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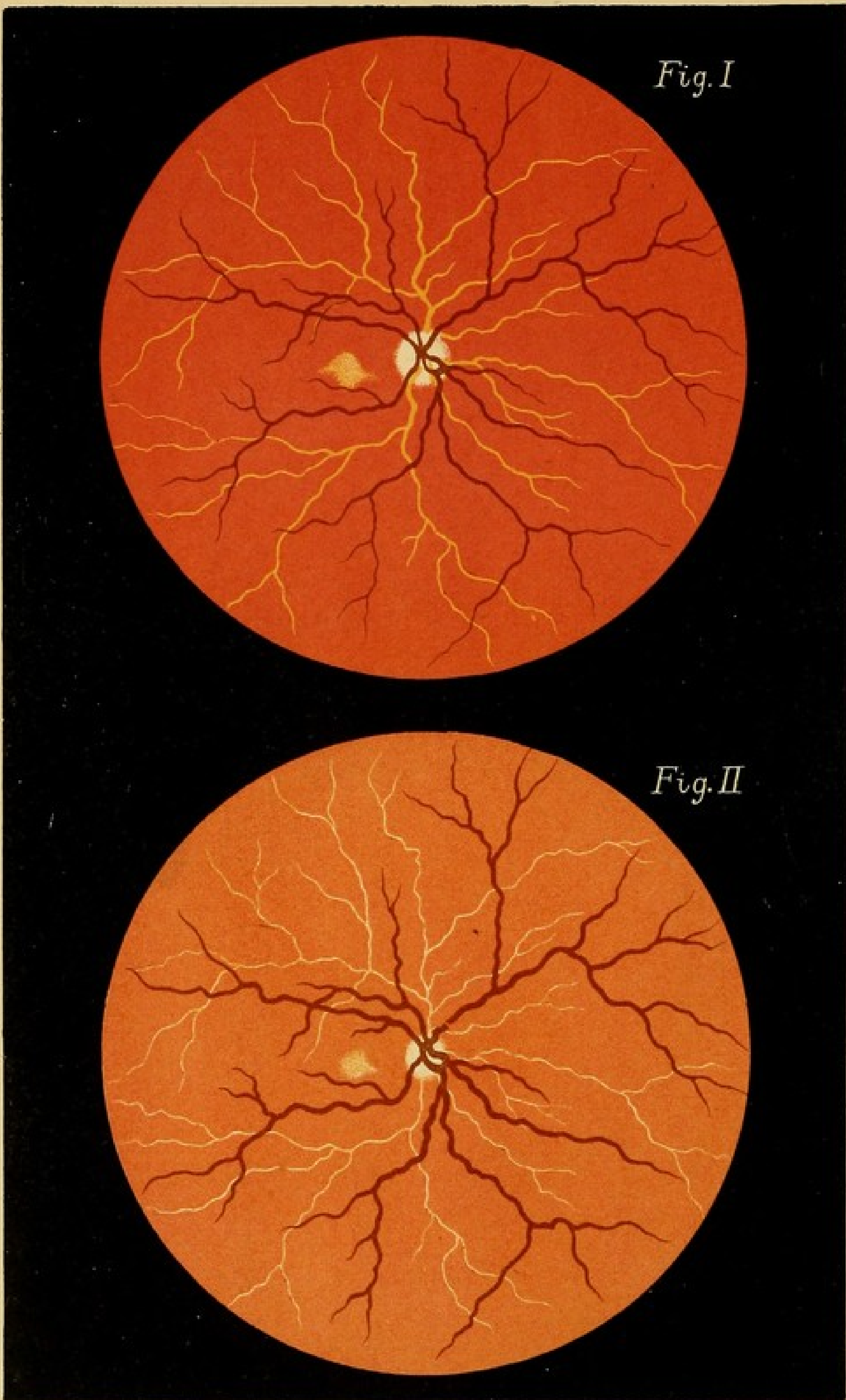

McLAGAN & CUMMING, LITH. EDIN.

Fig. 1. Circulation of Retina in Waking State.
Fig. 2. Circulation of Retina in Comatose State.

THE

INTRA-CRANIAL CIRCULATION

AND ITS

RELATION TO THE PHYSIOLOGY OF THE BRAIN

BY

JAMES CAPPIE, M.D.

EDINBURGH:
JAMES THIN, 54 & 55 SOUTH BRIDGE,
1890.

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PREFACE.

My aim in the following pages has been to give a contribution, on the one hand, to intra-cranial physics, and on the other to mental physiology. If any speculation in the latter direction may deserve attention, it will depend on the position I take up in the former being proved to be tenable.

It may here be advisable, however, to premise a few words in regard to my method, which, I may at once admit, is not the experimental. I am not a Physiologist. I am a General Practitioner, and as such belong to a grade that scarcely allows time for quiet, consecutive thinking, still less for the assiduous attention which careful experimenting requires.

Such a confession, I am aware, is not likely to recommend either my procedure or its results to those who are inclined to appreciate only those conclusions which have been tested in the physiological laboratory. The scientific spirit of the age walks by sight, and not by faith. It revels in facts. To make progress among the secrets of nature, its highway is Experiment and its watchword is Demonstration. For any interpretation of a natural phenomenon, it demands proofs that can appeal to the senses, and it looks with wholesome suspicion, if not contempt, on mere "arm-chair" speculation.

The marvellous success in advancing knowledge and in gaining command over the forces of nature that has resulted from its use, is convincing evidence that the scientific method of interrogation is the true one, and that it should always be adopted wherever possible. But it is not always easy to apply the method. The nearer we approach the region of subjective phenomena, the more difficult it becomes to test particular interpretations by an appeal to experiment. The galvanometer may detect agitation in a sensory surface, but it can tell us nothing about sensation. The convolutions of a dog's brain may be tampered with, but he will not describe to us his feelings. Consciousness alone can discriminate the facts of consciousness; and the character and succession or relation of these can only be detailed in terms of metaphysic.

That the nervous system presents special difficulties to experimentalists is admitted by themselves. Were one in the mood—which I am not—it would be no very onerous task to find numerous instances where, even in the last few years, conclusions have been confidently drawn from some experiment, and by their author made to appear as truth fixed once and for all time, and yet by the next investigator they have not only been controverted, but perhaps fairly overturned. "There is, perhaps, no subject in physiology of greater importance and general interest than the functions of the brain," says Professor Ferrier, "and there are few which present to experimental investigation conditions of greater intricacy and complexity. No one who has attentively studied the results of the labours of the numerous investigators in this field of research can help being struck by the want of harmony, and even positive contradictions, among the conclusions which apparently the same experiments and the same facts have led to in different hands." *

It is not as opposed to experiment, however, but as suggesting something complemental, that I would wish to lay some stress on the importance of certain general physical conditions being taken into account as bearing on the action of the brain. It is becoming trite to remark that, in the development and activity of everything living, its "environment," "surroundings," or "medium" may have an influence only second in importance to that of special structure. Now, what I would respectfully contend for is, that the physiological bearing of the brain's surroundings has not received the attention it deserves. The cranium has been regarded simply as an organ of protection, and much has been written to show how well adapted it is for such a purpose. By its form, and by the firmness and elasticity of its walls, it combines moderate weight with great power of resistance, and thus, while not a burden to

* "The Functions of the Brain," p. xxi.

the individual, it secures the delicate structure of the brain against physical injuries. It is more than likely, however, that, as I shall afterwards attempt to show, the properties of the skull exert a positive influence on the physiological action of the brain itself. Then, what indeed appears not a little surprising, is the circumstance that the peculiarities of the encephalic circulation —so numerous and so striking—now receive less attention than they did in the early years of the century. It is with some hope of reviving interest in these peculiarities, and to point out certain modes in which they can exert an influence on the brain's activity, that I now venture to submit the following essays.

The action of a muscle may be determined with great precision by a study of its leverage relation to the bones, and of the restraint of its investing fascia, although no knowledge be possessed of the physical and chemical changes involved in the contraction of its fibres. In like manner, the brain may be studied in its relation to certain broad physical conditions, and the influence of these on its working may be recognised, although the immediate source of nerve energy may remain a complete mystery. And it will simply be in accordance with such an assumption that I shall pursue my subsequent argument. I shall attempt to trace a relation between the brain's mode of working and certain peculiarities in its surroundings or conditions. I shall have no recondite researches to submit, but shall deal with well-established facts or generally admitted physical and physiological principles. In applying the latter I shall not hesitate to place confidence in some deductions which the exercise of plain common-sense may appear to warrant.

It is more than likely, therefore, that my physiology, like my method, may be considered old-fashioned. I am not at all unwilling to have it so regarded. I shall have to do, not with infinitesimal measurements, nor with microscopic or atomic detail, but with broad aspects. I have nothing to add to the already formidable array of facts; but, assuming the correctness of certain data, I shall attempt to trace a causal relation among them.

It is not in the way of apology I make any remarks in regard to my method. The latter, I submit, is perfectly legitimate. I base my conclusions on facts, and to the best of my ability I buttress them with facts. Very possibly some critic may discover that I have been taking too much for granted,—mistaking fiction for fact, and so far as any such charge can be proved against me, my reasoning, of course, will be vitiated. I can only say I have been at no small pains to prevent my argument from being exposed to such a drawback; and where I have occasion to take a side in some controverted matter, I have given my reasons—in one or two instances at considerable length—for preferring the view I adopt.

If simply to follow out a train of reasoning may appear something less brilliant than to make a successful experiment, it has the advantage that anyone who may take the trouble to master the premises may judge for himself whether the conclusions are legitimate. Unfortunately, however, some *effort* may be required to take a comprehensive view of the argument. We cannot help the circumstance that this is necessarily somewhat complex, and possibly its drift or bearing may not be recognised at once. It is comparatively an easy matter to accept conclusions which some experiment may seem to support, but very few are in a position to judge how far all the conditions necessary to evolve the whole truth have been fulfilled in any particular experiment. We have to a great extent to trust to the skill and good faith of the experimenter. Any one, however, if only he grapples honestly with the argument, is at liberty to sit in judgment on the method, data, and results of an author who has to confess that his speculations owe everything to the study arm-chair, and nothing to the physiological laboratory.

Nevertheless, I shall not despair to show that by the method I intend to pursue, more light may be thrown on the physiology of the brain than can in the meantime be expected from any analysis of its structures, however minute and accurate that may be. In every phenomenon there is of necessity a chain of causation, but the revelations of minute anatomy are too frequently only isolated links. They furnish interesting facts, rather than the explanation of wider phenomena. They show us instruments, but not action. Closeness of vision reveals many minute points of detail, but it interferes with perspective, or our notion of the relation of things in space; nor does it always throw light on that relation of events in time which is due to continuity in the flow of energy. No analysis of sea-water would ever explain the flow and ebb of the tide; nor will the microscope or test-tube ever explain the flow and ebb of consciousness. Possibly, however, some measure of success may be gained if we hold the brain, as it were, at arm's length, and take a bird's-eye view of its more palpable relations. In this way, I think, we may be enabled to recognize, not only facts, but also sequence. We may possibly get at least a few glimpses of that order of combination and succession which constitutes causation; that is to say, we may find positions which will naturally tend to the transference or transmutation of energy. To make some small attempt of this sort is, at all events, my present aim. I have a strong conviction that at least the *direction* I venture to point out is one in which progress is to be made, and I can only hope that one or two of the pathways I have attempted to open up may not be altogether useless to the future explorer.

"The physiology of the nervous system," says Professor Foster, "is still in its infancy." It can be no unworthy object of ambition in anyone to try and do something that may favour the process of development, and promote its advance toward adolescence. If any word of mine may have some influence in furthering this object, I shall be repaid for not a little time and thought spent on the subject. In whatever else these speculations may be deficient, I know they are at least the outcome of honest work.

J. C.

37 Lauriston Place, Edinburgh,
October 1890.

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APPENDIX.

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I.

THE PHILOSOPHY OF PHYSICAL CAUSATION.

In his veracious history of New York, Mr Diedrich Knickerbocker considered it necessary to begin with the creation of the world. He was thus enabled to give an appearance of philosophical completeness to his work. "For," as he sagaciously remarks, "if the world had not been formed, it is more than probable that the renowned island in which is situated the City of New York would never have had an existence." In carrying out his plan he finds himself confronted with "at least a score of ingenious methods in which a world could be constructed." Several of these he examines critically, but in some essential particular or other they all fail to give what he could consider a satisfactory or credible account of the earth's genesis. He therefore favours us with his own theory. This he expresses tersely and with unhesitating dogmatic emphasis. "One thing appears certain," he says, "and I make the assertion deliberately, without fear of contradiction, that this globe really *was created*, and that it is composed of *land and water*."

