58 62

MEDICAL ASPECTS OF COMPRESSED AIR ILLNESS

By

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CHAPTER 4

MEDICAL ASPECTS OF COMPRESSED-AIR ILLNESS

W. D. M. PATON

HISTORICAL INTRODUCTION

ALTHOUGH the ill effects of exposure to compressed air have been known for over a century, and despite the considerable volume of writing about it, there remain many gaps in our knowledge of compressed-air illness as it occurs in industrial undertakings. This is partly because it is mainly divers and (more recently) airmen, who have furnished material sufficiently controllable and homogeneous for clinical study. The rougher conditions of industrial labour make it very hard to establish even the simplest facts about the genesis, course and treatment of the disorder.

Accordingly our knowledge rests primarily on the work of J. S. Haldane, with his colleagues A. E. Boycott and G. C. C. Damant, who first satisfactorily studied decompression-sickness in animals (Boycott, Damant and Haldane (1908)), and devised the only generally satisfactory methods of decompression in existence (Haldane and Priestley, 1935). These workers employed animals for the most part, and the Decompression Tables were tested on divers. Later work, particularly during the World War II, has been reviewed by Harvey (1945) and Behnke (1945). An extensive but uncritical bibliography has been compiled by Hoff (1948). Useful accounts of experience in caisson and tunnel workings are given by Snell (1896), Keays (1909), Levy (1922), Norrie (1934) and Boulton (1942), but many items of useful information in this field are still lacking.

Much of the account that follows is based on experience gained during the construction of the Tyne Tunnel between 1947 and 1949, between Howdon and Jarrow (Paton and Walder, 1954). A discussion with any engineer having experience of compressed-air work will also prove of great value. Draft regulations issued by the Factory Department of the Ministry of Labour will be found in *Work of Engineering Construction* (*Factories Act*, 1937), *Revised Draft*, *Part VII* (*Work in Compressed Air*).

DEFINITIONS

Since there is apt to be some confusion about nomenclature, it is useful to state precisely what is meant or implied by some of the terms used.

The term, *compressed-air illness*, strictly refers to any illness resulting from exposure to compressed air. It may therefore include: (1) decompression-sickness proper, (2) disorders of the ears and cranial sinuses, and (3) (rarely) pulmonary disorder. Usually it refers only to decompression sickness, but, for purposes of compensation, ear disease has sometimes been included. In this article, therefore, the strict general sense first quoted will be used, which includes all the conditions named.

" *Decompression sickness* " refers to the disorder which arises from too rapid a reduction of the ambient pressure, causing a supersaturation of the blood and tissues with the gases dissolved in them (notably nitrogen) and consequent formation of bubbles. " Caisson disease " (or " diver's palsy ") and " aviator's illness " are the two complementary parts of this disorder, in which, respectively, the pressure previously raised falls to atmospheric levels, or pressure already at atmospheric levels is lowered still further by ascent (real or simulated).

Measurement of pressure.—Pressure is measured in atmospheres, pounds per square inch, kilograms per square centimetre, or feet of water: thus 1 atmosphere=14·7 pounds per square inch=760 millimetres of mercury=1·03 kilograms per square centimetre=33 feet of water. The *gauge pressure* refers to the pressure read on a gauge mounted in free air and connected to a compressed-air chamber, and it represents the *pressure difference* across the containing walls. The *absolute pressure* is obtained by adding the weight of the atmosphere (14·7 pounds per square inch) to the gauge pressure.

THE CAUSE OF DECOMPRESSION SICKNESS

Solution of gases in body fluids

If a fluid is exposed to a gas, some of the gas becomes dissolved, the amount dissolved being proportional to the pressure at which the gas is held. When the pressure of the gas is raised, a larger quantity dissolves; when it is lowered, gas diffuses out of the fluid into the gaseous phase again. The fluids of the body, exposed to the surrounding air, constitute just such a system, in which the blood occupies an intermediate position, as the carrier of gases to and from the tissues and the lungs. Of the components of the atmosphere, nitrogen is far the most important in this context, since it forms four-fifths of the total air mixture, is inert, and is particularly soluble in those fatty tissues which are the danger-points of the body—those of the spinal cord and central nervous system. Oxygen is much less important, since its consumption in the body lowers the content of it in the tissues considerably. Carbon dioxide, present in the atmosphere in traces, is also negligible, although this substance, formed by metabolism in a hard-working muscle, may contribute to decompression sickness in a way described below.

