or total absence of vascular hæmorrhages, are totally opposed to this theory."

[1] *New York Med. Record*, 1890, vol. i., p. 515.

CHAPTER X.

PATHOLOGY (CONTINUED): CRITICISM OF THE THEORIES ADVANCED.

IN discussing the pathology of compressed air illness, it is necessary at the outset to clearly distinguish the difference in the character of those symptoms, mostly connected with the ear, which manifest themselves during entry into compressed air, and those which accompany or follow exit. The former are obviously due to mechanical causes connected with the anatomical structure of the ear or frontal sinus. With a different anatomical arrangement these troubles would not occur; with a clear understanding of the risks incurred and the avoidance of entry if much inconvenience is met with, they would be minimised to a vanishing point. Hilton's classical use of pain as a danger-signal cannot be better exemplified; the causation and pathology of these conditions have been already treated of when the symptoms were discussed.

There remain to be considered those more important symptoms, which together may be described as compressed air illness proper, which resemble one another in their sudden onset during or soon after leaving the pressure, in their tendency, in the absence of a fatal event or complication, to disappear by themselves within a comparatively short time, and in their amenability to speedy recompression. A review of the various theories which have from time to time been advanced to account for the accidents which may follow a stay in compressed air, causes us to observe that those which appear to be worth consideration group themselves into three classes :—

I. Theories suggesting exhaustion, carbonic acid poisoning, and the like, as the cause.

II. Theories ascribing the symptoms to the mechanical congestion of different viscera.

III. Theories depending on an increased solution by the blood of the gases of the compressed air, and the liberation of these gases on the pressure being removed.

I. All the theories of the first class depend directly or indirectly on the presumption that a sojourn in compressed air, on account of the larger amount of oxygen contained in a given volume of that air, is necessarily accompanied by an increased amount of metabolism. Most of the supporters of these theories have considered this a necessary consequence, requiring nothing more than its expression in words to ensure its general acceptance. A few have apparently considered the postulation of such a statement a work of supererogation and have at once proceeded to inquire into the possible effects on the system of the increase of carbonic acid and other waste material which they suppose to accumulate during a stay in compressed air. While there remain one or two others, notably Vivenot and those who have approached the subject from a therapeutic point of view, who have been at great pains to show that an increase of chemical activity, resulting in the formation of an excessive amount of carbonic acid and other products of metabolism, will accompany or follow the stay in compressed air.

If this increased chemical activity can be disproved, the whole of these theories fall to the ground ; if it cannot be substantiated they remain, until the question is finally determined, without any rational basis.

We have therefore to examine the evidence which has been adduced for and against this supposition.

Hervier and St. Lager long ago made experiments at the suggestion of Pravaz; they give no figures, but they state that they found that carbonic acid was first of all increased by compressed air, but that afterwards, when the pressure was further raised, it was lessened.

Guérard, Elsässer, Jaminet and Bauer, considered an increased oxygenation and production of carbonic acid as not requiring demonstration.

Vivenot's and G. Lange's experiments and conclusions have been already detailed, and the questionable value of their methods and results criticised.

Panum wavers considerably in his conclusions, but in the main appears to support Vivenot's statements. Not having obtained access to any account of Panum's original experiments, I am only able to report his conclusions as recorded by Bert. Panum, however, did not regard this possible slight increase of chemical activity as capable of explaining the symptoms of compressed air illness.

On the other hand, Milliet denies that any increase of chemical activity takes place in compressed air, and points out that the air, by being compressed, is not modified in its chemical constitution, and the laws which regulate our organism do not cease their natural action.

Sandahl is of opinion that if more oxygen is used in the body in a given time, the temperature of the body will rise, and declares that the most careful experiments have failed to find any rise in the temperature.

G. von Liebig's experiments give results diametrically opposed to any increase of metabolism taking place.

The experiments of Regnault and Reiset, which have never been controverted, on the effect on animals of an atmosphere in which oxygen is in excess, show that, under these circumstances, there is no increase in the amount of oxygen used by the system. An atmosphere in which 20 per cent. of nitrogen is replaced by an equal amount of oxygen might be expected to have exactly the same effect on the system, so far as the oxygen is concerned, as an atmosphere compressed to half its normal volume, since the *partial pressure* of the oxygen is the same in the two cases. It is difficult to believe, therefore, that although no increase of metabolism takes place in the former, we have an increase in the latter condition. At least, some very convincing proofs must be exacted before such an apparent anomaly can be accredited.

Jourdanet,[1] who wrote voluminously on the influence of rarefied and compressed air on the human system, says that it is not certain that analyses of any sort have shown that a more active combustion goes on on account of an increase in the amount of oxygen. The numerous experiments of Bert on animals supersaturated with oxygen prove, on the other hand, in the most formal manner that the general internal temperature diminishes notably, rather than increases. Oxygen in excess in the blood indeed produces convulsions and death when it arrives at a density equal to an external pressure of 3 or 4 atmospheres of this pure gas. All the phenomena appertaining to life, and which depend on oxygen, become more feeble under a sufficiently compressed atmosphere; temperature goes down; fermentation is hindered; putrefaction is stopped. The writings of M. Bert make this point quite clear.