If any enthusiast in science, ambitious to give an exhaustive explanation of some apparently simple phenomenon, such as the movement of the pen in writing these words, were to emulate the boldness of Mr Knickerbocker, and determine to begin at the beginning, he, too, would likely be obliged to make an arbitrary commencement. However far back in time his analysis or his imagination might carry him, he would at last be glad to take refuge in a dogma, and be obliged to build his synthesis on an assumption. He might, for example, very possibly "make the assertion deliberately, without fear of contradiction," that the universe really *was created*, and that it is constituted by *matter and energy*.

Like other dogmas this one draws on faith for some of its support; but if accepted as sound doctrine, one might then proceed by its aid to show how worlds have been fashioned and are still kept rolling in space, and how event has followed event in unbroken, far-reaching succession. Less venturesome than the illustrious historian of New York, however, I shall not attempt any such flight. Simply assuming that the postulate embodies important truth,—whether or not something more or less than the whole truth,—we may consider how it may be applied toward explaining events as we now find them occurring.

As Mr Knickerbocker's "land and water" made one globe, so matter and energy constitute one Something with two aspects; or, if we are to consider it in relation to ourselves as conscious beings, it presents itself in three aspects. Matter without properties, or energy without a medium, is alike "unthinkable;" and matter or energy (or matter *and* energy) without motion is to us as non-existent. Matter must have assumed bulk or mass,—must have proved its claim to a share of space, —before even the imagination can have anything to do with it, and energy only reveals itself to us by some change or motion produced in matter. Virtually, therefore, every appearance or event is constituted by a trinity: —matter, the basis or medium; energy, the spring, the power, or spirit; and motion, the evidence, or mode of revelation. As an abstract notion, any of these may be the object of thought, but every concrete illustration, so far as it affects ourselves, must include all three.

Energy compels our assent as a fact, but its nature baffles our powers of insight. Matter and motion, in some of their grosser aspects, we so far comprehend that illustrations of their existence and peculiarities may be directly recognised by one or more of the senses; but the essence of energy, by virtue of which alone matter can express itself, is likely for ever to elude the scrutiny of finite intelligence. It dwells in a sanctuary, over the portals of which is inscribed:—MYSTERY OF MYSTERIES, ALL IS MYSTERY. No High Priest of mortal mould may gaze on its inner shrine.

But energy, if beyond comprehension, is not wilful. It may be subtle, but it is rigidly law-abiding. To account for the fact of weight may be puzzling, but the law of gravitation can be expressed with a precision that leaves nothing to the imagination. Energy is ever awake—is ever ready to respond to an appropriate stimulus. We may either say it conditions everything, or that all its own manifestations are strictly conditioned. Its all-pervading influence is shown in the tremors of the ether and in the hardness of the diamond; in the behaviour of atoms and molecules as well as in that of suns and systems. Its mode of working is inviolably fixed, and if by successful interpretation of nature its secret can be sufficiently mastered, it becomes a docile slave whose behaviour can be predicated with the greatest precision.

To attempt some interpretation of nature is instinctive independently of any desire to obtain sway over its forces; to interpret correctly and to reduce to rule, if a laudable ambition, is not always an easy task. Many have been the professed interpreters; many, also, have been the methods pursued, and immensely varied has been the value of the results.

The interpreter to whom the greatest licence is given is the Poet. To nature he imputes moods and will, and doing his best to place himself in harmony with these moods, he gives us his not uninteresting version of her modes of existing and working. His own imagination is his instrument of research. Ignoring reason, he yields himself up to the mood of the moment, and as that changes, so does his estimate of whatever may come within the range of his vision.

More in earnest and less at liberty to contradict himself, the Metaphysician also animates nature with virtues, affections, powers. All appearances and events are the outcome of the exercise of these. His mode of interpretation to some extent is—and ever will be—universally employed. As a provisional method, it is necessary even to the most thorough-going scientist. To metaphysic we owe a vast number of the substantive terms that imply action or the possession of properties, and to the end of time we may be sure that such words as nature, life, weight, motion, will continue to be in use and to convey very definite ideas.

As a method of interpretation, however, metaphysic is defective when it remains satisfied with far-off glimpses of the truth;—when its votary surveys and speculates and formulates his conclusions from the simple survey;—when he is content with a Mount Pisgah view of the promised land, but disinclined to come down into the plains and do battle for possession; or when he deems it undignified so to handle the tools that nature works with as to become acquainted with their varied properties.

The votary of Science, on the other hand, delights to come to close quarters with nature. His aim is to give precision to facts and terms, and to the conditions that influence the sequence of events. He numbers, and weighs, and measures; he describes, compares, and classifies; he speculates as to the what and how of agents and conditions not directly revealed to the senses, and he puts his notions to the test of experiment, or he gathers facts that may bear on their proof. He endeavours, on the one hand, to make all the facts of nature to cluster around central ideas—to exhibit them in their family affinities; and, on the other hand, to trace their causal relations in that unresting procession of events which gives to us our notion of time. His ambition is also to recognize the rigour of law in every phenomenon,—to discover and formulate some truth or rule that can bear wider application than to the special instance before him. But no law, however universal, is the *cause* of any event,—energy itself is alone privileged to exercise actual power, and is therefore, sole efficient cause. But law reveals likeness or relationships that may be lying far from the surface; or it gives definite expression to the conditioned mode in which some form of energy must work.

The power of energy to produce motion—and, therefore, to do work—depends on the circumstance that it can be subjected to stress,—to concentration, to repression or compulsory imprisonment. Under stress it reacts against the barriers that oppose its diffusion or disturb its balance. According to its own intensity or the nature of its surroundings, it may remain quiescent and potential; or it may escape gradually in the direction of least resistance, producing molar, molecular, or atomic motion; or it may bursts its barriers with explosive force.

Causation, then, cannot be adequately considered apart from the play of some form of energy. Wherever we find physical change, there we have the expression of actual energy; and whatever transfers or liberates energy is a cause. Whatever opposes or favours, condenses or diverts its course is also a cause. Causation includes the sum of the causes,—the co-ordinate properties of "agent" and "patient," and all the conditions of action and reaction. It specifies not simply the agent which may appear dominant, or be supposed to have set the series of changes in progress, but also all the surroundings that affect the direction, intensity or transmutation of the energy or energies involved in producing any specific effect.

In attempting to explain some particular event, we have to determine the individual factors concerned in its production, and, as far as may be, to appraise their value. The agent or form of energy that may appear dominant, and those that are to be overcome, or which may be co-ordinate, and the mechanical adjustments that affect their amount and direction, are given with such detail as may be necessary or possible.

In mechanics we find the simplest illustrations of a chain of causation where every link can be recognised. Given a moving power, the law of leverage enables us to trace the course of what energy it supplies through, it may be, a long series of various forms of lever, and to foresee with unerring accuracy the last result. Thus, the movement of the hands of a watch or the fly-wheel of a steam-engine can be traced to special antecedent arrangements. The required energy in the one case being given by a coiled spring, and in the other by boiling water, we know how the nicety of movement in the one instance, and the powerful force in the other, depend on the adjustment and combined working of certain instruments having appropriate qualities, and how the result may be modified infinitesimally by changes in the arrangements. Instances like these furnish us with an ideal of what constitutes physical causation.

In nature, however, we are surrounded by phenomena whose intimate mechanism eludes our observation. Results are seen, but processes are hidden. A multitude of causes are interwoven and contribute to one effect. Here metaphysic finds scope for its subtle and useful faculty of comprehensive vision or imagination, which enables it to endow a figment with vitality and fruitfulness, or to bridge over a chasm by a term. The word "life," for instance, denotes a process in which may be comprehended a very world of mysterious operations. But here, too, scientific faith comes into operation, and affords "the evidence of things not seen." It gives assurance that, let the way be ever so hidden or complex energy, working with physical agents and in accordance with stringent law, is still the efficient cause. Whether the result be shown in the destructive effects of the earthquake, or in the delicate hues and fragrance of a petal, energy dominates at every stage of the process. Whether acting through the ether or through atoms, through molecules or masses,—whether sweeping swiftly and unchanged, or transmuted more or less by resistance, it ever conforms to a universal law, according to which it must pursue its relentless, unbroken course in the lines of least resistance.

In dealing with phenomena represented by a metaphysical term, the scientist must leave its substantive form out of sight, and give all his attention to the adjective. He does not attempt to grapple with an entity *life*, but with the conditions which go to constitute something *living*. He will only have to do with a concrete living individual or living structure, and the sum of the changes it presents constitutes its life. The textures and organs of which it is constructed—be they simple or complex—and the relations of these to one another and to the medium in which they exist and operate, are the immediate objects of his study. When he meets with a mechanism which he cannot comprehend, he tries to ascertain as many as possible of the conditions that affect its working; if he cannot trace the chain of causation link by link, he may at least try to make sure that between particular points there exists an unbroken series of connections. If he has to speak of this series as a single process, or if he has to recognise some cluster of conditions as a single cause, he must, of course, use or invent a term to express it, and until research may reveal the nature and relation of its constituent factors, it is legitimate to use it as if it represented an individual entity or unit. But however transcendental that term may be, he will, so far as the process comes within the scope of his enquiries, regard every step in the sequence, or in the combination of conditions, to be the result of, and to be constituted by, physical agency.

It need hardly be said, however, that within the sphere of consciousness, metaphysic reigns supreme. Sensation, perception, ideation, and so forth, take no cognisance of molecular action in the brain. The metaphysician, therefore, ignores the latter, and formulates a sequence of events independent of all physical conditions. He endows the mind with faculties; and "faculty" implies the capacity to act and to be acted on. To him the ideal of active power is the Will, and the idea of "cause" he is inclined to trace to the feelings we experience in the exercise of that faculty.

Such a process having the merit not merely of necessity, but also of ease and simplicity, the temptation to apply it to sequences outside of consciousness, becomes natural and strong. Inherent "principles" thus become endowed with active powers, and "life" is the cause of the highest phenomena in nature; yet, as positive entities, neither has any existence.

The necessity of keeping in view the distinction between physical and metaphysical causes has often been insisted on, but sometimes it seems difficult to discriminate between them, and thus considerable confusion not unfrequently results. For example, it is now generally admitted that during sleep the amount of blood circulating in the vessels of the brain is lessened as compared with the same circulation during the waking state. Now, some physiologists express themselves to the effect that sleep is the *cause* of this altered circulation. If such a notion were correct, sleep must be regarded as a form of actual energy,—it is spoken of as the cause of a specific physical effect. The inclination to sleep is at times irresistible, and it is therefore evident that some powerful agencies are at work, but a consideration of what sleep itself is constituted by, may show that to speak of it as an active physical agent is entirely incorrect.

The poet, of course, is at liberty to endow it with no end of active powers. It

> "Knits up the ravelled sleeve of care."

> "The soft hand of sleep had closed the latch
> On the tired household of corporeal sense."

To be "seized" by sleep is one of the poet's favourite expressions.

But if "life" be a metaphysical term or cause, not less so is "sleep." It is a condition having on one side a relation to the mind, and on the other to the brain. In both directions its phenomena are of a negative character. On the one hand, the mental functions are more or less completely suspended; and on the other, the brain is in a state of physiological rest. If we attend to the mental aspect only, it may possibly not be incorrect to speak of sleep as a cause. It may be said to produce a certain degree of unconsciousness, as distinguished, for example, from coma, which produces a more intense degree of the same state. Even here, however, it would perhaps be more correct simply to say that sleep is constituted by—is a condition whose special characteristic is—a certain amount of unconsciousness. But if we regard the brain aspect of sleep, then every change here is physical, and, as such, must have a physical parentage. I shall afterwards have what may perhaps be thought more than enough to say as to the nature and sequence of these changes, but here I would simply protest against a metaphysical explanation being considered sufficient to account for their occurrence. When, therefore, we are told that "sleep must be regarded as the cause rather than the consequence of the so-called cerebral anæmia which obtains in the substance of the brain during repose,"* I would respectfully submit that the philosophy of the author

* Lyman, "Insomnia," p. 28.

must be considered seriously at fault. If any one were to say that "night must be considered as the cause rather than the consequence of the disappearance of the sun which obtains in nature during the nocturnal hours," the absurdity of the statement would be seen at once. Nevertheless, it would be just as correct to speak of night driving away the sun, as of sleep driving blood out of the vessels. What may be legitimate and interesting when coming from the licensed imagination of the poet, may be absolute nonsense if regarded as the expression of sober fact.