The tissues of the body, therefore, eventually come into equilibrium with the surrounding atmosphere. This process of saturation (or of de-saturation) with gas takes time, and its rapidity varies with the tissue; tissues such as those of the liver or kidney, or blood itself, equilibrate within a few minutes or less; but some tissues, either because they are rich in fat (which will dissolve 5 times as much nitrogen as does water), or because the blood supply to them is slow, take much longer, so that the slowest tissues (for practical purposes) must be allowed more than 4 hours to reach equilibrium.

Supersaturation, formation of bubbles, and production of " bends "

If the pressure, after equilibrium has been reached, is rapidly lowered, the tissues come to contain more gas than they can hold in solution and, just as in a carbonated drink when its stopper is released, the gas begins to separate from the tissues, not by diffusion to the blood and out through the lungs, but as discrete bubbles within the tissue, which may either block the blood vessels, or burst them or the adjacent structures, or pass to the heart and there create an air-lock. Such formation of bubbles has been demonstrated, after a very rapid and substantial decompression, in almost every tissue of the body, and it is undoubtedly responsible for the symptoms and lesions in severe cases of decompression sickness. These bubbles have been shown, by direct analysis, to consist chiefly of nitrogen. It is true that no one has ever succeeded in demonstrating bubbles in any pain-producing site under the conditions of relatively slow decompression in which cases of " bends " occur in practice. The evidence that ordinary " bends " is due to formation of bubbles is therefore purely circumstantial. But there is no other reasonable explanation, and it accounts perfectly for the effectiveness of re-compression in treatment.

Too great a supersaturation, therefore, causes bubble formation. But quite an appreciable degree of supersaturation can exist without the appearance of bubbles. It has been found that, for the range of pressure used in engineering, it is always safe to reduce the pressure to half of the absolute pressure of gas in the most saturated tissue. On this fact depends the decompression procedure now almost universally used. After an exposure to pressure, the pressure is lowered to such a level (calculated and given in the Tables) that the maximal rate of diffusion of gas away from the tissues to the lungs is obtained, short of the above dangerous degree of supersaturation. As the tissues lose gas and become less supersaturated, the surrounding pressure is progressively lowered to keep the diffusion head as great as possible within the limits of safety, until the surrounding pressure reaches atmospheric level. Hence derives the typical sequence of the decompression procedure: (1) first a prompt reduction in pressure to half the absolute pressure prevailing in the most saturated tissue; this establishes the maximal safe diffusion head; (2) then a further gradual fall, at a rate determined by the rate of de-saturation of the tissue concerned; this maintains maximal diffusion as the gas is eliminated.

Theory of nuclei.—Recent research has shown that other factors enter into bubble formation. It has been found, for instance, that solutions can be prepared, very highly supersaturated indeed with nitrogen, which do not form bubbles spontaneously; but if they are seeded with suitable materials, explosive formation takes place. It has therefore been postulated that there must exist a " population " of nuclei in the body on which such bubbles can develop. If this is the case, then the properties of such nuclei may be of decisive importance, or it may be that certain conditions, by creating such nuclei, predispose to decompression sickness. For instance, it has been suggested that muscular work—by causing local reductions in pressure at insertions of muscles, and by causing locally high concentrations of carbon dioxide (from the muscle metabolism)—may favour the initiation of a bubble, which is thereafter maintained by the diffusion into it of nitrogen from the surrounding tissue.

Particular conditions favouring " bends "

War-time studies on aviators have made it clear that there are many conditions predisposing to " bends ". It is not certain how far these also apply under the much more complicated and rougher conditions of industrial work, but there is no reason to doubt that the general picture should be the same.