[1] "Influence de la pression de l'air sur la vie de l'homme." Paris, 1876.

Dr. Hunter at the Forth Bridge made a number of observations on the temperature—taken in the axilla—and found that this was sometimes normal, sometimes above, and at other times below this.

Observations of my own—taken in the mouth—gave similar results.

Sukhorski N.[1] states that when compressed air is respired the absolute amount of oxygen inspired and of carbonic acid expired is diminished, and that the therapeutic action of compressed air may be referred exclusively to its mechanical action on the organism.

If any excess of metabolism occurs we should expect to find an increase in the amount of urea excreted. The estimation of urea must obviously be made for a considerable time, and include estimations of the average amount excreted when the compressed air is not entered. It is impossible to obtain reliable results and accurate twenty-four-hours specimens of urine from the men. I have therefore made a series of observations on myself. I found that the average amount of urea excreted per diem was 392 grains. The daily range varied from a minimum of 167 to a maximum of 702 grains. I was unable to observe that any increase necessarily occurred after any unusual exercise. For example, a fifty-mile bicycle ride was sometimes followed and sometimes not by an amount of urea above the normal. Also a stay in compressed air of some hours was not followed or accompanied by any excessive excretion of urea. It is true that, with a range of daily excretion varying from 167 to 702 grains, any increase on account of the compressed air would have to be emphatic in amount in order to be appreciated; yet if an increased metabolism occurs in compressed air of

1 "Compressed air in health and disease." St. Petersburg, 1885.

any moment we might expect to see some evidence of it in the amount of urea excreted.

It would appear, then, that the basis on which must rest these hypotheses concerning exhaustion, carbonic acid poisoning, and the like—namely, an increased combustion or chemical activity within the body—is not only without any substantial proof, but in the present state of our knowledge attains to a position of extreme improbability. It would not be well, however, to dismiss them at once, without inquiring into any further reasons which may have been advanced in their support.

Jaminet ascribed the symptoms of this illness to "exhaustion of the system"; he noted that when men ascended ladders or undertook any great exertion after leaving the pressure they appeared more susceptible to the illness; also if they went to work without having first had a meal. Both of these observations may be correct; but if severe and often excruciating pain in the limbs and elsewhere, paralysis of the legs, bladder, and rectum, and sudden death, are each and all to be ascribed to "exhaustion," this term must surely be employed in some more special and technical sense than is usual.

Dr. G. Thompson ascribes the symptoms to "carbonic acid poisoning"; we know very well that in poisoning by carbonic acid no such symptoms are met with.

Professor Bauer, of St. Louis, in search, one would think, of a theory that no one had thought of before, suggested that, on account of the increased waste of organic tissues going on in the body while in compressed air, the blood carries more carbonic acid and other bye products. While the person remains in the pressure the hyperoxygenation goes on, and no ill effects are experienced; but when the pressure is removed, the hyperoxygenation immediately ceases, and the accumulation of waste materials acts as a poison to the system. Even if it were possible to ascribe the characteristic symptoms of compressed air illness to poisoning by "waste materials," why, in the name of all that is reasonable, does their accumulation not commence to produce symptoms before the pressure is removed?

Such theories as we have been considering cannot, I think, be regarded as serious attempts to deal with the problems at issue.

II. The theories which attempt to explain the symptoms of compressed air illness on the ground that the pressure on the periphery of the body causes the viscera to be congested, differ somewhat in detail from one another and in the temerity with which their authors have attempted to apply them to the elucidation of a few only, or of all, of the accidents possibly arising from compressed air.

In the first place it is necessary to point to an error in the premises with which Smith and others preface their argument—namely, that the different solids and liquids of the body vary in their "resistance to compression." This can only mean one thing: that they differ in their compressibility. Theoretically, and with enormous pressures, solids and liquids are compressible, and differ in their degrees of compressibility: practically, and with the pressures with which we are dealing, solids and liquids are incompressible. The human body is practically compressible only in so far as it contains free gases. The only free gases normally in the body, which are not in a direct communication with the outside air, are those contained in the alimentary canal. The bronchial tubes, the air cells and vesicles of the lungs, the nasal cavity and those sinuses and cavities opening into it, are in the present connection merely an extension of the external superficies of the body. The only contents of the body undergoing a diminution in size on entering compressed air are the free gases in the stomach and intestines. The potential space formed by this diminution is the only one to be occupied by the pressing inwards of the external parts of the body. We have thus determined that the only compressible portion of the body is a part of the contents of the abdomen. We have now to meet the more important question as to the manner in which this diminution occurs. Is it that the abdominal parietes are simply pushed inwards, or is it that the blood from all parts of the periphery of the body is forced towards the large vessels of the interior of the abdomen? That the pushing inwards of the abdominal walls is largely responsible is shown by the common experience of all who enter compressed air with a belt on, that the belt is looser, and requires tightening, on arrival in the pressure. It is still possible that some share in the process may be taken by blood from the periphery of the body—in fact, it would appear highly probable; but this is a matter which, for the time, we must leave in the realm of conjecture. It might be urged that sufficient autopsies have now been described, where "congestion" was met with in the abdominal viscera, to furnish proof of this flow of blood towards the abdomen. I am of a contrary opinion. A re-perusal of these autopsies will show that "congestion" is so often the only abnormality found, and its distribution is so universal that its description fails to impress us with a sense of the scientific value of the autopsies. Not only this, but these autopsies were made after deaths which followed *exit* from the compressed air. That is not what we are considering. It is the *entry* which is engaging our attention, and which furnished the supporters of these theories with their arguments.