It has been no part of my task to dwell on the question of causation from the purely metaphysical point of view. What is involved in the *idea* "cause," or how it has originated in the mind, has given rise to no end of controversy. The discussion is one of great interest, and it may be seductively attractive as an exercise in mental gymnastics. I have been content, however, to look at the question from the simply physical point of view, as that which alone will have any interest to us in subsequent enquiries.

II.

THE CORRELATION OF MIND AND BRAIN.

OF all the contrasts that might be thought of by poet or orator, none could be greater than the one that may be made by taking consciousness, with its myriad modes of feeling, intelligence and will, and comparing it with the brain either as a whole or as dissected into its ultimate elements. At no single point can any resemblance or relationship appear to be traceable. On the one hand, we have an agent, subtle, intangible, conscious of itself, and comprehending nature in a great multitude of its aspects and modes of working; and, on the other hand, a mass of pulpy matter, into the inmost recesses of which the anatomist may pry in vain to discover what may be the purpose it is likely to serve in the animal economy.

Although simple inspection of its structure can throw no light on the function of the brain, a long series of observations has enabled the physiologist to determine that between its activity and that of the mind there exists a relation of the most intimate nature.

Such a fact, however, does not lessen the contrast they present, and the study of either must in the first instance be altogether independent of that of the other. Thus, the phenomena of mind have for ages been investigated simply by attention to the facts revealed in consciousness, and a whole library of literature attests to the interest of the study. Nor can the phenomena of mind be recognised or classified in any other mode. Consciousness alone can discriminate the facts of consciousness, and the characteristics or relation of these can only be described in terms of metaphysic. Sensation and perception, memory and imagination, ideas, feelings, intelligence, will,—such are some of the subjects that have been rather extensively enlarged on. This kind of research may be prosecuted with scarcely any reference to the brain—indeed, it is frequently done without any reference whatever, except perhaps, in regard to what may relate to the exercise of the senses. The mind when alert and healthy, rejoices in a feeling of independence and freedom. In the full flow of ideas and their expression, it is not conscious of being hampered by shackles. Introspection does not reveal any physical mechanism, the condition of which may either favour or impede its operations.

In nature, however, all action is conditioned, and mental phenomena are no exception to the universal law. The mind must have a medium in which it can exist, and through which it can express itself. Such being the case, the physical conditions involved, whatever may be their nature, become an essential factor in adequately considering the problems of mental being and action.

The brain is frequently spoken of as the organ of the mind, and the relation of his instrument to the musician is referred to as something analogous. An instrument, however, cannot transcend its own capacity. However deftly it may be handled, any response it can give must still be rather in accordance with its own structure and qualities, than with any power or property in the agent which may be acting on it. The volume and quality and harmony of musical sound are immediately correlated, not to the fingers of the player, but to the tremors within the instrument.

If, then, the brain be the organ of mind, the outcome of mental action, even as revealed to one's own consciousness, will depend not simply on some ideal, self-acting energy asserting itself, but it will depend also on the compass and quality and adjustment of a material organisation. Every form of mental activity must have its somatic side. Coherence of thought will imply orderly activity of brain function. The subtle reasoning of the highest intellect, not less than the ravings of lunacy, finds itself conditioned and limited by the capacity and quality of the organic medium by which it works, or through which it was to be manifested.

The mystery of consciousness itself remains as great as ever. No form of physical energy affords even the semblance of an analogy to its peculiarities, nor will the physiologist ever be able so to unravel the links of connection between mind and brain, as to perceive how the activity of the latter should of necessity be associated with the infinitely varied modes of manifestation presented by the former. But he is also compelled to accept the fact of such association. Apart from organic structure, he knows of no form of mental action. Without pretending to settle the question how one quickens the other, he has to assume that between their respective activities there is an intimate, if not an absolute, correlation. Although, therefore, in pushing his inquiries as to the intimate nature of their connection, he soon finds that he must content himself with very general notions, these may not be the less true so far as they may pretend to go. He may not be able to explain the fact of consciousness, but he may at least determine why one mode of consciousness rather than another is present; why it is present with a felt amount of intensity, or why, in certain circumstances, it is obscured or suspended. The nexus between molecular activity of brain and activity of thought and volition may for ever remain "unthinkable," but many of the modifying conditions of the molecular activity may certainly be determined, and the remote, but necessary, influence of these on the mode, quality, or intensity of mental action may thus to some extent be recognised.

In regard to the brain itself, its functional capacity depends on a comprehensive series of conditions being fulfilled; and the outcome of its activity may be greatly modified by slight changes in any one of these. Among the more important may be specified the amount and quality of its material; the number and depth of its convolutions; and the development of particular portions related to certain specific functions. It will not be my intention, however, to enlarge on any of these points. In the following pages I shall rather give prominence to the circulation as one of the essential factors in conditioning the brain's activity. The blood is to the grey matter of the brain what atmospheric air is to fuel in ordinary combustion. It is at once a stimulus and a necessity. However favourable may be the quality and disposition of the molecules, or the arrangement of cell and fibre, the consciousness will fail to respond to any impression, and every cerebral function will be impaired or suspended, if the circulation be lowered below a certain amount. If its balance through the vessels of the brain be altered, the outcome of activity will also be modified. A consideration of the laws that affect the distribution of blood, and the influence of local surroundings in modifying the working of these, must therefore be of the first importance in any attempt to take a comprehensive view of the brain's physiology. But, except by Dr Carpenter, this has very seldom been attempted. Volumes have been written on the relationship of mind and brain with scarcely more than a passing reference to this aspect of the subject. While considerable progress has been made in delimiting the immediate sphere of activity in certain mental acts, and especially in mapping the centres for voluntary motion, very little attention has been given to the influence which the many peculiarities of the encephalic circulation must have on the mode in which the brain may exercise its functions.

The circulation within the skull contrasts remarkably with that in other parts of the body in several respects. In the arrangement of the blood vessels themselves, in the relation of their contents to the pressure of the atmosphere, and in the circumstance that the whole mass of blood within the skull must for longer or shorter periods of time continue nearly uniform, we have peculiarities sufficiently striking to warrant us in supposing that they cannot be without some definite physiological significance. It therefore becomes necessary, in the first place, to give some detailed account of each of these peculiarities.

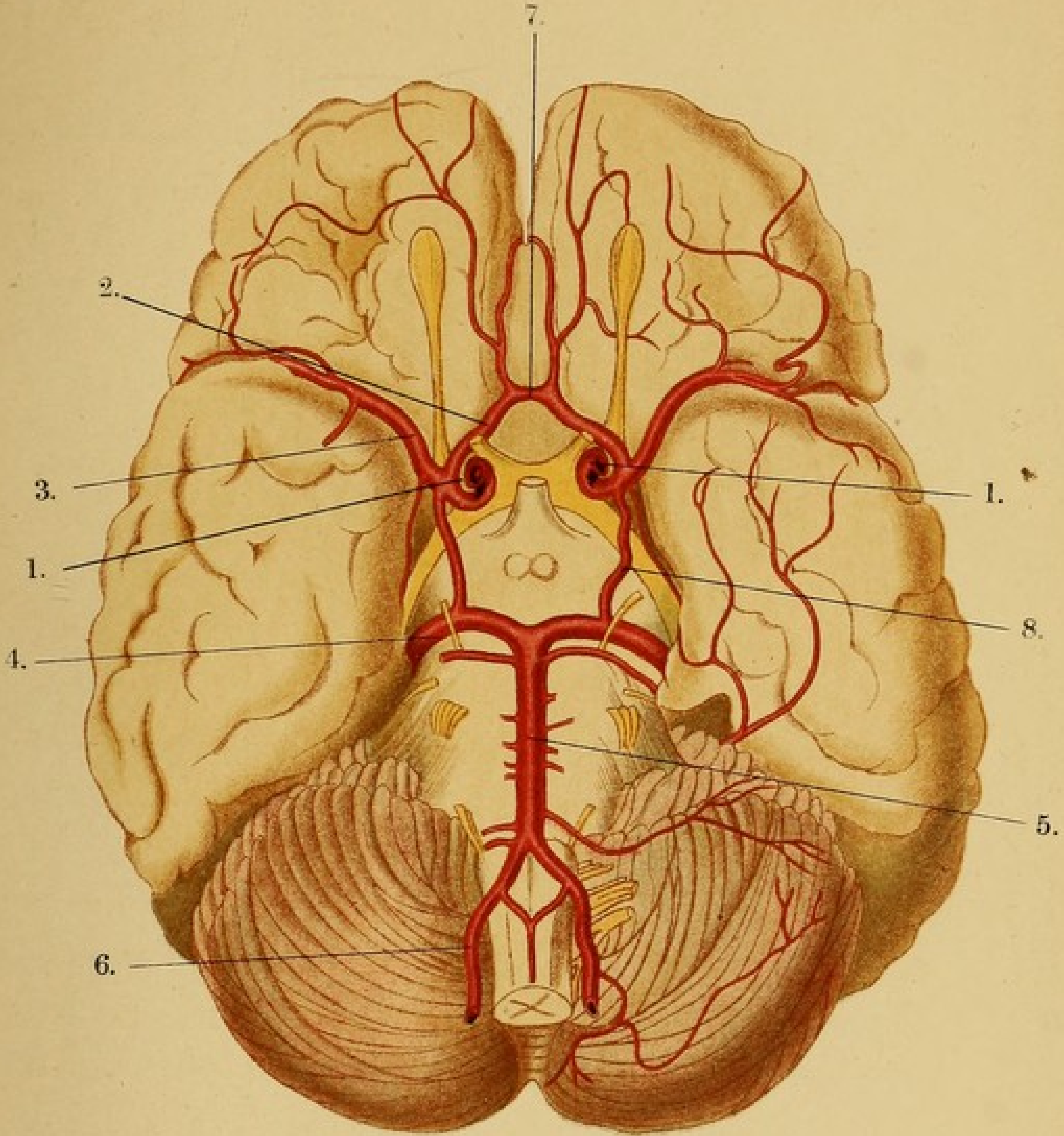
III.

THE INTRA-CRANIAL CIRCULATION.

Of all the systems in the body, that of the circulation is the least intermittent in its activity. While other organs may have periods of more or less complete rest, the heart must ever keep toiling at its unceasing task. And of all the organs to which it ministers, the brain is functionally the most important, and it is also the one least tolerant of any failure in the heart's action.

The mechanism by which a supply of blood is secured to the brain is very efficient. Scarcely has that fluid left the heart when a very large proportion of it is directed into four channels—the two carotid and two vertebral arteries—that go straight to the skull.

The carotids keep their course upwards along the side of the windpipe. At the angle of the jaw each divides into two vessels. One of these supplies the external parts of the head, the mouth, pharynx, &c. The other—the internal carotid—reaches the base of the skull, and penetrates the latter through a tortuous canal. On entering the cranial cavity it almost im-



ARTERIES AT THE BASE OF THE BRAIN.

1. Internal Carotid Artery.	5. Basilar Artery.
2. Anterior Cerebral Artery.	6. Vertebral Artery.
3. Middle Do. Do.	7. Anterior Communicating Artery.
4. Posterior Do. Do.	8. Posterior Do. Do.

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mediately divides into three branches. Two of these—the anterior and middle cerebral arteries—supply a large part of the front and middle lobes of the brain, a third proceeds backwards and inosculates with another vessel from a different source.

The vertebral arteries take a course less exposed than that of the carotids. Each of the cervical vertebræ has a projection outwards from the side of its body—the transverse process. In the upper six vertebræ, each process is perforated by a foramen, and the vertebral artery is transmitted through this. It ascends, therefore, through a succession of foramina till it reaches the upper part of the spinal canal. There it pierces the dura mater, and enters the cranial cavity, along with the spinal cord, through the large occipital foramen. Proceeding forwards, along the base of the skull, under the medulla oblongata, the two vessels gradually approach one another, and at the edge of the pons varolii they unite, to form one large vessel—the basilar artery. From this, branches are thrown off to supply the cerebellum and the posterior lobe of the brain.