General factors

Exertion during decompression.—It used to be thought desirable to take exercise during decompression, in order to increase the circulation through the limbs and hence promote the elimination of nitrogen. In aviators, however, it has been found that exercise is the most reliable way of inducing a " bend ", and evidence suggesting a similar result with divers has been obtained. It appears, therefore, that any benefits due to increased blood-flow are more than outweighed by increased bubble formation, due to the muscular activity.

Cold during decompression.—The general impression that cold predisposes to decompression sickness has been fully substantiated, and evidence exists that this is due to a reflex vasoconstriction in the region of the joints, caused by the cold, leading to a slowed elimination of nitrogen from the region.

Low fluid intake.—Low fluid intake increases the incidence of " bends " in aviators, and high fluid intake decreases it. This may be due to the corresponding fall or rise (respectively) of surface tension of the plasma (Walder, 1949), making it more or less easy for bubbles to develop.

Age.—Although it is widely stated that advancing years predispose to " bends ", the evidence is scanty in high-pressure work. It is well established for aviators, however, and it is also known that blood flow in the tissues decreases considerably with age.

Obesity.—Again, evidence in practice that obesity leads to " bends " is scanty. In animals, however, fatty tissue is known to become particularly rich in bubbles, and fat animals survive severe decompressions less well than do thin ones.

Type of work.—" Bends " are much commoner in shift-workers than in those entering compressed air for brief tasks involving light work. There is some evidence that, among shift-workers, those engaged in the hardest physical work (such as miners' labourers) are most susceptible of all.

Variations in susceptibility

Variations in susceptibility, due to these and other causes, reveal themselves at a compressed-air working, not so much by the presence there of men with widely differing experience of " bends ", but by the elimination of the susceptible subjects. One finds, for instance, that among workers who suffered from " bends " once or more in the first 5 days of employment, only 49 per cent are still employed 2 weeks later; whereas of those who did not, 89 per cent are still employed after this time (Paton and Walder, 1954). In considering the problems of compressed-air illness in industry, it must be borne in mind that the labour force is highly selected by a strict " survival of the fittest " (" fitness " in this case meaning resistance to " bends ").

Acclimatization

There is also evidence of acclimatization with repeated exposures. It is usually difficult to detect this for certain in the case-histories of single individuals; but with a group of men, followed up for several months, it is possible to show that the average incidence falls considerably with prolongation of experience. Such acclimatization seems to be most rapid during the first 1–2 weeks (Paton and Walder, 1954). These two factors may be the cause of the occasional " epidemic " character of an outbreak of " bends " during an undertaking. It is usually associated with an influx of new labour at a point where a new part of the work is being started. The " epidemic " clears up when the susceptible subjects have been eliminated and the others acclimatized.

Physiological basis of variations

The physiological basis of variation in susceptibility and acclimatization is entirely obscure. There are so many variables in tissue structure and blood flow, in the dynamics of movement, in the response to environmental stimuli, and in individual morale, that it will be long before any clear picture will emerge.

SYMPTOMS AND SIGNS OF DECOMPRESSION SICKNESS

" Bends "

Far the commonest important symptom of decompression sickness is a steady aching pain, localized usually to one or more joints of a limb, particularly the knees or shoulders. Wrists, elbows and ankles are also affected, or else the limbs between the joints. Usually the pain is not well localized, but is greatest around the joint, radiating more or less diffusely away from it. Occasionally an intensely painful, single point can be found by palpation in or near an affected joint. Typically in goats, and often in human beings, the pain causes flexion of the joint, apparently in an attempt to ease it; to this may be due the name. The pain varies in intensity from a mild ache (often referred to as the " niggles ") to a pain so severe as to prevent movement of the limb and to incapacitate the sufferer; it is usually comparable with a rheumatic pain, which (in general) it seems to resemble in other respects. " Bends " occur most commonly in the joints and muscles most used, and may be restricted entirely to these.

Cutaneous symptoms and signs

Itching.—A harmless, though sometimes tiresome, symptom is itching (the " sandbug itch "). This is commoner under higher pressures (such as are used in diving). The itching is usually felt in the trunk or the central part of the limbs—in the warm clothed parts, rather than those that have been exposed. In character it is identical with other itches (such as flea-bites), and may lead to social embarrassment if, as sometimes happens, the delayed onset causes the itching to appear while the victim is using public transport on the way home.