It is not, however, congestion of the abdominal viscera on which they rely to account for the symptoms ; this, as we have seen, although unproved, would not be difficult to admit. It is congestion of the brain and spinal cord which is invoked to explain the illness, a condition which is much less easy to assent to. Why should entry into compressed air produce congestion of the central parts of the nervous system ? Truly they are encased in a hard envelope of bone, but at the same time this hard encasement is *filled* with brain, and spinal cord, and blood, and cerebro-spinal fluid, matters which are as incompressible as bone. If an additional quantity of blood is forced in here it can only be accomplished by blood or cerebro-spinal fluid being squeezed out there. If an increased blood pressure occurs only (say) in the carotid arteries, an additional quantity of blood goes to the brain, and there are numberless outlets for the excessive pressure. But on entry into compressed air, blood pressure everywhere is raised, and every one part of the body presses with a greater force on the adjacent part. The free communication afforded by the vascular system from near to remote parts of the body is probably a ready means by which this increased tension is at once conveyed and distributed ; but the conveyance of an increase of tension from one part to another is very different from a conveyance of blood.

The late Dr. Moxon, in his Croonian Lectures[1] of 1881, was so struck with the plausibility of the congestion theory of compressed air illness, which seemed to support his views of the functions of the cerebro-spinal fluid, that

[1] *Lancet*, 1881.

he said: "It needs no experiment to show that great increase of atmospheric pressure must drive the blood away from the surface of the body, and into any parts that are accessible to blood and not to air. Such parts are the interior of the cranium and the spinal canal." I am contending that a very strong proof must be forthcoming before such an extraordinary hypothesis can be accepted. The cranium and spinal canal are perfectly filled by substances which are incompressible. The compressed air supplies an evenly distributed pressure to the surface of the body. Why should it follow that blood should be forced into the cranium and spinal canal, and cerebro-spinal fluid be squeezed out? The increased air pressure is impelling the cerebro-spinal fluid to remain in its position just as powerfully as it is urging the blood to enter and expel it. Necessarily no change can take place, and matters, in this respect at least, remain in the compressed air just as they were in the open air.

Is it necessary to say more concerning the untenable position of those who would attempt to explain the multiform symptoms of compressed air illness by mechanical variations in the distribution of blood? I believe not, unless it should be to point out their hesitation in ascribing to this cause all the symptoms that may arise.

Dr. Moxon, after discussing the alleged alteration in the distribution of the blood, attempted to show, by a consideration of the anatomical arrangement of the vascular supply of the spinal cord, "why the after-effects of atmospheric pressure should involve only the lower part of the spinal cord." Of over two hundred cases of compressed air illness, that I have seen at the Blackwall Tunnel, only three showed symptoms suggestive of a lesion in the lower portion of the spinal cord.

Babington and Cuthbert only attempted to explain cases of paralysis by the congestion theory. The more numerous cases of "bends" received no explanation at their hands.

Foley met with no cases other than those presenting pains, generally in the limbs, or severe itching; to these he confines his remarks, and explains them by "arterial congestions," presumably in the parts where the pains occur.

Pol and Watelle speak of congestion of the brain and lungs. We should have anticipated that if the brain were congested at the expense of the periphery of the body, it would also be at the expense of the lungs, since these form, in this connection, an important part of the periphery of the body, and that they would therefore rather be anæmic than congested. Pol and Watelle were not satisfied with the universal application of their theory, and ascribed the symptoms sometimes to the circulation of hyperoxygenated blood through the capillaries of the nervous system. This circulation, however, of hyper-oxygenated blood goes on during the stay in compressed air; the excess of oxygen must gradually disappear after exit. If the circulation of hyperoxygenated blood is capable of producing such results, why does it not do so when the oxygen is at its maximum amount—*i.e.*, before the compressed air is left?

Dr. A. H. Smith is the most thorough-going of the advocates of "congestion"; he ascribes all the symptoms to this condition, and I have on this account given previously a lengthy quotation concerning his views on the pathology of the illness. Even supposing we could admit the congestion he speaks of, he does not make it at all clear why an obstacle should sometimes arise to the normal redistribution of the blood on leaving the air. Why should the capillaries become "clogged with effete blood"? Why are the capillaries "clogged"? And why is the blood "effete"?