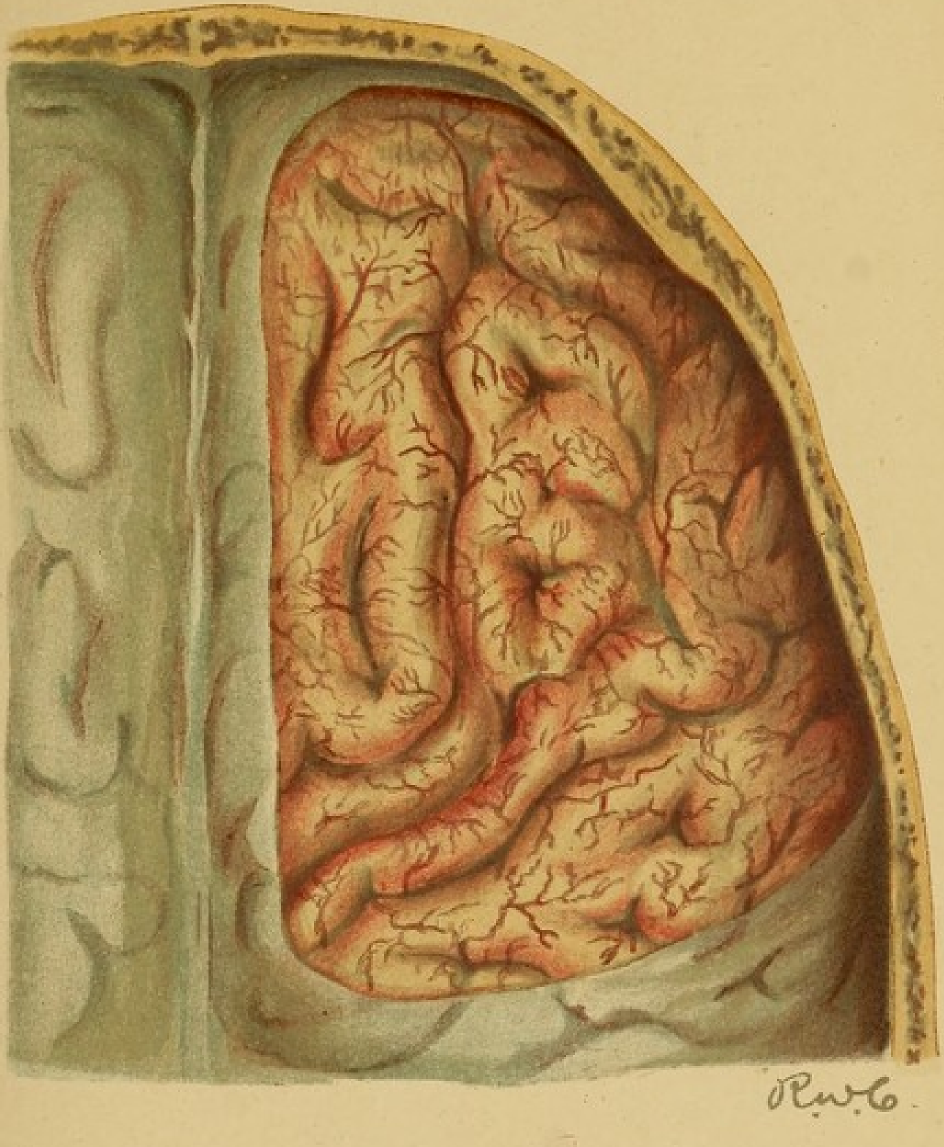
The mass of blood conveyed by these four arteries is very large. It has been calculated that they transmit one fifth part of all the blood in the body. Even if one half of that quantity is sent to the brain, the proportion would be still considerable. The brain does not weigh a fortieth part of the whole body, yet it would thus receive one tenth of all the blood.

Provision has been made to prevent such a large mass of blood from impinging too abruptly on the delicate brain tissue. In and above its canal through the temporal bone, the carotid is curved like the letter S, and the vertebral arteries have also a very winding course at the upper part of the spinal column, and on reaching the cranial cavity.

The arterial circulation at the base of the brain is remarkable for the manner in which some of the larger vessels anastomose. From one of the divisions of the basilar artery a branch is thrown forwards, and it inosculates with a division of the internal carotid; and the anterior cerebral arteries also communicate with one another by a cross branch. A complete circle of somewhat irregular shape—the Circle of Willis—is thus formed. We can readily understand how important such an arrangement must be. It makes provision for a ready and full determination of blood being permitted to any part of the brain where a demand for it may have been set up.

We do not here require to trace in detail the destination of the various arteries. Suffice it to say that they all lose themselves in the fine membrane—the pia mater—which immediately invests the brain. They there divide and sub-divide into extremely fine terminal vessels. Before they penetrate the nerve substance they have become almost, if not altogether, capillary in size.

Directing attention now to the intra-cranial venous



SUPERIOR SURFACE OF FRONTAL LOBE.
Dura Mater is cut away to show Vascular Structure of Pia Mater.

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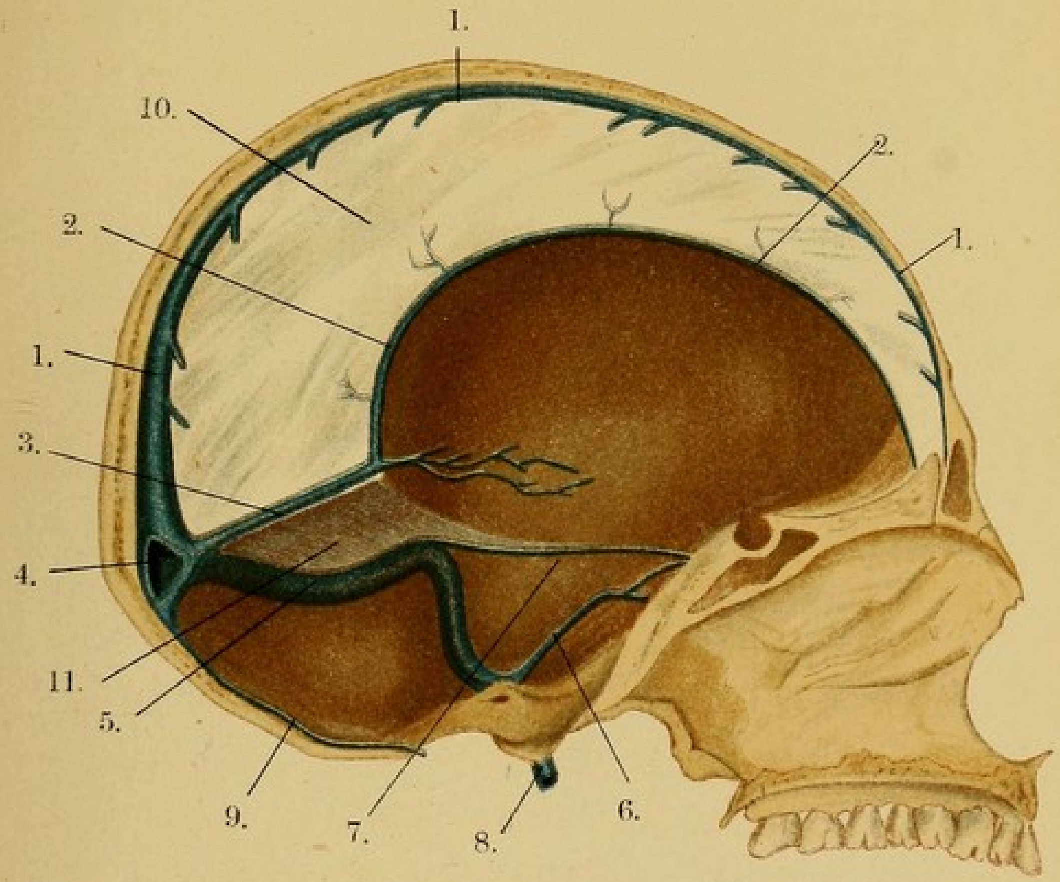
system of vessels, we find that this also contrasts remarkably with that of other regions. In the brain mass it is, like the arterial, practically capillary. Only on reaching the pia mater do the vessels so coalesce as to form veins of appreciable size. They then, however, become a conspicuous object on the cerebral surface. When the upper part of the skull has been removed, and the dura mater has been cut away, the most striking object which presents itself is the great number of dark coloured tortuous vessels that present themselves coiled in the meshes of the pia mater. They are seen lying in the furrows between the convolutions or crossing the latter in all directions.

In all parts of the body the capacity of the veins is, as a rule, greater than that of the arteries they accompany or correspond to. This is strikingly the case in the circulation within the skull. While the larger arteries are limited in number, the veins of noticeable size are scattered over the whole surface of the brain, or lie in fine coils between the convolutions.

The structure of the pia mater is thus of a most unique character. It is a complex of vessels united by extremely fine fibrous tissue. Through one set of these vessels all the blood that goes to nourish the brain must pass, and through another set all the returning venous blood is transmitted. The membrane keeps in close contact with the cortical surface of the brain in all its foldings. While the dura mater only dips between some of the larger masses,—lying, for example, between the opposing surfaces of the cerebral hemispheres, or separating the cerebrum from the cerebellum,—the pia mater not only covers the brain as seen when the dura mater is removed, but it dips to the bottom of every fold, and separates the layers from one another. When the convolutions are separated, it is seen to lie like a fine velvety pad between the opposing surfaces. At certain situations it is continued into the cavities or ventricles. In the lateral ventricle in each hemisphere, the choroid plexus—a curiously convoluted cluster of vessels—is a conspicuous object. If the membrane be gently raised at any point, numberless extremely small vessels are seen to connect its inner surface with that of the brain substance. These are so delicate that they break with the slightest traction.

There is still another peculiarity in the arrangement of the intra-cranial blood vessels. The veins, instead of all converging to form trunks differing only in bulk from one another, are emptied into what are called the sinuses of the dura mater. These are channels tunnelled in various directions in that membrane. They are fifteen in number, five being pairs, and five single.

The most important characteristic of a sinus is the circumstance that its capacity cannot be greatly, if at all, altered. It is formed of tough, inelastic membrane, and is so constructed that its walls can neither be made to collapse by pressure from without, nor to yield to dis-



Sketch showing the position of the Sinuses of the Dura Mater.

1. Superior Longitudinal Sinus.
2. Inferior Do. Do.
3. Straight Sinus.
4. Torcular Herophili.
5. Lateral Sinus.
6. Inferior Petrosal Sinus.
7. Superior Do. Do.
8. Internal Jugular Vein.
9. Occipital Sinus.
10. Falx Cerebri.
11. Tentorium Cerebelli.

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tending force within. We need here describe only one of them.

On examining the internal surface of a skull, a groove is seen running from before backwards along the vault at its centre. Small at the lower part of the frontal bone, it becomes broader and deeper as it approaches the occiput where it terminates. That groove corresponds to the course of the great longitudinal sinus. This is lodged in the process of the dura mater—the falx cerebri—which lies between the cerebral hemispheres. Beginning in front as a small slit in the falx at the base of the skull, it runs upwards and backwards, keeping close to the cranial wall and receiving in its course the contents of veins from the pia mater. If a vertical section be made, it is found to be triangular in form—the base being outward, immediately under the cranial wall, the apex pointing toward the centre of the brain. It is small in front and increases gradually in size as it runs backwards. The mode in which the veins from the pia mater enter it is also peculiar. They open obliquely in a direction opposite to the current of the blood—that is to say, while the current in the sinus is from before backwards, the veins, where they open into the sinus, have a direction from behind forwards.

The ultimate destination of the blood in the venous sinuses is, of course, the jugular vein, which is reached by a foramen different from that by which the arteries entered.

Looking, then, simply at the anatomical arrangement and structure of the vessels, the intra-cranial circulation contrasts in several respects with that of other regions of the body. In the quantity of blood being larger in proportion to the size of the organ to be nourished,—in the free manner in which the larger arteries communicate with one another,—in the circulation of the brain mass being practically capillary,—in the circumstance that the larger arteries and veins, instead of keeping company, lie apart from one another,—and in the venous blood being in the latter part of its course transmitted through channels with tough inelastic walls, we have a series of peculiarities which cannot be without some physiological significance.

IV.

THE CAPILLARY CIRCULATION.

Before further specifying the peculiar physical conditions under which the brain has to discharge its functions, there is a point in the general physiology of the circulation that has to be discussed, as a large part of my argument will hinge on the soundness of opinion I may adopt regarding it.

That the main current of the circulation is sustained by the action of the heart may be assumed without question, but there may be a difference of opinion as to the mode by which the blood is determined to individual parts of the body. *Ubi stimulus, ibi fluxus,* is an old aphorism which embodies the principle that the local distribution of blood is to a great extent regulated by local demands or conditions. And it is easy to perceive that such a principle must be of the first importance. As it is the object of the circulation to convey material of stimulus and repair to the various organs and to carry off waste products, and as the need for such material varies greatly according as an organ is quiescent or functionally active, some mechanism appears necessary so to regulate the supply to individual parts, that while this may be sufficient for the wants of the texture, it shall not be so great as, by its bulk or otherwise, to interfere with the proper exercise of function. And as a matter of fact we find that the supply of blood to individual parts is usually regulated by the need for it. When the mammary secretion is being established, the afflux of blood to the gland becomes several times greater than when its function was dormant. When the mucous membrane of the stomach is stimulated by food and the secretion of gastric juice begins, the surface becomes intensely injected with rapidly moving blood; then, after digestion has been completed and the stomach is empty, the membrane again becomes comparatively bloodless. In short, wherever growth, and especially where the transformations that accompany functional activity go on with greater vigour than usual, there is an increased determination of blood towards and through that part.