Bruising.—With serious cases of " bends " or with paraplegia, bruising of the skin may occur, giving more or less extensive areas of ecchymosis and (very rarely) of subcutaneous emphysema. The vigorous friction and application of heat or counter-irritants, to which a joint with " bends " may be exposed, can, however, also cause some cutaneous effusion of blood, which must not be confused with the above.

Spinal paralysis

The most important and serious form of decompression sickness is a spinal paraplegia; this is recorded frequently in the literature, and occurs readily whenever grossly inadequate decompression is used. The lesion is usually in the lower thoracic portion of the spinal cord, mostly in the white matter. The symptoms and signs are those of any other spinal lesion. Usually motor paralysis and numbness of the legs are the presenting symptoms, but intense bilateral pain may occur. Incontinence of urine is the rule.

If the condition is treated promptly, almost complete recovery may occur; but if re-compression is delayed, a permanent paraplegia remains, although with lapse of time some improvement is probable. When re-compression can produce no further benefit, treatment is that of any other spinal lesion.

Other symptoms

Bubbles may also form in the brain (causing a wide variety of neurological lesions, with aphasia, deafness, dizziness, cranial palsies, or unconsciousness). Bubbles in the pulmonary vessels may cause coughing and thoracic pain, particularly on inspiration. Bubbles in the abdominal viscera can give rise to abdominal pain and vomiting.

In the presence of any of these symptoms, re-compression is vital.

Development of bone disease

In rare cases, moderate or severe " bends " may be followed, months or years later, by an avascular necrosis of the bones of the affected limb (Swain, 1942). When this lesion affects the shaft of the bones, no functional disorder or pain is felt; but an avascular necrosis of the head of the femur or humerus may occur, giving rise to the arthritis typical of such a lesion when due to other causes. A typical case is that of a man who suffered from " bends " after escaping from the submarine " Poseidon", and developed an arthritis months later (James, 1945). If the diagnosis is made sufficiently early, the necrotic bone can be removed, and the articular function partially restored. Usually the diagnosis is made at a much later date, and it may be hard to distinguish the disorder from a degenerative arthritis.

No reliable information exists about the frequency of the condition; not many cases have been reported. Some cases will certainly fail to be distinguished from other forms of arthritis. Careful radiographic examination of the bones of 20 men who had had " bends " several times over a period of several years (Lewis and Paton, 1951) failed to reveal a case. The bony lesion must therefore be far less common than " bends " itself, and there may well be some other factor involved.

THE PREVENTION OF DECOMPRESSION SICKNESS

Use of the Decompression Table

The main weapon for preventing decompression sickness is a Decompression Table, together with a procedure for ensuring that it is used. Satisfactory Tables are now available, and a revised version, calculated by Capt. G. C. C. Damant and the writer, for decompression in compressed-air workings, is given on p. 120. Tables for divers can be obtained from the *Admiralty Diving Manual* (Admiralty, 1943). These are self-explanatory, and can easily be interpreted in the light of the previous account.

Equally important, however, are measures for ensuring that these Tables are adhered to by the often rough and irresponsible labouring force. Although this is not a strictly medical matter, the medical attendant can save himself a good deal of worry by satisfying himself about this. Even though the Regulations issued by the Factory Department of the Ministry of Labour lay down clear instructions on the matter, there are always a handful of men on a given site whose previous immunity to " bends " has given them a false sense of security. It is one of these men, too often, who becomes a paraplegic patient after a single careless decompression. Important points are as follows: (1) that every decompression shall be entered in a book, with names and times; (2) that every decompression shall be under the control of a competent lock-keeper outside the decompression chamber, and *not* under the control of anyone inside the lock, at least so far as accelerating decompression is concerned; (3) that a locked barographic record should be kept of the pressure changes in the chamber, as an additional check on the decompression; (4) that a good medical orderly should help by explaining (in suitable terms) the basis of decompression procedure to those men who come for treatment; (5) that the foreman should accept and enforce the procedure. An average rate for " bends " of 2 per cent of all compressions is generally accepted as an upper limit of the incidence; lower rates can be obtained, although temporarily higher ones (particularly among miners' labourers) are very difficult to avoid.