Allied to these theories of congestion is a suggestion of Corning's, that the symptoms may be due to anæmia of the cord; he gives no reasons for the supposition, and it is difficult to imagine why the spinal cord should be anæmic, and how such a variety of symptoms as this illness presents can be ascribed to this one hypothetical condition.

III. In regard to the third set of theories, which attempt to explain the symptoms by the increased solution by the blood of the gases contained in the compressed air, there is this to be said in their favour, that they take as their basis a physical condition—the increased solution of gases by the blood—to which it is difficult to refuse assent. Whether this physical change is sufficient to account for all the symptoms is a matter requiring very careful consideration.

The Law of Henry and Dalton states that the weight of a gas dissolved by a liquid is directly proportionate to the pressure. At 0° C., and under a barometric pressure of 760 mm., one volume of water will dissolve—

·02035	volumes	of	Nitrogen.
·04114	„	„	Oxygen.
1·7967	„	„	Carbonic acid.

Double the pressure, and twice these amounts are dissolved. These are the co-efficients of absorption of these gases in water. The co-efficients of absorption of these gases in blood are more difficult to obtain, since all the gases obtained from blood by immersion of it in a vacuum are not in *solution*. From 100 volumes of blood may be obtained —

	Nitrogen.	Oxygen.	Carbonic acid.
Arterial Blood	1 to 2 vols.	20 vols.	40 vols.
Venous Blood	1 to 2 vols.	8 to 12 vols.	46 vols.

The larger proportion of this oxygen we know to exist in a state of chemical combination with the hæmoglobin. That an increase of the amounts of these gases dissolved takes place under increased pressures has been shown by Paul Bert, though he found that this increase did not exactly obey the Law of Henry and Dalton. He found, for instance, that at increased pressures the oxygen in the blood is increased only to a small extent; carbonic acid not to any appreciable extent; and nitrogen more than either oxygen or carbonic acid, though not to the extent that would be expected from the Law of Henry and Dalton.

It is equally clear that if the blood dissolves more free gases during the stay in compressed air, this excess of dissolved gases will be given off on or after the entry into the open air. Can this escape of gases from the blood produce the variety of symptoms we have been considering? We are familiar with the respiratory troubles and sudden death produced by the entry of any quantity of air into the large veins of the thorax. What would be the result of the escape from the blood of minute bubbles of gas throughout the whole of the vascular system?

M. Paul Bert has made a large number of experiments on animals at high pressures, often as high as 10 atmospheres. He has caused decompression to be effected in periods varying from twenty seconds to three minutes. Sudden death frequently followed, and post mortem were found free gases in the blood, but especially in the right side of the heart. In some cases paralysis of the lower limbs appeared, and at the autopsy he often found bubbles of free air in the spinal vessels, even in the smaller vessels of the spinal cord itself. When death had not immediately occurred the free gas was not present, but, instead, patches of softening in different regions of the cord. Occasionally he found subcutaneous emphysema; sometimes small foci of hæmorrhages into the spinal cord could be seen. All of the experiments where such definite observations were noted were made at pressures over 5 atmospheres; the time of compression, however, was never long, generally occupying only a few minutes, and never exceeding two hours. It is very probable, indeed, that if Bert had employed longer periods of compression, at lower pressures, he would have obtained similar results; we know that at lower pressures, even with 2 atmospheres and less, we have met with sudden deaths in men on exit from the pressure, and numerous cases of paraplegia. It is impossible to suppose that these latter owe their origin to a different cause to that which is proved by the experiments to be responsible at higher pressures. Moreover, the saturation of the whole blood of the body, with its full amount of gases, on entry to compressed air, must be a matter of time; only that in the capillaries of the pulmonary vesicles can be engaged at a given moment in absorbing from the air vesicles the surplus of free gases; before the whole amount of blood of the body has received its full complement of free gases—*i.e.*, before the acme of danger from this cause is reached—we must suppose that a space of time measured by hours must be spent in the pressure.

We see, then, that this theory is fully capable of explaining cases of sudden death or of paralysis; it needs no effort of the imagination to account for the formication that sometimes ensues in the same manner. It is in the highest degree improbable that the more subjective symptoms, such as pains in the limbs and elsewhere, are due to any other cause; that these are not due to any derangement of the central nervous system is shown by the local tenderness, and the occasional swelling that sometimes accompanies them. Whether the lesion is in the nerve sheaths or the periosteum or elsewhere can only be a matter of conjecture; we should anticipate that most pain would be caused when the lesion occurs in those vessels that are surrounded by resisting structures, or by sensitive nerve filaments, and that no pain would occur where these conditions are absent.

These considerations lend great interest to that post-mortem examination described by Pol and Watelle, where subcutaneous emphysema was present; they give plausibility to that case which I have described, where I thought I felt some crepitation in the substance of the muscles of the lower portion of the thigh; they help to throw light on the causation of the local swelling which is occasionally met with and the local ecchymotic patches that have sometimes been seen; they have considerable support given to them by the carefully performed autopsies described by Leyden and Schultze.