While the general current of the circulation, therefore, may be sustained by the action of the heart, there must be some other factor to assist in modifying the local distribution.

Two views have been strongly held as to the mechanism of the capillary circulation. According to one view, the sole moving force is the action of the heart, and wonderful calculations have been made as to the number of "foot-pounds" work this organ must accomplish every twenty-four hours. "The heart's action," says Professor Allen Thomson, "is continued onward through the capillaries, and is sufficient to return the blood through the veins, back as far as the heart."* "The real cause of the flow," says Professor Foster, "is the ventricular stroke, and this is sufficient to drive the blood from the left ventricle to the right auricle."† According to this view, the complementary factor by which some control is obtained over the local circulation, is the action of vaso-motor nerves. These appear to get credit for being veritable physiological "demons." Their unsleeping vigilance foresees and provides for all local wants. They so regulate the calibre of the smaller arteries, that they turn on or shut off the blood current as may seem to be necessary.

According to the other view, the action of the heart requires to be supplemented by certain forces acting at the capillaries themselves. "In the natural state," says Professor Alison, "there must be some vital power concerned in *aiding*, not *opposing*, the impulse from the heart. . . . Local determinations to certain parts of the body, are to be ascribed to 'a mutual vital attraction or affinity between the blood and the tissues of the body.' . . . This suspicion becomes much stronger when it is remembered, that a circulation of fluids is carried on throughout the whole vegetable kingdom, and in the

* "Cyclopedia of Anatomy and Physiology," vol. i. p. 671.

† "A Text-Book of Physiology," 5th ed., p. 219.

lowest animals without any perceptible aid from the contractions of solids; and certainly without any such peculiarity of structure as can explain the determinate direction of the movement; that even in the lower of the animals that are provided with circulating vessels, a part of the circulation is still of the *diffused* kind, and apparently not referable to the contractions of these vessels; and that in the commencement of existence of all animals, most of the organs acquire a determinate form before the blood exists, or the heart or any contractile part has begun to beat. . . . As the vital affinities obviously act with greater energy in individual parts of the body at some times than at others (*e.g.*, at the lungs during inspiration, at the stomach during digestion, or at the uterus during gestation), we can understand how local determination of blood should be produced (by attraction rather than propulsion) by causes exciting the vital actions at the ends of the arteries. The increase of nutrition, secretion, or excretion, is in such cases, at least in the first instance, the cause, not the effect, of the increased flow of blood to the parts concerned; just as the excitement of vital action in the branch of a tree exclusively exposed to the sun, is the cause, not the effect, of an exclusively increased flow of sap into it."*

In adopting the latter as the more correct view, I would by no means wish to suggest that the other is

* "Outlines of Physiology," 3rd ed., pp. 62-63, 64-70.

unimportant. Many well known experiments have placed it beyond doubt that the ganglionic nerves can exert considerable influence on the local circulation. The tension or tone of the small arteries seems to be greatly under their control. But it is not very well understood how, in ordinary conditions, their influence is called into operation. It is not improbable that in many instances their action is reflex,—that the molecular agitation first transmits its wants to a vessel controlling ganglion, and that the efferent dilating or contracting process is in response to this stimulus. In healthy nutrition, therefore, the two agencies work in harmony, and should be studied together. It may often be impossible to say where the causal influence of either begins or ends.

But recently there seems to be a tendency to ignore, if not altogether to deny, the active influence of local molecular or metabolic change on the capillary circulation. Such a tendency is, I believe, unfortunate and seriously retrograde.

That the tissue molecular changes can cause the movement of fluids in capillary tubes without the aid of evident mechanical impulse, the whole vegetable world bears witness. The movement in the bud initiates that in the stem; the molecular activity in the foliage conditions the ascent of sap from a long distance below. In animal physiology, too, we may find abundant instances, such as those quoted above, where the circulation of fluids must be occasioned by forces other than that of the heart's action.

As evidence on this point, I would submit that afforded by an important peculiarity in the venous system of vessels. I allude to the portal circulation. The large mass of blood returned from the stomach, intestines, pancreas, and spleen, is collected into one large vein, but instead of being poured directly into the vena cava, it has first to traverse an extensive ramification of vessels through the liver. On reaching this organ, the portal vein divides into two branches—one for each lobe. These again divide and subdivide like arteries, until they form a minute capillary plexus in the lobules or ultimate structure of the liver; then gradually enlarging, they unite to form the hepatic vein, and through this the blood is transmitted to the vena cava.

In submitting this peculiar kind of circulation as evidence that some force supplementary to the action of the heart is necessary to transmit blood through the capillaries, I do not refer to the distance of the vessels from the heart, nor to the zig-zag route the current has to take. I refer rather to the circumstance that if the blood only circulates under the influence of a *vis a tergo*, the whole stress of whatever force may be needed to transmit it through this portal system of vessels must be borne by the mesenteric veins. It will be at once admitted that the amount of force required for the purpose must be considerable; and, of course, in accordance with the law of pressure in fluids, the backward pressure in the portal vein must be as great as the force required to send the blood onwards. This backward pressure, therefore, will be transmitted to the minutest rootlets of the mesenteric veins. Now these vessels are in no way constructed to bear such a strain. They are destitute of valves, their walls are thin, and they have no external support that need in the least be taken account of.

How then is the portal circulation carried on. We have here an organ, large, compact, comparatively solid, through which—through innumerable vessels of capillary minuteness—a large mass of fluid must be made to flow. The resistance from friction in front must be seriously great, and yet mechanical force from behind seems out of the question. It is obvious that no influence of vaso-motor nerves can in the least assist us here. The vessels being a little more or less patent could not do away with the enormous backward pressure. There must therefore be a *vis a fronte.* There must be a force which, for want of a better expression, we may say will suck the circulation onwards. It would be difficult indeed to conceive of any test more crucial than the experiment we find here of nature's own providing, in proof that positive aid is afforded to the circulation by local molecular action in the tissue.

If the structure of the liver becomes so altered that metabolic changes are interfered with, we soon get evidence of obstructed circulation in the effusion of watery fluid into the peritoneal cavity. From simple mechanical tension—from backward pressure—in the vessels the serous part of the blood oozes through the walls, and fluid to the extent of gallons may thus accumulate in the abdomen. Such a fact speaks volumes as to the small capacity of the mesenteric veins to bear any positive strain from backward pressure.

I assume, then, that we have evidence sufficiently cogent and valid to let us maintain that some forces acting at the capillaries have largely to do with the movement of blood through these vessels,—that "the fluids in living bodies are subject to a cause of motion peculiar to the living state, but independent of any impulse, or change of impulse, from living solids."* In the healthy flushing of the tissues, something more is required than slightly to enlarge some convenient sluice. The reaction of the tissue molecules on the blood through the capillary wall is not less important than the force acting from behind.

As to the nature of these forces, or their mode of operation, this belongs to the region of molecular physics, where the imagination must outrun the faculty of perception. Mental pictures—nebulous, perhaps, yet real—may possibly be framed, but their expression will lag far behind, and seem clumsy and inadequate.

* Professor Alison.

While it is usual to think of the tissue as unceasing in its demands for nourishing elements, it would be no less correct to speak of the blood as rushing eager to prey on the tissues. It certainly does not flow passively. It is largely charged with energies which at the capillaries have an opportunity of discharging themselves. The products of decay which it carries off may be regarded as evidence of its prowess. But whether the various agents concerned are to be considered as clashing and warring, and alternately overcoming, or as exerting subtle sympathy and yearning for each other, the immediate result is commotion on each side of the capillary wall. Action and reaction —change and interchange—are vigorous, largely diffused and incessant. Attraction, discharge, repulsion, go on with the rapidity of ether waves in a ray of light. Were this mutual action to cease, attraction of cohesion would assert itself, and the impulse of the heart's action would fail to make the blood pass evenly along the vessels. The lowest view, therefore, which we can take of the local force is, that the points of most active interchange constitute the line of least resistance along which fluids under pressure must of necessity tend to move.

But this cannot be the whole of the assistance rendered to the circulation by the molecular forces,—it cannot explain the free procession of the blood through the portal system of vessels. We must infer the existence of a kind and amount of agitation that can reveal itself in grosser forms of motion. Motion produces motion,—attraction is followed by repulsion, —currents, subtle but energetic, are created, and the result of the infinitely numerous impulses that thus accompany interchange is to produce a positive force which assists, and indeed is a necessary complement to the action of the heart in promoting the capillary circulation. Under its influence the blood may move onwards although the *vis a tergo* has failed; if it ceases, the blood becomes stagnant although the action of the heart may continue strong. Check the blood-current, and the agitation in the tissue molecules—with, of course, the function involved in their activity—is at once suspended or modified; stimulate the molecular movement, and the blood is transmitted with greater energy. The physiology which would ignore—or, indeed, does not largely take account of—this reciprocal action takes a backward step of more than half a century.

Until the physicist can throw more light on the *modus operandi* of these attractions and repulsions, we must be allowed to characterise them as vital. Now, it is more than probable that every change occurring in organised tissue might be resolved into co-ordinated physical and chemical motions. But these motions are so subtle and intermixed that only the grosser results are traceable. The term *vital* is appropriately applied to the intimate process, as including the sum of the

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physical or other motions. Therefore if we may be allowed to speak of "vital change" or "vital energy," then, I submit, it must be quite legitimate to use the language of the older physiologists, and to speak of "vital attractions and repulsions." These are no evidence of a new force being developed. They simply result from an interlaced tangle—not necessarily a tangle that may never be unravelled—of several co-ordinated forces working in harmony to one end.

Some of the physical changes which accompany combustion are sufficiently analogous to afford us an illustration. When combustion in a furnace is languid, the draught of air through it is sluggish, or artificial means may be necessary to sustain it. But if the chemical action be brisk, so also is the current of air. This is drawn with some degree of energy from one direction, and it is more or less rapidly urged onwards in another. Other things being equal, the strength of attraction or the force of the current will be in proportion to the extent and rapidity of the act of combustion. So in nutrition, the greater the amount or rapidity of change in the organic molecules, the more strongly is blood attracted to the part, and the more quickly does it circulate through the capillaries.

V.

THE UNIFORM MASS OF BLOOD WITHIN THE CRANIUM.

THAT the mass of blood within the cranial cavity can be neither diminished nor increased directly, and that the extent to which it can be altered by ordinary physiological causes within short periods of time must be very limited,—such is the thesis I would now wish to submit and defend. At one time its truth was regarded as almost self-evident, but since the publication by the late Sir George Burrows on "The Cerebral Circulation," its soundness has not only been questioned, but physiologists and surgeons seem to agree in regarding it as an exploded and indefensible dogma. I am inclined to think, however, that the doctrine rests on a secure foundation, and that the last word in its defence has not yet been said.

It has long been observed that in cases of decapitation, while the vessels of the scalp and face may have been completely emptied, those within the cranial cavity would be found as full as usual. The latter present no evidence of having been drained of any of their contents, notwithstanding the open condition of all the blood-vessels in the neck. On the other hand, in the case of death by hanging, while the surface veins may be so gorged as to cause great distortion of the features, no impression is made on those within the cranial cavity. These do not appear more congested than they would have done if death had occurred from any other cause. Naturally, some surprise has been expressed at such appearances, and yet the explanation is sufficiently obvious. They are simply the necessary result of the physical qualities of the cranium, and of the relation which its contents hold to the pressure of the atmosphere.

The cavity of the cranium differs from the other great cavities of the body in having its amount of space rigidly fixed. In the chest and abdomen, changes are constantly occurring in the bulk of their contents, and the elastic or pliable walls of these cavities are at once enabled to adapt themselves to every such change. But the firm bony wall of the cranium cannot be altered without physical violence. The bulk of its contents must therefore continue absolutely the same—that is to say within such periods of time as the ordinary growth of the bone does not materially affect its size.

We may conveniently regard the cranial contents to be constituted by (1) the brain substance, (2) the blood, and (3) the cerebro-spinal fluid. The fibrous textures may be left out of view, as a lengthened period would be necessary to affect their bulk.