Use of heat

" Bends " will be minimized (in general, though not invariably) by anything increasing blood flow in the limbs. Hence warmth in the decompression chamber (by means of electric fires and blankets) and hot drinks should be provided, as well as dry clothing, if possible, to be worn during decompression when the men have been in wet surroundings. It is uncertain whether exercise during decompression is beneficial or not, despite many dogmatic assertions in the literature; it is known to predispose to bends among aviators, and has never been clearly proved to be useful when workers are leaving high pressures; since it is usually awkward, it may well be dispensed with.

Rest and food

It is desirable that the men should remain on the site for 1–2 hours after a shift, preferably in some warm room where they can get food and hot drinks. After this time, serious " bends " are unlikely to occur, although mild cases may still appear many hours later.

Liaison with hospitals

To ensure prompt treatment, it is usual to notify the hospitals of the region, so that the condition of men brought to them suffering from decompression sickness may be recognized as such as soon as possible and they may be brought to the re-compression chamber.

Limitation of exposure to pressure

The oldest method of preventing " bends " is to limit the duration of work in compressed air, and, during the long period before satisfactory decompression procedures were evolved, this was the main protection used. Severe limitation of duration of exposure to high pressures is still practised today, particularly in the United States of America.

Given satisfactory decompression procedure, however, it is usually much more economical of time to have a single working shift, with one fairly long decompression, than to have 2 shifts of half the length with 2 slightly shorter decompressions. This is particularly true in the case of long shifts, since the risk of " bends " increases little with prolongation of exposure over 4 hours; thus an 8-hour shift requires the same decompression time as does a 4-hour shift, and half that of an 8-hour shift divided into 2 parts. The main limit to prolonging exposure to pressure, so far as present information goes, is that of general environmental conditions, rather than the probable occurrence of " bends ".

Despite what is said above, periods occur during work on a contract when bad working conditions, high pressures, and an influx of new labour produce a very high incidence of " bends ". Under these conditions the most practicable immediate remedy is temporarily to shorten the length of the shifts.

THE TREATMENT OF DECOMPRESSION SICKNESS

Principles of treatment

Treatment is based on the belief that the symptoms are due to the presence of bubbles in the tissues. The patient is returned to compressed air, so that the bubbles will be reduced in size and go into solution again; then the pressure is lowered once more at such a rate that the bubbles will not re-form, and such that the re-compression itself will not cause further fresh bubbles.

Cases divide themselves fairly readily into two groups:

(1) ordinary " bend ", of various degrees of severity;

(2) cases with additional and more dangerous features.

A medical orderly, after some experience, acquires a very sound knowledge of group 1, and it is a fairly straightforward matter to stipulate that he shall be responsible only for such cases, and shall obtain medical advice on more serious cases from a doctor. Unfortunately, the doctor is often unfamiliar with this particular disease, and may make matters worse by instituting faulty re-compression. It is advisable, therefore, that the medical orderly should remain in charge of the re-compression itself.

The ordinary case of " bends "

The " bend " usually comes on more or less slowly, and the workman will appear, complaining of pain, at any time from shortly after the decompression to 10–12 hours later, or (rarely) even longer, according to the decompression, his morale, and his resistance to pain. Often the affected part has been treated vigorously by the patient himself, with massage, hot-water bottles, liniments, and so forth before he comes for treatment; these measures may leave a residual soreness after compression.

Methods of treatment

Various schemes of treatment have been proposed, and none has been uniformly successful. The following method is as successful as any other in treating the ordinary " bend " and is usually convenient:

(1) compress the patient to the working pressure;

(2) maintain this pressure for 10 minutes;

(3) decompress, as for a 6–hour exposure to the working pressure, reducing the pressure rapidly to half " absolute " and then slowly, as in the normal decompression.

If the bend recurs, this procedure may be repeated. It is important to remember, however, that it is rarely that all discomfort can be removed. As is mentioned above, the patient himself may have done enough to leave some soreness; there is also often a residual effect, due to damage done by the expanding bubble, which cannot be reversed by removing the bubble.