Moreover, this theory is remarkably adapted to explain the principal factors in the ætiology of the illness; it explains why the danger is increased at higher pressures, or by longer exposure; it makes it clear how a decompression extending to forty-five or sixty minutes may be very effective in diminishing or doing away with the liability to illness; it would lead one to anticipate that those men beyond middle age or with a degenerated arterial system would be more liable to illness than those who are younger and more healthy. It also lends considerable interest to, and opens fields for fresh inquiry in connection with, any observation relating to the importance of a very efficient ventilation in order to minimise illness. Is it that, since carbonic acid is eighty-eight times as soluble as nitrogen and about forty-five times as soluble as oxygen, it is to that extent the most dangerous gas in this connection? Is it so very important as a determining factor of the illness that at a pressure of 30 lbs. to the square inch its increase from ·04 per cent. to ·08 or ·1 per cent. is the forerunner of a large amount of illness? Observations and analyses made at the Blackwall Tunnel would seem to suggest this. On the other hand, Bert made analyses of the bubbles of gas which he found in some of his experiments; he found that the large proportion of gas so collected consisted of nitrogen; he does not, however, give us particulars as to the length of time intervening between the decompression and the collection of the gas. This is an all-important question; for Demarquay has shown conclusively that when free gases exist in the tissues of the body, different gases are absorbed at very different rates. After numerous experiments he concluded "that all these gases are absorbed after a longer or shorter time, and with a rapidity that varies from forty-five minutes (carbonic acid) to several weeks (nitrogen)."[1] Thus, while an amount of carbonic acid will all have disappeared in less than an hour, a similar amount of nitrogen may remain unabsorbed for weeks. Further observations on this point are therefore desirable before we form any conclusions as to the particular gas which is most liable to be set free by the blood when decompression is effected.

1 "Essai de Pneumatologie Médicale." Paris, 1866.

An adherence to this theory assists us in understanding why the illness is never produced on entering compressed air, why it does not come on during the sojourn in the air, however long that sojourn be prolonged, and why, if it occurs at all, it is on or after leaving the pressure. We are enabled at once to understand why rapid recompression is so universally beneficial, and why, if it be too long delayed—that is, if some actual injury to tissues is caused by the escaping bubbles of gas—recompression is practically useless ; and we are in a position to anticipate that, in the absence of complications, the illness will tend to disappear by itself in a few days or a few weeks, and that relapses will not occur.

There is one apparent difficulty in the way of this theory—namely, the usually sudden onset of the illness ; it may occur at once on the lowering of the pressure, it may occur some hours afterwards ; but when it does come on its onset is usually sudden. Although, however, the onset is sudden, the maximum of pain is not usually experienced at once ; the pain gradually increases for a short time. Also, when two limbs are affected the onset of pain in both is not simultaneous ; it comes on first in one limb and perhaps an hour afterwards in another. This we might anticipate ; but why is the onset usually sudden ? This can only be explained by supposing that some actual stretching or rupture of nerve filaments is the cause of pain. The escape of minute bubbles of gas would be slow ; their arrest in the capillaries as emboli would not occur while they were minute. Not until their increase or accumulation would they produce any harmful result, or stretch or rupture the capillary walls to escape into an area of less tension.

So beautifully does this theory harmonise with our knowledge of the illness, that we may rest assured that we are at least looking in the right direction for the true cause of the symptoms.

Something should be said here concerning the cases of vertigo. Where this is associated with middle ear disease, or obstruction of the Eustachian tube, the affection of the semicircular canals is indirect, and the vertigo improves with the local condition. Where, however, there is also some temporary or permanent internal ear deafness, there must obviously be some lesion of a semicircular canal. The most natural supposition at first would be to regard hæmorrhage as the probable cause. Yet in one of my worst cases, which I saw within a few minutes of its occurrence, I had the man at once taken to the medical air lock and recompressed. The improvement in the vertigo was immediate, and the man could walk by himself. This improvement was permanent. Could this, then, be due to a hæmorrhage? One would think rather that there is, in such a case, an alteration of tension of the endolymph, brought about possibly by the escape of a minute bubble of gas; that the re-absorption of this is rapidly facilitated by the recompression, and its reformation prevented by a slow decompression. In those cases where recovery is effected in a few days or weeks, the same process may be supposed to be accomplished naturally, while in some cases possibly some mechanical injury is suffered by the nerve filaments serving the purpose of audition, producing permanent internal ear deafness on the affected side. It is possible in the worst cases that the escape of a bubble of gas is accompanied by a minute hæmorrhage, absorption of which is never complete.

For the present we must await the time when morbid anatomy may throw some light on this question, though it would not be inopportune to observe that if there is one situation in the body where the sudden intrusion of a small bubble of gas might be expected to produce immediate and sudden symptoms of a grave character, that situation is the delicately constructed interior of the bony-walled cavities of the internal ear.

CHAPTER XI.

TREATMENT.