It is obvious, then, that no change of mass can occur in any one of these contents without at the same moment affecting inversely that of the others. If the amount of blood be augmented while the more solid structures remain unchanged, there must be a decrease in the cerebro-spinal fluid, and *vice versa;* if any two of the contents remain unaltered, the third must also continue unaltered during the same period.

So long, therefore, as the brain substance and the serous, extra-vascular fluid continue unchanged, the absolute volume of blood in the intra-cranial vessels must remain a stable quantity.

In regard to the brain substance, time must be a necessary element in producing any change in its bulk. If some degenerative form of nutrition set in, wasting of nerve tissue may result, and we must then have an increase in one or both of the fluid contents. Evidence may thus be got of extreme congestion, or of serous effusion, or of both. Even during the healthy exercise of function, it has been supposed that the destructive or disintegrating (katabolic) form of nutrition predominates over that of the constructive (anabolic),—that waste of nerve tissue is then more rapid than its repair,—and if such be the case, compensation must be made by the fluid contents being augmented. In all these instances, however, a more or less lengthened period of time is required. Waste and repair are, on the whole, so nicely balanced, that any immediate decrease of bulk in the brain substance cannot possibly occur.

So far, then, as any immediate alteration in the intracranial volume of blood is possible, it must depend on whether rapid variations can take place in the amount of cerebro-spinal fluid. We have, therefore, to consider what are the circumstances likely to affect the behaviour of the latter. Is the nature of its surroundings such that it can readily be made either to increase or diminish in quantity?

The whole upper surface and sides of the brain are in close contact with the dura mater, being only separated from the latter by the vascular meshes of the pia mater. Over the whole extent of that surface there are no spaces for fluid to accumulate to any appreciable extent. The membranes are moist, but there is no collection of water.

The base of the brain, on the other hand, is very uneven. It presents rounded elevations and deep indentations where one part of brain substance overlaps another. The pia mater maintains close contact with the nerve tissue, and dips into every indentation to its furthest depth. The dura mater is less penetrating. It bridges across some of the overlapping parts, and thus spaces—or possible spaces—are left. So closely and economically packed, however, is the brain mass, that in the healthy condition these spaces are very small. With the exception of the "lateral ventricles," one of which is found in each hemisphere, they may easily be overlooked. Wherever the overlapping surfaces are not in close contact, or not occupied by blood-vessels, there we may have cerebro-spinal fluid collected.

No question can exist as to the importance of the function which this fluid subserves. It is complementary to the blood itself in equalising pressure through the cranial cavity. It affords such hydrostatic support as is most likely to prevent jolt or jar to the delicate nervous structures.

In regard to its behaviour, it will be conceded that its movements must be perfectly passive and in accordance with simple physical laws. Its amount at any point will depend on influences outside itself. Thus it may be augmented either by an increase of pressure within the smaller veins, or by these vessels receiving lessened support. The remarkable increase of intra-cranial serum that takes place in cases of death from cold, illustrates the former cause; its increase in senile atrophy of the brain is an example of the other mode. On the other hand, its amount is diminished by such an increase of nerve substance as occurs in hypertrophy of the brain. In some cases of the latter condition, the fluid is said to have been entirely absent.

At present, however, we have nothing to do with the results of pathological change, or of conditions that imply a considerable lapse of time. The question is, Can the cerebro-spinal fluid be immediately affected to an appreciable extent by ordinary healthy action? That it can—that the fluid can with the utmost ease flow backwards and forwards between the cranial cavity and the spinal canal—is the opinion usually held; that it cannot is the view I would very strenuously maintain. Some reasons must therefore be given for rejecting the former alternative.

In the first place, there are the objections which have been already referred to. On the one hand, before the fluid can be squeezed into the spinal canal, something in the latter must make way for it, as the cavity there is already tensely full; and, on the other hand, there is no mechanism within the canal to raise the fluid immediately into the cranial cavity. If the dura mater which sheaths the spinal cord is the tough fibrous membrane it appears to be, it will resist the intrusion of more fluid; if it be a flaccid, yielding membrane, it will not have sufficient elasticity to throw the fluid upwards into the cranial cavity.*

Another objection may, I think, be found in the circumstance that for efficient exercise of function, the hydrostatic support to the brain structures must be perfectly steady. An important function of the fluid is to equalise pressure, but if it can fluctuate readily—if it can be directly squeezed out of the cranial cavity, or be easily got rid of in any way—its power to give the required support would be seriously interfered with.

* The notion that the atmospheric pressure can raise the cerebro-spinal fluid from the vertebral canal into the cranial cavity will be examined in Appendix B.

To perceive the bearing or importance of this argument, we have, for a moment, to consider certain points in the physiology of nerve action.

Whatever opinion may be held as to the nature of nervous energy, the phraseology used when its discharge is spoken of is such as to imply the presence of a certain amount of *stress* in the nerve centre. It is sometimes spoken of as a form of "molecular vibration;" sometimes the term "explosion" is used. Now, vibration cannot occur without *tension,* and explosion implies previous *repression.* The string of a musical instrument will not give a clear tone when it is relaxed; and if the chamber in which a cartridge is exploded is not perfectly rigid, the effect on the bullet is weakened.

If we are at liberty to regard the brain as an instrument which is expected to give immediate and correct response to certain impressions, and that the quality of the response depends on the clearness of the molecular vibration, then a certain amount of tension in the nerve centre will be absolutely necessary. The stored-up energy is to be liberated in a particular direction, and in no other if the motor or mental correlative is to be precise or coherent. In many forms of mental activity, as in that presented by the orator or debater, the musician or the athlete, a severe strain has to be kept up for some time. The orator, for example, has, perhaps for an hour or longer, to keep in view some definite effect he wishes to produce on his audience; he has to keep a firm grasp on a variety of particulars, and to have the perspective of his line of argument kept clear and balanced; and at the same moment his immediate ideas must receive ready and correct expression in words. The musician, who has some complex composition to play, can finger his instrument with a rapidity and precision that to the uninitiated onlooker is simply bewildering. The touch of the engraver's burin must be so exact and delicate that it cannot verge to the fraction of a hair's-breadth to one side or the other of some line. Instances like these, where we have both a mental and a physical strain to be sustained, might be multiplied to any extent. This strain, it is evident, can only be kept up by a corresponding molecular tension or stress on the part of the nerve centre. Now, stress in the nerve centre implies stress in its circulation,—it implies acute erethism, and this involves pressure outwards and equally in every direction. If, then, the energy is to be liberated with ease, and with exactness in regard to amount and direction, support to the structures immediately concerned must be as little yielding as possible. Physical weakness or failure at any point will affect the outcome of activity, just as certainly as that a string will not vibrate efficiently if its attachment be loosened. But if the cerebro-spinal fluid is at liberty to flow and ebb as readily as some writers assert, this steady support would be absent. The brain, in such a case, would resemble an instrument with slackened strings, and refuse to give a clear response to impressions. Ready, or exact or powerful voluntary effort would be seriously interfered with. For here, as everywhere, the discharge of pent-up energy will take place in the direction of least resistance. If there be a pressure outwards on the part of the organ, and if its support can be displaced more readily than some intended result, such as the movement of a limb in a particular direction, can be produced, the movement will not be successfully accomplished. Some of the energy will be wasted in the form of simple mechanical effort on the surroundings, and the result, whether mental or motor, will be less precise than would otherwise be the case.

Again, if there be a constant flow and ebb of fluid between the spinal canal and the base of the brain, how will this be likely to affect the nerves that make their exit from the cranium? The brain is, as it were, anchored to the floor of the latter by twelve pairs of nerves. If it be floated upwards by an ingress of spinal fluid, either the nerves must be lying so loosely that the distance between their origin and the point of their exit can be changed by a change in their position, or their structure must be so elastic that it can be stretched with impunity. Is such an occurrence in the least probable? In regard to the first pair, or olfactory nerves, it is evident that either of these events is impossible. The olfactory bulb lies close to the dura mater, and the nerve threads that proceed from it would inevitably be torn if fluid were to insinuate itself under the brain where they penetrate the ethmoid bone. Without going over all the cranial nerves in succession, it may be sufficient to refer to the optic and pneumogastric nerves, as certain, from the importance and delicate nature of their functions, to resent any attempt at disturbance, either at their origin or at any part of their course.

This leads us, lastly, to refer to the very serious nature of a patient's condition when from any cause the cerebral fluid has been positively augmented. It becomes then a difficult—usually an impossible—task to dislodge it from the cranium. When death has occurred from exposure to cold the principal pathological condition discovered is the presence of fluid at the base of the brain, and it is to the occurrence of this that the great danger arises in such cases. "Whoever sleeps will wake no more," was Dr Solander's well-known note of warning to his weary companions when crossing the ice-clad mountain in Terra-del-Fuego. The effusion results from simple mechanical stress within the venous vessels, and when it has occurred to a certain extent, no amount of warmth or stimulus to the surface of the body will enable the brain to recover its functions. The progress towards a fatal termination is usually steady, and sometimes very rapid.

The conclusion, then, we are forced to adopt is:— While it would be rash, and, in all probability, incorrect, to assert that the absolute mass of intra-cranial blood cannot be altered by physiological means, the extent to which it can be immediately increased or lessened must be so extremely limited, that, practically, it need not be taken account of. Experimental proof to this effect was long ago attempted by Dr Kellie, but as the experiments and opinions of this author have been a fruitful source of controversy, I shall reserve for the Appendix * a full exposition of these, and also an examination of those of Sir George Burrows.

* Appendix A.

VI.

THE RELATION OF THE CRANIAL CONTENTS TO THE PRESSURE OF THE ATMOSPHERE.

A GENERAL knowledge of the facts concerning the pressure of the atmosphere on the surface of the body is sufficiently familiar. Its enormous aggregate amount and the reason why such a weight does not injure the most delicate of organic structures are well known. Bearing with a ratio of nearly fifteen pounds to every square inch of surface, an equal and contrary pressure of the fluids within serves to preserve an equilibrium so nice that no sensible effects need be noticed. But the presence of a great energy is at once shown if the external pressure be removed from any part of the body's surface. The moveable fluids in the neighbourhood are immediately and powerfully directed toward the spot. Of this circumstance the surgeon takes advantage when he produces the once familiar effects of cupping, or drains away hurtful fluid from some cavity by aspiration.

In the animal economy there appears to be no end to the uses to which this form of energy is made subservient. It secures compactness of structure, while it permits the most ready mobility. It aids in forming the dimple of infancy and the wrinkles of age. At the joints it keeps the bones in steady contact and enables them to work smoothly. The mechanism of all the cavities of the body seems specially adapted to take advantage of its influence. As the heart not only contracts, but also dilates with some amount of force, the filling of its cavities after contraction must be simultaneous with their expansion. With the least tendency in the right auricle to dilate a suction force is exerted, and equilibrium of pressure is maintained by the inrush of blood which takes place under the influence of force from without. The auricle would be very helpless if the blood in the vena cava were withdrawn from the influence of the atmospheric pressure. The latter thus becomes an essential auxiliary to the whole circulation. It is also a necessary factor in the movements of respiration. When the diaphragm descends in contraction and tends to form a vacuum in the thorax, it produces the inrush of air into the lungs. When the inspiratory act is over, the natural resilience of the lung comes into play and tends to produce a vacuum in the other direction. The diaphragm is therefore sucked upwards by the contracting lung. But this movement could not take place unless the abdominal walls were pliable. The atmospheric pressure thus not only enables these to adjust themselves to every change of bulk which so frequently occurs in the contents of the intestinal canal, but it also affords positive and necessary support to the weighty abdominal viscera. When the body is in the erect posture, the ligaments by which the liver is attached would prove very inefficient to keep that organ in position if the weight of the atmosphere could bear directly on its upper surface during respiration.

Coming now to the cavity in which the most important organ of the body is lodged, we find the contents of the cranium have a relation to the pressure of the atmosphere very different from what we have found in other regions of the body. Whatever may be the changes going on in its interior, pressure from without cannot directly affect them. The compact, comparatively rigid bony walls of the skull cannot expand and contract like those of the chest and abdomen.

We do not require to consider whether the cranial walls could resist the weight of the atmosphere if a complete vacuum were created within them, nor need we even discuss whether an infinitesimal amount of change may not be accomplished by moderate physical means. The relief afforded in certain forms of headache by tying a handkerchief tightly round the head would seem to show that internal support to the brain may be modified by external pressure. Still, it is very evident that any effect so produced must be extremely small, and that even in the cranium of the infant we have an amount of resistance of which we have no example in any other cavity of the body, except in that of the spine.