An alternative method.—Alternatively, a longer re-compression may be used, as follows:

(1) compress to working pressure, and hold at this pressure until 10 minutes after the patient has recovered from his symptoms;

(2) lower the pressure at the following rates:

between 40 and 30 lb., 1 lb in 3 minutes;
between 30 and 15 lb., 1 lb. in 5 minutes;
between 15 and 0 lb., 1 lb. in 8 minutes.

This method, however, has no higher a success rate in ordinary " bends " and takes a long time (225 minutes, against 108 minutes by the previous method for a working pressure of 40 pounds). The time taken is sometimes important. Not infrequently several members of a shift get a " bend " (after a faulty decompression of the whole shift), and return for treatment thereafter at various intervals, placing considerable strain on re-compression facilities. Handling this is made considerably easier if the re-compression procedure is economical in time.

Treatment of pain.—A patient with a " bend " tends to recover spontaneously in time, even if not treated. If the pain is not severe, and re-compression has been only partly successful, aspirin or codeine is often adequate to complete the cure. For minor cases, radiant heat is sometimes a useful alternative, although no systematic investigation of its use has yet been made.

General instructions.—There is no need for a medical orderly to accompany the patient into the lock. The patient should be encouraged to exercise his limbs gently and to move about at intervals.

The severe case

A definition of " severe ", for practical purposes, is necessarily arbitrary. But since it is important that these cases should be recognized and treated appropriately, some such regulation as the following should be supplied for the medical orderly's guidance.

Treatment of Severe Cases of Decompression Sickness

General procedure

(1) Any case in which there is loss of consciousness, inability to walk, numbness, pains in chest or abdomen, or other serious symptoms must be treated by the *Special Procedure*, shown below, as soon as possible.

(2) Only those cases which are typical " bends " should be treated by the usual re-compression methods. Other cases, where doubt is present, must be treated by the *Special Procedure*.

(3) The *Special Procedure* must be used repeatedly in a case for so long as the man is relieved by pressure. Only if a sufferer does not recover after exposure to full pressure for an hour can attempts to cure him be abandoned. He should then be very carefully decompressed (*see* para. 3 of *Special Procedure*) to avoid making him any worse. In no circumstances must the pressure be lowered while a man still has symptoms which are removable by raising the pressure.

(4) Care must be taken that the man has really recovered, and that, for instance, numbness does not return without being noticed. The man should walk about at intervals during the decompression to make sure of his being normal.

Special procedure

(1) Compress to working pressure, and hold at this until 10 minutes after the man has recovered from his symptoms.

(2) Lower the pressure at the following rates:
between 40 and 30 lb., 1 lb. in 3 minutes;
between 30 and 15 lb., 1 lb. in 5 minutes;
between 15 and 0 lb., 1 lb. in 8 minutes.

(3) If symptoms return, compress immediately to working pressure again, hold this for 10 minutes, and lower the pressure at the following rates:
between 40 and 30 lb., 1 lb. in 4 minutes;
between 30 and 15 lb., 1 lb. in 6 minutes;
between 15 and 0 lb., 1 lb. in 10 minutes.

(4) If symptoms still return, compress again to working pressure for 10 minutes longer and repeat (3). Continue this process as long as is necessary, making the decompression still slower if need be.

Danger of injury to the spinal cord

The main danger in such cases is that of bubbles in the spinal cord. If the sufferer is taken sufficiently quickly and properly treated, almost complete recovery may be obtained. But any delay in treatment, or any excessively fast reduction in pressure, may allow a bubble to form and to be present for sufficiently long to cause permanent damage. Although decompression sickness of the spinal cord is far less common than that of joints, when it does occur, the consequences of neglect are far more serious.