I. *Preventive Treatment.*

It may occur at the inception of an engineering undertaking, such as a tunnel, to be carried out by the help of compressed air, that the determination of the depth to be reached, and therefore of the pressure to be encountered, may be to some extent within the discretion of the engineer ; he will have to compare, on the one hand, the engineering difficulties to be encountered by a too close proximity to the river-bed with the dangers to the men, on the other hand, to be met with if the depth, and therefore the pressure, be too great. Mr. A. R. Binnie, the Engineer of the London County Council, in projecting plans for the Blackwall Tunnel, preferred to run the great risks involved by allowing the top of the tunnel to approach within 5 feet of the river bed, at its deepest portion, rather than to cause the tunnel to be constructed at a lower level, where the air pressure would have exceeded 35 lbs. to the square inch. With increased engineering experience and improved medical precautions, such difficult questions may be rendered more easy of solution. At the present time we do not know what is the maximum air pressure which may be worked in with impunity, but we know that by our increased medical knowledge we are able to deal with pressures of 30 and 35 lb. with far less harm than formerly.

Concerning the maximum length of time that men should be allowed to remain in compressed air, this must be determined mainly by the pressure. I believe that, before the Blackwall Tunnel was constructed, nowhere have men worked for eight consecutive hours daily in pressures of 30 and 35 lbs. to the square inch. In determining this time consideration was given to the fact that men prefer to work eight hours consecutively rather than in two separate shifts of four hours each, separated by an interval of (say) four hours. As a rule this arrangement has worked well, though I believe that the illnesses, when the high pressures were reached, would have been less frequent had the length of the shifts been shortened. Where the other conditions are very favourable, long shifts may be worked; but when illnesses are of frequent occurrence and every possible precaution has to be resorted to, the length of the shifts must be reduced until the desirable freedom from illness is met with. At the St. Louis Bridge, when a pressure of 50 lbs. was being encountered, the length of the shifts was cut down several times. Mr. Eads says that after these were reduced to one hour's duration no serious case of illness occurred.

The third important point to be attended to is the ventilation of the compressed air chamber. Where a tunnel is being made through a porous ground the ventilation will of necessity be good, and possibly ample enough without artificial escapes for the air. Where, however, an impervious face exists, or where, as in the sinking of caissons, the open end of the chamber is in a horizontal plane, a relatively small supply of air is sufficient to keep back the water; and then appears the necessity of excessive vigilance in the daily estimation of the supply of fresh air. Where the air compressors are limited in size or number, and they cannot rapidly be supplemented, the number of men working at one time can be cut down, and so the air supply per man be increased. Regarding the amount necessary at different pressures to minimise the risk of illness, it is not possible at the present time to tabulate a list of pressures with a corresponding list of the respective amounts of fresh air per man per hour required at each pressure; other circumstances in each case will vary, and each case must be judged separately. But certain general principles can be enunciated. At the ordinary atmospheric pressure a man at perfect rest requires to be supplied with 3000 cubic feet of fresh air per hour in order that the air of his room may not contain more than ·06 per cent. of carbonic acid, and that the room may be described as well ventilated. A man engaged in heavy work requires fully three times this amount of fresh air, or 9000 cubic feet, to preserve the same healthy conditions as regards the atmosphere; it is certain that nothing *below this* is admissible in a compressed atmosphere. A glance at the tables given previously will show that up to pressures of 25 lbs. this amount, although diminishing the number of cases of illness, does not prevent them altogether, and that at higher pressures, up to 30 and 35 lbs., much larger amounts may be called for. It is true that, in allowing for the supply of such quantities of fresh air, an item of expense in engines and coal has to be estimated which has not before received consideration from this point of view. But we have at the same time to bear in mind the fact that when men are sent down to work in a chamber nearly hermetically sealed, such as a caisson may be, and they are not kept supplied with an adequate amount of fresh air, a very grave responsibility is incurred; when, moreover, the contained air is compressed, and we have the best reasons for knowing that an abundant ventilation is one of the most important factors in preventing illness, or even death, that responsibility assumes a very tangible character.

In addition to securing a sufficiently large supply of fresh air, it is necessary to provide for the proper distribution of that air throughout the compressed air chamber; this will be attained after considering the position of the chief outlets, and arranging, and if necessary subdividing, the inlet in the most advantageous way.

The duration of the "locking in" process is of little moment to those who can readily accommodate their ears to the increasing pressure. With moderately patent Eustachian tubes no difficulty will be found in entering a pressure of 30 lbs. in one miuute. The "locking out" process is of more consequence. From what has been already said it may be inferred that if by lengthening this process it is hoped to diminish illness to any appreciable degree, it will have to be prolonged to an extent which will be very inconvenient. At the Blackwall Tunnel the air cocks were of such a size that when turned on fully they admitted of exit from a pressure of 30 lbs. being effected in four minutes. When ventilation was efficient the illnesses were reduced to a vanishing point, so that it is impossible to ascribe any harm to this rather rapid exit. It is possible that at higher pressures, where every available precaution might be necessary, it would be well to increase this "locking out" process to fifteen or even more minutes, though for pressures below this such a precaution would appear unnecessary. A proper selection of the men, on the lines already indicated, is very essential. In order to ensure this a systematic examination of all men before commencing work, and again at stated intervals, should be carried out. I have, as far as possible, only passed men who had what insurance companies would describe as first-class lives.