That the cranial contents are removed from the direct action of atmospheric pressure is a proposition that may be accepted on the evidence of common sense. By simply taking a comprehensive view of the situation its truth may be proved as convincingly as by any amount of experimental testing. "One of my oldest physiological recollections," says Dr Kellie, "is of this doctrine having been inculcated by my illustrious preceptor in Anatomy, the second Monro—a doctrine which he used to illustrate by exhibiting a hollow glass ball filled with water, and desiring his pupils to remark that not a drop of fluid escaped when inverted with its aperture turned downwards." Of course, if such an experiment were made with a dried skull, all the water would speedily be run off. The air, entering by the optic and other foramina, would very speedily displace the heavier fluid. But let all the precautions which we find in nature be attended to. Let the eye-sockets be plugged with closely fitting, incompressible balls, and let every fissure and foramen be carefully guarded by firm layers of fibrous texture. If the same experiment be now repeated, we may be certain that, just as happens with the glass globe, none of the water will be dislodged by gravitation. Not a drop will be able to escape till something else enters to take its place.

Now, looking at the natural cranial structures, it becomes not less evident that, when the cavity is once filled, nothing short of physical injury can directly affect the bulk of its contents. There does not exist a single inlet by which pressure from above can be brought to bear directly on these. At first sight one might be apt to suppose that transmission of atmospheric pressure might take place through the optic foramen, but closer attention shows this to be simply impossible. Behind the eyeball the foramen is securely plugged. The optic nerve and other textures take up the whole space, and their adhesions would require to be broken before pressure from without could affect deeper structures. It may therefore be assumed that practically all the contents of the cranial cavity are removed from the direct influence of the atmospheric pressure.*

All the more important, however, must be the indirect influence conveyed through means of the circulation. Bearing on the general surface of the body, the atmospheric pressure is, of course, readily communicated through the soft parts, and it will thus be directed to the interior of the skull, through the blood-vessels which enter or make their exit from its cavity. In all the vertebrates, even where a large part of the body is clad in a panoply of rigid plates, we have in the throat such an arrangement of soft textures, that both arteries and veins there can be brought directly under the

* This point will be further discussed in Appendix A.

influence of pressure from without. As any active impulse or passive resistance to which fluids are subjected is communicated equally in all directions, then, by means of the blood, the whole contents of the cranial cavity are brought completely and equally under the potential energy of the atmospheric pressure.

We may assume, without argument, that an equilibrium must at all times be preserved between the pressure on the surface of the body and that within the skull. In any other case the circulation of blood through the latter would be impossible. Equilibrium here implies absolute fulness of the cranial cavity, and this, again, involves the peculiarity, that for any quantity of blood made to enter the cavity through the arteries, an exactly equal amount must at the same moment be discharged from the venous sinuses into the jugular veins.

In attempting to determine with greater detail how the atmospheric pressure can affect the changes which go on in the interior of the cranium, we require to distinguish between its mode of acting on the arterial and on the venous vessels. In the one case it acts in the direction of the circulation, in the other it is opposed to the current; in the one case it may assist the action of the heart, in the other it opposes the return of blood from the head.

At first sight it may be thought that the distinction I wish to make between a pressure on the arteries and on the veins is unnecessary, for, so far as the general circulation to and from the head is concerned, these forces must balance one another. The amount of pressure is the same on both sets of vessels. The cranial cavity being full, and the pressure within the cavity being made to balance that on the surface, the amount of blood making its exit by the jugular veins will depend simply and entirely on the amount that is made to enter the intra-cranial arteries. It will be convenient, therefore, to regard the atmospheric pressure as a constant quantity. It, of course, actually varies, but any variation will affect both systems alike, and thus no disturbance in the encephalic circulation is occasioned by the rise and fall in the barometer.

To see how energy so potent as that of the atmospheric pressure can be converted into a force that shall produce tangible results within the skull, we require to take into account the greater or less activity of certain dynamic forces operating within the skull itself.

I have already insisted on the importance of the tissue molecular forces in sustaining and modifying the capillary circulation. In all parts of the body they are an essential complement to the action of the heart. The constant force directed on the encephalic circulation by their means would tend to keep the vessels of the brain full even although its mass were exposed to the unimpeded weight of the atmosphere on its surface; and in fact it keeps them full when such exposure is partial.

It has been urged that serious disturbance should be expected on removal of part of the skull if it be true that in the natural state of the parts the brain is altogether withdrawn from such exposure. But in making this objection, the existence and energy of the molecular forces have been overlooked, and the fact that these are active in the brain of an infant with an open fontanelle, as well as in the adult with a closed skull. Indeed, when part of the latter has been removed by injury, it is the protrusion of the brain tissue, or the preponderance of the internal pressure, that is probably the more prominent phenomenon, at all events in the waking condition. Instead of collapse, we may have over-distension. As is well known, however, vascular disturbances within the head are more readily produced in the infant, and the direction of the disturbance can often be readily observed on the surface. When there is an actively congestive tendency within, the scalp at the open fontanelle is raised, and may have the appearance of a tense throbbing tumour. On the other hand, in atrophy of the brain, or when there has been a rapid drain on the fluids of the body, as in choleraic diarrhœa, the internal pressure being lessened, the surface sinks at the fontanelle and a depression is formed. Not unfrequently its shape is defined with great sharpness by the scalp falling in abruptly and tightly at the edge of the frontal and parietal bones.

I have already hinted that, in supplying blood to the brain, the action of the heart may be assisted by the atmospheric pressure. When the body is in the erect posture, as it usually is when the brain is most active, and when it is therefore of the greatest consequence that the supply be full and uninterrupted, the influence of gravitation is opposed to the free determination of blood to the head. Considering what a mass of this fluid is sent to the vessels within the skull, it is obvious that were the brain exposed to the unimpeded weight of the air on its surface,—if the cranial wall, for example, were as pliable as that of the abdomen,—serious draining of its vessels would inevitably result on the head being raised. To induce syncope, it would in all probability be sufficient to rise from a recumbent to the erect posture.

In some of the lower animals we see even greater necessity for some means being provided to counteract this untoward tendency of gravitation. For example, if the giraffe be at one moment, with its fore-legs set awkwardly apart, sipping water from a pool, and at the next be licking in with its mobile tongue the leaves from some high branch, there may perhaps be a difference of fifteen or eighteen feet between the two positions of the head. Here the construction of the skull serves not only to prevent the vessels of the brain from becoming too full when the head is low, but also from becoming drained when the head is raised.

But this is not all. The forces acting at the capillaries are, we assume, not simply permissive—they exert positive energy in attracting the blood from one direction and urging it on in another. If such be the case, then, acting in a chamber which excludes all pressure from without, except what can come through the blood-vessels, these forces must exert an active suction power on the blood in the carotids. That is to say, they must tend to form a vacuum behind them, and, to prevent this, the weight of the air transmitted through the soft tissues of the throat will assist, not simply in sustaining, but also in actively directing the necessary amount of blood to the head.

If now we direct attention to the effect of the atmospheric pressure on the blood in the encephalic veins, we find it is opposed to the movement of that fluid. There is here what may be called a *backward* pressure, the tendency of which is to keep the blood within the cranial cavity. As resistance to a moving fluid reacts with energy on the fluid itself, and therefore on the channel through which it flows, that tendency will have effect on the internal surface of the encephalic veins through their whole extent.

The current in the veins of the pia mater, then, is acted on by two opposing forces—the weight of the air from without pressing backwards, the ordinary current of the circulation through the capillaries from within urging onwards. The stress so occasioned must, of course, tend to dilate the vessels themselves. The result will therefore depend on the support these receive on their external surface. If this support be steady and stable, the flow of blood will also be steady and uniform—if the former be of a changing character, the movement of the blood will also be subject to variations.

The required support to the vessels is afforded by the brain mass. Now, this cannot be regarded as a perfectly stable support. We have found that the dynamic forces in its tissues vary greatly in strength, and that according to their activity the pressure of blood within the capillaries is stronger or weaker. If we take the brain when, for example, its function is in active exercise, its circulation is then at its fullest, and the whole organ is most expanded. A certain amount of pressure or support is then directed against the *external* surface of all the veins of the pia mater. Now, what will happen if that external support be lessened? This, of course, must happen when the functional activity, and therefore the dynamic forces acting at the capillaries, shall begin to be relaxed. Evidently the dilating force *within* the vessels must bear with greater effect. A balance must certainly be preserved between the pressure within the cranial cavity and that on the surface of the body if the circulation of the brain is to be maintained. The cranial wall cannot contract to keep up the necessary amount of support on the brain mass, neither can the pia mater leave the inner surface of the dura mater unless some fluid is made to intervene. The most likely result, or rather, I would say, the *necessary* result, will be that the lateral pressure *within* the veins will now bear with greater effect in dilating these vessels. The flow of blood through them will be retarded, and, until a stable equilibrium is again reached, more blood will enter the veins of the pia mater than will be discharged into the jugular veins from the venous sinuses. The brain is thus allowed to become less vascular, while the mass of blood within the cranial cavity continues the same as before. Its mode of distribution alone is altered. A less proportion remains within the arterial and capillary vessels, while an increase is presented in the veins of the pia mater.

As I consider this point one of great importance (its physiological bearing will appear immediately), I may be allowed to state it in another way. In every elementary work on physics, stress is laid on the distinction between potential and actual energy. Now, taking as before the brain when it is active and its circulation is at the fullest, the weight of the atmosphere, tending to keep back the blood within the head, is a form of potential energy. It produces no sensible effect, because it is balanced by the counter-pressure of the brain mass permeated by moving fluid, and so long as this balance is preserved the movement of blood in the veins will be steady and easy. But if the least remission occur in the counter-pressure, an opportunity is afforded for the potential to be converted into actual energy. If the support of the veins in the pia mater becomes weakened, either their walls must be sufficiently rigid to resist the weight of the atmosphere (as may possibly be the case in the tough fibrous venous sinuses), or the vessels themselves must yield to the internal distending pressure. The latter effect, there can be little doubt, is what is actually produced. Then if, from recuperated energy or increased stimulus, the molecular activities of the nerve cells are again roused and the arterial circulation quickened, the brain mass will assume the offensive. It will expand, and in doing so it must compress the veins so that these can retain less blood within them. Thus an ebb and flow may go on, and I believe does go on in the circumstances we will now have to consider.

VII.

THE CAUSATION OF SLEEP.

It is not my intention here to dwell on what may be called the natural history of sleep. The general characteristics of this state are familiar to all, and in the writings of Macnish, Carpenter, Holland, Hammond, and others, these will be found methodically and fully detailed. Neither shall I venture to meddle with its meta-physiology. Whether, as many insist, thinking, though possibly of a nebulous sort, goes on in the soundest sleep; or whether, as physiologists seem inclined to believe, dreaming is an intrusion and indicates imperfect sleep, will not be discussed. Simply accepting the doctrine that an intimate correlation exists between organisation and the manifestations of consciousness, I shall try to determine some of the points in which the sleeping contrasts with the waking brain, and to trace the steps by which the latter gradually merges into the former.

Apart altogether from any knowledge of its intimate physiology, the important function that sleep fulfils in the economy is well understood. It is "tired nature's sweet restorer,' and here the physiologist cannot improve on the poet. Storage of brain energy is its "final cause;" functional rest is its immediate condition; suspended consciousness is its specific characteristic.

During the period of wakefulness the whole world of mind reveals itself to us. The consciousness—that subtlest of all the facts of nature—is then alert, and in its mode it responds to the circumstances of the moment. It may in succession be engrossed by impressions from without, or by efforts of recollection and comparison, of imagination, or reasoning, or voluntary motion. These successive states or acts may be noted—a whole system of mental philosophy may be framed—with scarcely any reference to the brain itself.

In considering the occurrence of sleep, on the other hand, we are at once led to recognise the tyranny and supreme importance of physical conditions. Consciousness, it need hardly be said, conveys us only a very short distance toward a knowledge of its phenomena. These are to be studied, not by self-introspection, but by external observation. Impressions from without are now felt obscurely or not at all. The feeling of drowsiness is a matter of experience, but so soon as sleep has fairly asserted its supremacy, the higher consciousness which recognises and discriminates the realities and relations of existence and succession is for the time lost.