THE SELECTION OF MEN FOR WORK IN COMPRESSED AIR

At the present time the examination of men for work in compressed air is made by doctors in practice near the place at which the work is to be done. As a rule, these practitioners have no special knowledge of compressed-air illness; this, on the whole, makes them very cautious, and a man in whom any abnormality at all is found is excluded from work. This is probably sound practice so far as the working population is concerned; but it excludes too easily such people as engineers, contractor's agents and inspectors, whose exposures are normally brief and who do not perform manual labour. It is questionable, too, whether the habitual absolute exclusion of the old and the fat is always necessary.

Grounds for exclusion

The main hazards are (1) those due to the compression of air-containing spaces of the body, or (2) decompression sickness.

Compression of air-containing cavities

The necessity for clearing the ears excludes those whose eustachian tubes are permanently obstructed. It also excludes those to whom the effort of ear-clearing (which may require a violent forced expiratory effort with closed mouth and nose) may be dangerous (including sufferers from hernia, heart disease or respiratory disease). The sinuses appear to offer possibilities of discomfort rather than of danger; since pain during compression may be severe, however, for a person with occluded sinuses, it would probably be wise to exclude cases of chronic sinusitis.

If the lungs contain any air-containing space not in free communication with the trachea, compression and decompression should be avoided. This excludes: (1) cases of pulmonary disease in which there is any possibility of obstruction of a bronchus by pus or diseased tissue; (2) cases with pneumothorax; (3) cases with emphysematous bullae or air-cysts of the lung. Sufferers from simple emphysema are quite likely to feel better under compressed air, because of the increased oxygen tension.

Susceptibility to decompression sickness

Susceptibility to decompression sickness has been discussed in the past almost entirely in terms of rates of saturation and de-saturation of the tissues (as affected, for example, by blood flow and by the fat content of the tissue). There is no information available to attack the problem in any other way, and this approach will be adopted.

Age.—This factor has been frequently discussed in this connexion. There is, however, a dearth of satisfactory data. From Snell's figures, however, it appears: (1) that men are of low susceptibility if they are less than 25 years of age; (2) that between 25 and 45 years their susceptibility is a little greater, but does not increase with age; (3) that over 45 years of age susceptibility increases again (Snell, 1896). This appears to agree with more recent experiences. There is, therefore, no good reason for restricting a man's exposure until the age of 45 years is reached.

Weight.—The evidence about this is equally inadequate. It appears that only with gross obesity is there any serious question of increased susceptibility. In addition, there is no easy way of determining whether an abnormally high weight is due to fat or muscle. There seems no adequate reason for restricting a man's activity, unless he is, say, 2 stone or more heavier than the normal for his age and height.

Disease.—Provided that the man is fit for work at all, the question is simply whether or not his condition alters the saturation rates of his tissues. Some disorders (chronic pulmonary disease, uncompensated heart failure, arteriosclerosis) will clearly do this. In view of the recent establishment of bone necrosis as a rare sequel of " bends ", it is probably also necessary to exclude men with any disease of bone. But such disorders as chronic skin disease, controlled diabetes, gastric ulcer, the anaemias, early arterial hypertension, and so on, need not be expected to increase the hazard.

Alternatives to exclusion

Increased susceptibility to decompression sickness need not imply complete exclusion from work in compressed air. Thus, in an old man, it seems likely that his tissues mostly have slow saturation times. If this is so, he should be less susceptible during short exposures than a younger man. In any case, the increased hazard is easily countered by restricting the duration of exposure. Thus, with a limit to exposure of 1 hour maximum of time and 50 pounds maximum of pressure, tissues of 75 minutes' half-time or over can never be dangerously saturated, provided that their saturation rate is not temporarily increased when under pressure (for example, by physical work).

Principles of selection

It is thus possible to suggest the following rules for guidance in selecting men.

(1) Shift-workers and those to be engaged in manual labour must be completely healthy, of normal weight and less than 45 years of age. Temporary infections need not, of course, exclude a man who is otherwise healthy for longer than the infection lasts.

(2) Other men, who will not be engaged in physical exertion, need be completely excluded only if:

(*a*) there is evidence of chronic ear disease, chronic sinusitis, chronic lung disease or hernia;

(*b*) there is very great obesity, arteriosclerosis, or uncompensated heart disease;

(*c*) there is evidence of chronic bone disease.