Careful instructions to each new man as to the method of inflating his ears, and a warning to him not to enter the pressure at any time when he has pain in the ears, should always be held essential, and would do much to prevent ear accidents and diseases.

A printed set of rules, as to the advisability of rest after leaving the compressed air, and as to the necessity of a rapid change into warm and dry clothes, should be in evidence.

The construction of a well-warmed and comfortable room should be a *sine quâ non*, in order to encourage the men to carry out these rules.

The lighting of the compressed air chamber should be effected by electricity; the use of a certain number of candles will often save expense where a portable light is required in dark or out-of-the-way corners, but on account of the contamination of the atmosphere, both by carbonic acid and by smoke, their employment is to be greatly deprecated. Where candles are employed, even to only a limited extent, the expectoration of a man with a cough, who has been working in the chamber, will often retain a black, sooty character for months after he has discontinued the work.

It has been the custom at some works to provide coffee for the men on leaving the compressed air. The system has been carried out at Blackwall, and has been appreciated by the men. When under pressure the blood tension is augmented, and the amount of the perspiration and of the urine is increased. This, however, is not accompanied by any feeling of thirst. During a balloon ascent the opposite conditions appertain, and thirst is experienced. It is not to be wondered at that, on emerging from compressed air into the open air, when the blood tension is again lowered, some feeling of thirst should be frequent. This is indeed the case, and a gentle stimulant like hot coffee would appear to be a very appropriate beverage; it is certainly very comforting after spending some minutes in the air lock, the atmosphere of which is always cold and misty during the "locking out" process.

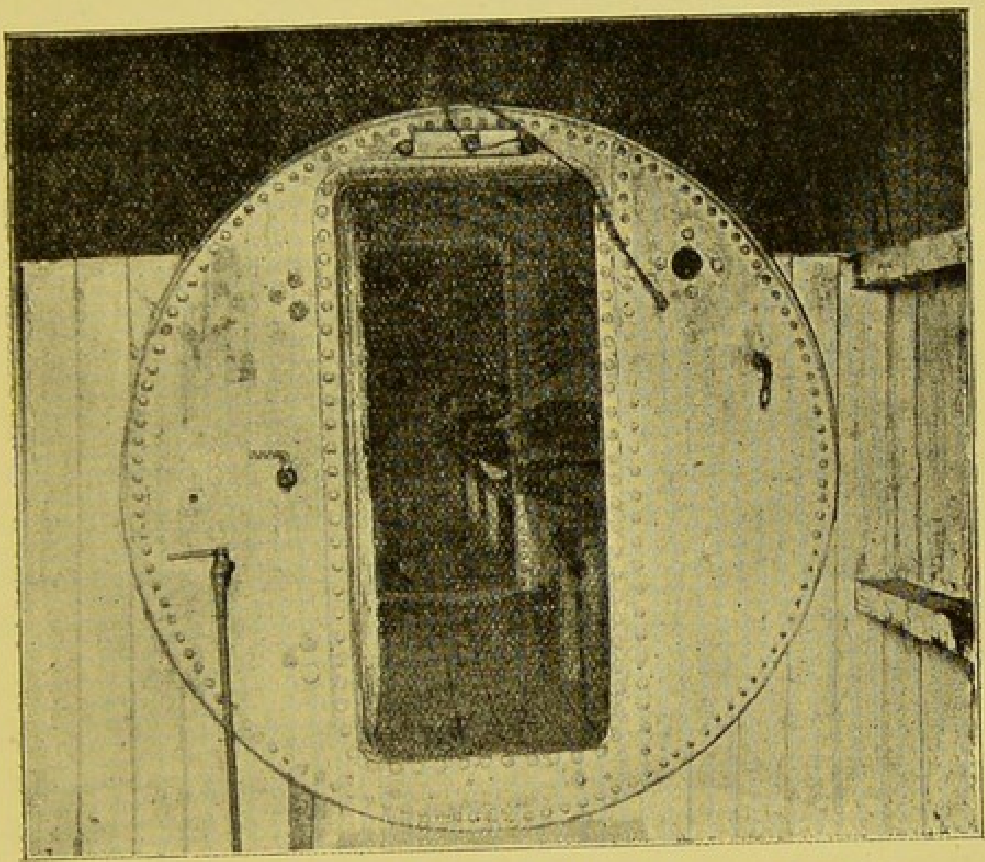
Most observers are agreed that the excessive use of alcohol is a predisposing cause to compressed air illness. It is therefore well to reject or at least to warn men who show signs of having contracted this habit, and also to prevent men at all under the influence of alcohol, from entering the compressed air.