(3) Those who do not come under these categories, even if they suffer from other chronic disorders, or are overweight, or are over 45 years of age, provided that they would be fit for surface work, may enter compressed air for not longer than 1 hour, and with pressures not exceeding 50 pounds per square inch of gauge pressure.

SPECIAL PROBLEMS

"Decanting"

The usual type of work involved permits a slow reduction of pressure from the working pressure after the shift is completed. Under some conditions there are not facilities for this, and the procedure termed " decanting " may be used. With this, the men on the shift are decompressed as rapidly as possible to atmospheric pressure, transferred to a decompression lock, compressed again to the original working pressure, and then subjected to a normal decompression. This is certainly safe if the time from starting the first decompression to reaching full working pressure in the medical lock is less than 5 minutes. There appears to be a certain interval required for the formation or growth of bubbles to a significant size. It is still not known how much longer intervals than 5 minutes can be employed.

" Bends " will certainly occur under these conditions from time to time, and should be treated as usual. The most important preventive measure to be taken is to ensure that the danger period is always kept as short as possible.

" Phase " decompression

In other circumstances, particularly in large tunnelling operations, it is possible to divide the workings into regions with different pressures. Thus the chief working face may be at the highest pressure, while parts of the tunnel to the rear are maintained at a lower pressure, with an air-lock in between. The system may offer advantages when work can be done in the low-pressure zone; for then the final decompression time of men exposed to the highest pressure can be reduced by an amount depending on the duration of stay in the low-pressure zone. The permissible allowance depends on the circumstances, and requires calculation for each particular case.

" Tidal variation "

In many undertakings, particularly when the mud-cover of a river-bed is scanty and overlies gravel or ballast, there is a large variation of the pressure of the workings according to the tide. Variations over a range of 5 pounds per square inch are common, and they may be as much as 10–15 pounds per square inch. Under these conditions, the effective working pressure to which men have been exposed during a shift may differ significantly from that existing at the moment of leaving the working. When the tidal variation is more than 5 pounds per square inch, therefore, the men should be decompressed as though they had been working at that pressure which is the mean of the pressures half-way through and at the end of the shift. This correction permits them a correspondingly briefer or longer decompression according to the phase of the tide.

REFERENCES

Admiralty (1943). *Admiralty Diving Manual.* London; H.M. Stationery Office.
Behnke, A. R. (1945). *Medicine*, **24**, 381.
Boulton, G. E. (1942). *J. Instn. Engr., Australia*, **14**, 1.
Boycott, A. E., Damant, G. C. C., and Haldane, J. S. (1908). *J. Hyg., Camb.*, **8**, 342.
Haldane, J. S., and Priestley, J. G. (1935). *Respiration.* London; Oxford University Press.
Harvey, E. N. (1945). *Bull. N. Y. Acad. Med.*, **21**, 505.
James, C. C. M. (1945). *Lancet*, **2**, 6.
Keays, F. L. (1909). *Publ. Cornell Univ. med. Coll.* (*Dept. Medicine*), **2**, 1.
Hoff, E. C. (1948). *A Bibliographical Source Book of Compressed Air, Diving and Submarine Medicine.* Washington; Navy Department.
Levy, E. (1922). *Compressed Air Illness and its Engineering Importance: Technical Paper No.* 285. Washington; Bureau of Mines.
Lewis, H. E., and Paton, W. D. M. (1951). Unpublished.
Ministry of Labour and National Service (1951). " *Work of Engineering Construction* " (*Factories Act*, 1937): *Revised Draft of Regulations as to Safety, Health and Welfare in connection with such Work*; *Part VII* (*Work in Compressed Air*). London; H.M. Stationery Office.
Norrie, C. M. (1934). *Proc. Inst. civ. Eng*, **235**, 279.
Paton, W. D. M., and Walder, D. N. (1954). *Compressed Air Illness.* Medical Research Council Special Report No. 281. (In the Press.)
Snell, E. H. (1896). *Compressed Air Illness.* London; Lewis.
Swain, V. A. J. (1942). *Brit. J. Surg.*, **29**, 365.
Walder, D. N. (1949). *J. Physiol.*, **108**, 51P.