As it appears exceedingly likely that compressed air illness owes its origin to the presence of carbonic acid in the compressed air, it would seem reasonable to reduce the amount of this impurity, not only by an efficient ventilation, but also by removing the carbonic acid from the air as it is pumped in by the compressors; this could easily be effected by passing the air through some strongly alkaline solution, such as caustic soda; in this way a large proportion of the carbonic acid always present in the atmosphere could be removed, and the air of the compressed air chamber kept even more pure in this respect than the outside atmosphere.

There remains one point, in connection with the general hygienic condition of the compressed air chamber, to which it is my duty to direct attention. It may not have anything to do with compressed air illness; on the other hand, while our knowledge concerning the true causation of the illness is not absolute, it may. In any case, the matter is important from a general health point of view. I refer to the natural necessities of the men while at work ; either they should be compelled to leave the air chamber when necessary, in spite of the loss of time, or some readily and frequently removed earth closets should be provided near at hand. I understand that at Blackwall the former alternative was supposed to be adopted and enforced by the possibility of dismissal. I do not know how strictly the rule was adhered to, but I do know that results made it appear a dead letter. When it is remembered that a section of the tunnel may be closed from free communication with the outside air for a space of many months, and that there is a possibility of the lower portion developing into a cesspool, it is apparent that the very strictest precautions and rules are called for. When some portions of the iron lining of the tunnel have been subsequently cleaned out, it has been a cause of wonderment to me that very serious and general illness has been averted.

II. *Curative Treatment.*

If the case comes under notice soon after its commencement, there is one treatment that should immediately be resorted to—namely, recompression. In order that this may readily be done, without the necessity of conveying the patient down lifts or ladders to the ordinary air locks, a medical air lock should be constructed in a convenient situation. This may be easily done by having an ordinary boiler fixed horizontally, and a door fitted at one end. If this be divided by a diaphragm provided with a door, the outer chamber serves as a lock whereby the inner can be entered or left without lowering the pressure. When this is provided with bunks, electric light, and the requisite air cocks and connections, we are in possession of a very appropriate medical lock. The patient should be placed in this and the pressure rapidly raised until the pain or other symptom is alleviated. It is sometimes not necessary to raise the pressure to the full amount that the patient has recently left; if it is, let it remain at that pressure for half an hour, or until some relief is obtained. If the symptoms have been present many hours, no relief is usually



THE MEDICAL AIR LOCK USED AT THE BLACKWALL TUNNEL.

met with, and it is useless continuing the pressure. The exit should be effected slowly—in fact, the patient should be allowed to "leak out" in about forty-five minutes. Any improvement obtained by the pressure will then generally be maintained.

If this plan could always be adopted at once, we should seldom find it necessary to seek for other assistance.

Unfortunately, cases do not all come under notice early enough, or the man may have gone home, possibly several miles, and then have sent for advice; and it is often out of the question to cause him to be conveyed to the medical lock.

Sometimes the pain is so agonising that relief is called for before recompression can be effected; and then Morphia must be used hypodermically.

Ergot has been highly extolled in this connection, and on that account I have used it frequently, and also injected Ergotinin hypodermically, though the cases have been very few where any relief appeared to be traceable to its employment. Thinking that the supposed good effect of Ergot might be due to its action on the vascular system, I have tried Digitalis, but with no apparent result.

A stimulating liniment, such as Lin. Terebinth Acet., is very useful, though for the worst cases of "bends" one containing Aconite and Belladonna seems to be preferable.

Injections of Atropine have been employed, but they are not so useful in obtaining rapid relief as Morphia, though this is only called for in the worst cases.

A Faradic battery has been very frequently tried, but the only effect that I could trace to its use was that it acted as a beneficial placebo to the attendant who administered it.

I have often found that the application of a moderately tight bandage to the painful limb has given relief.

Lehwess suggested the use of Salicylate of Soda for pains in the limbs.

For theoretical reasons M. Paul Bert was led to suppose that the inhalation of oxygen would be remedial; he tried it on some of the animals which he had submitted to experiment, and in which the sounds of the heart indicated the presence of free gases; he considered that life was thereby prolonged, but in no case was death averted. I have only recently been aware of Paul Bert's observations on this matter, and have not had an opportunity of giving the remedy the proper trial which it deserves, though it is not probable that it can be superior to recompression, except in its portability.

Epigastric pain is usually relieved rapidly by recompression, though the slighter cases yield readily to a carminative.

Complications, such as paralysis of the bladder and rectum, must be treated as in ordinary spinal cases; a prolonged course of strychnine is beneficial.

The cases of ear disease sometimes caused by entry into compressed air in no way differ from the corresponding conditions arising from other causes.

Prolonged cases of vertigo show themselves little amenable to the influence of drugs; tonics appear to be of the most use.

Wherever compressed air is going to be used on an extensive scale, a small hospital close at hand should be provided. The painful necessity of conveying men, sometimes dangerously ill, to a distant hospital or to their homes, would then be avoided.

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