Although, psychologically, sleep thus contrasts with wakefulness as night does to day, physiologically we have in both the same organic instruments to deal with. And any theory of the causation of sleep must be in harmony with the physiology of active function. Only so far as we can speak positively as to details in its working condition can we infer as to the modifications of these involved in its rest. We must, therefore, be able to predicate with sufficient certainty some facts in regard to the behaviour of the brain elements and forces during wakefulness, and then our problem will be to determine in what respect that behaviour is modified in the production and continuance of sleep. It is evident that some inhibitory influence is at work in the brain. The rest of the latter is enforced; some mechanism "acts with power, putting the brain into compulsory abeyance, and depriving the subsidiary organs of their sense." * The question, therefore, now comes: how far can this inhibitory mechanism be traced?

Some physiologists have expressed themselves very strongly to the effect that the subject is one beyond the scope of physiological enquiry. Thus, Sir Benjamin Brodie, in answer to the question "What is sleep in itself?" or "What is the condition of the nervous system on which it immediately depends?" replies that it "certainly cannot be answered." "It is plain," he adds, "that in some respects the condition of the nervous system must be different during sleep from what it is when we are awake; but it seems impossible we

* Moore, "On going to Sleep."

should know in what that difference consists, when we consider that neither our unassisted vision, nor the microscope, nor chemical analysis, nor any analogy, nor any other means at our disposal, enable us to form any kind of notion as to the actual changes in the brain or spinal cord on which any other nervous phenomena depend." *

Now I shall have nothing to say as to the "actual changes" that occur in the brain tissue either in the waking or the sleeping conditions. Even were these all intimately known we would still have to be silent as to the mode in which their energy is transmuted into any conscious state. But if we can gain sufficiently precise knowledge of the conditions in which alone these changes occur and by which they can be modified, it becomes legitimate to discuss the causation of any phenomenon associated either with the organ's activity or repose. It will only be by looking for such conditions we will now attempt to unravel some part of the mechanism by which functional rest is secured to the brain.

I have already hinted as to certain respects in which the brain during sleep must contrast with its working condition. At the risk of some repetition of detail, I have now to state my argument consecutively.

The physiological changes which accompany the flow and ebb of consciousness constitute a circle, in tracing which any point may be studied as a *terminus a quo* or

* "Psychological Inquiries," pp. 131, 132.

as a *terminus ad quem.* At each and every stage—whether the consciousness be latent or alert—the molecular motions, the blood currents, and the intra-cranial pressure or tension are all correlated to one another and to the state of the mental functions. Simply as a matter of convenience, therefore, we will here begin with the stage of first awaking from sleep.

In the eye of science, scarcely any change can be said to be more wonderful than another. The magnitude or unexpectedness of results may in some cases be more impressive than in others, but everywhere the mystery of immediate causation remains equally inscrutable. Yet, if the feeling of wonder be permitted in any case, it may well be indulged in when contemplating the change from sleep to wakefulness. The world of consciousness is quickened anew; order and light and intelligence take the place of chaos; the reason and will, from being spell-bound, become potent for infinite good or infinite mischief.

To this immense psychical change the brain is most intimately correlated. Its special function as a part of the animal economy is called into active exercise; its structures are raised to a state of high tension; and they are ready to respond to stimuli from without or from within.

I assume that in bringing about this state of activity, the molecular motions in the brain tissue are almost infinitely quickened, but I have nothing to say as to the exact nature of the chemical and other physical changes involved. My argument would not be in the least affected were the biologist able to specify these in minute and accurate detail. I shall restrict attention to certain broad conditions involved,—to the manner in which these may be modified by varying circumstances, and how in their turn they may modify the action of the brain.

One of the most absolute of the conditions of brain activity is the circulation of healthy blood. I need not here again discuss the dependent, or, at least, very sensitive, relation of the capillary circulation to metabolic changes. From the biological point of view, the molecular movement in the brain tissue and the movement of blood in the capillaries cannot be separated. Anatomically, such separation is difficult; physiologically, it is impossible. As an organ which stores up, transmutes, and liberates energy, the brain is as much dependent on its supply of blood as the burning fuel is dependent on a current of air; and, again, the flow of blood in the capillaries depends as much on activity in the molecules as the draught of air through a furnace depends on the act of combustion.

The more immediate result of the combined molecular and vascular commotion is an increase in the bulk of the brain; a second result is an increase of stress through the whole cranial cavity. The flushing of the capillaries with rapidly moving blood is the cause of the first; the tendency of the expansion to go beyond the limited space of the cranial cavity is the cause of the second.

That there is a decided tendency to expansion of the brain itself during activity may be regarded as a matter of fact. When the organ has been so exposed from injury that its behaviour can be observed, it has always been noticed that while during sleep it tends to sink or to retire from the inner surface of the skull, in wakefulness it is seen to expand. It not only fills the whole cranial cavity, but part of its substance may protrude beyond an aperture in the bone. Evidently, some forces are at work in the latter state which are quiescent or less powerful in the former, and their tendency is to make the brain increase in bulk. If its rigid envelopes were suddenly to give way when, for example, severe muscular efforts are being made, the momentum of the blood would cause further distension of the vessels; these in a moment would become more tensely filled, and the organ would instantly expand beyond the bulk it could possibly occupy while its encasing walls were entire.

For a number of hours—the time varying according to habit and other circumstances—the molecular forces keep in full play, and the natural correlative is some psychical or motor change. Fleeting impressions from without register themselves faintly or more sharply, according to their intensity or the attention they receive; teeming fancies within chase one another with aimless chance-directed procession, or disciplined thought steers steadily onwards to some destined goal; or movements of the body, overcoming resistance and doing work, give evidence to outsiders that a powerful energy is being liberated.

After a time, a law, potent in physics as well as in physiology, comes into play. Energy cannot be liberated without immediate loss to the instrument, and unless the loss is made up, failure of function must sooner or later ensue. Of the operation of this law the brain presents us with a notable illustration.

In animal structures, capacity for function depends on a certain standard of composition being maintained. The process of nutrition by which this standard is kept up involves unceasing change, but by a delicate balance of operations, the same composition is preserved to the texture. In the higher organs, a distinction is to be made between the nutrition—or, rather, metabolism—of active function and that of rest. In the brain the process goes on with a regular ebb and flow. During its rest the action is recuperative, energy is stored up, adjustment is improved. The molecular structure becomes more sensitively disposed to respond to stimuli, and the attraction of its elements for the oxygen of the blood is more powerful.

In the active discharge of function the process is modified. The metabolic changes are not simply more rapid; the mode too is altered. The disintegrating—

katabolic—part of the process so predominates that repair for the time fails to compensate for the waste, and thus the nice adjustment on which functional capacity depends is disturbed. As this goes on, a positive change of composition or of constitution results. It may not be so gross that the microscope could detect it, but lessened capacity for the exercise of function gives us a sufficiently crucial test. The structure, as a whole, responds less readily or less accurately to its accustomed stimuli. The cell elements become so disposed that liberation of active force becomes less easy; they have less powerful attraction for the oxygen of the blood, and the infinitely subtle vibrations of the molecules begin to play with less energy. This lessened molecular activity is the first stage in the series of changes which culminates in the production of sleep.

The next link in the chain of causation, and one which springs naturally and inevitably from the first, is a modified circulation in the capillaries of the brain. Here, as in other parts of the body, nutrition or metabolic change and the circulation act and react energetically on one another. In a texture of such delicate organisation, functional capacity cannot be maintained without fresh currents of blood, and without the subtle attractions between the latter and the tissue molecules, the currents of blood cannot be kept up. When rapid katabolic change or combustion is going on, the movement of the blood is only remotely dependent on the heart's action. That fluid then flushes the capillaries with an actively dilating influence, the vessels become tensely full, and the immediate result is a positive increase of volume in the organ. But if the activity among the molecules subsides, the circulation becomes quieter. Its excitement stood in the relation of effect to the other excitement as cause, and as the latter subsides so must the other. With the abatement of the actively distending force, the capillaries will become more readily emptied of blood, either by the natural elasticity of their walls, assisted, it may be, by the operation of ganglionic nerves, or by pressure applied externally from any direction.

In discussing the physiology of almost any other organ in the body there would be little to add to such a statement. With activity of function—for example, in a secreting surface—the circulation is quickened; with quiescence of function the vascularity subsides.

In regard to the brain, however, some peculiarities have to be noticed. It occupies a close, rigid cavity which of necessity must be constantly full. It cannot, therefore, recede from the inner surface of the cranial wall (which, of course, it must do if it is to diminish in bulk) without some other material taking its place. We may be certain that "nature's horror of a vacuum" is here absolute. If the vascularity of the brain, then, is to be lessened, there must be a special mechanism by which that end is to be secured.

Such a mechanism will, I believe, be found in the arrangement and relations of the veins of the pia mater. These vessels constitute, as it were, a reservoir, ready, on the one hand, to accommodate superfluous blood, and, on the other, to afford space by yielding it up again. The mode by which either result may be gained can, I think, be readily traced.

There is at all times a special stress on the blood within the veins of the pia mater—it is subjected to pressure from various directions. In the first place, there is the forward pressure of more blood from the vessels of the brain—the combined cardiac and capillary forces urge it onwards from behind.

There is, secondly, the passive resistance occasioned by the weight of the atmosphere which tends to keep the blood within the cranial cavity. Acting on a moving fluid it produces a backward pressure.

Thirdly, there is the pressure on the external surface of the veins caused by the brain mass itself. The capillaries of the latter being flushed with briskly moving blood, the whole organ expands outwards, and thus the veins, which lie completely outside the brain itself, are pressed against the dura mater.

The first and second of these forms of pressure will tend to fill or dilate the veins; the third will tend to compress or obliterate them. Here, therefore, we have a simple problem in the composition of forces.

We conveniently regard the atmospheric pressure as a constant quantity. Let the individual be awake or asleep, in the erect posture or recumbent, its influence is unceasing and practically uniform. The other two forces vary greatly in their intensity, and on them therefore the result will more immediately depend.

If we take the encephalic circulation at any moment, we find that a certain balance exists, and the movement of blood goes on smoothly. This steady movement will continue so long as all the factors remain unchanged. The backward pressure of the atmosphere will produce no sensible effect so long as it is balanced by the support afforded to the vessels of the pia mater by the solid brain structures.

But what will happen if the molecular and capillary forces become relaxed, and thus the support given to the veins be weakened? Evidently, the balance of active pressure will now be altered. The brain mass will not bear upwards or outwards with the previous amount of force. The backward pressure, therefore, will now act with greater effect. The immediate result must be that the movement of blood in the veins will be retarded, and the vessels themselves become distended. This distension will go on until the opposing brain resistance can again balance the pressure on its surface. This will occur when the more simply conservative form of nutrition prevents the capillaries from being further drained.

The mode in which this altered circulation occurs may be expressed in another way. If the brain tends to retire from the inner surface of the skull (and that it does so is the unanimous testimony of all who have observed its behaviour through an opening in the bone), it must exert a certain amount of suction force. Now, on what can suction effort here bear with any effect? Evidently the cranial wall will resist it. The rigid bone cannot follow the retiring brain mass. As evidently, it cannot be exerted on the cerebro-spinal fluid within the vertebral canal, for this is removed from the direct action of the atmospheric pressure. The only fluid or tissue which can be immediately affected by such suction is the blood in the veins, and it will act by retarding the flow of blood through these vessels. The result must be that *a new balance of the encephalic circulation will be established—less blood will circulate in the arterial and capillary vessels of the brain, and to an exactly corresponding extent more must be held by the veins.* To any one who will be at pains to take a survey of all the various conditions and relations involved, the occurrence of such a change must, I think, present itself as a *physical necessity.*

Assuming, then, that the balance of the intra-cranial circulation has become altered, what is its physiological significance?

Before answering this question we will, for a moment, turn to a pathological condition presented in certain affections of the brain. A study of this may possibly give us a clue to the direction in which to look for a satisfactory answer.

The condition to which I refer is that of coma. This, in all its varieties, is characterised by a more or less deep state of unconsciousness. It differs from sleep in the circumstance that ordinary means are insufficient to bring back a state of alert wakefulness. The psychical phenomena are those of sleep in an exaggerated degree. The breathing goes on, and in many cases is tranquil; the circulation may not appear in the least affected; but sensation, intellect, and voluntary motion are so completely suspended that the patient cannot be roused to consciousness.

The important point in regard to coma to which I wish at present to give prominence is the fact that in many cases its production is traceable to a particular alteration in the condition of the brain. Its symptoms may be produced by whatever may cause pressure to be directed on the surface of the brain. I do not need to enquire whether such pressure can be proved to exist in all cases of coma; a poisoned state of the blood is not unfrequently the primary cause. For my present purpose it is sufficient that, in pathology, the experience of both physician and surgeon gives ample evidence of the efficiency of pressure on the brain to keep all evidence of mental activity in abeyance. If a portion of bone be depressed in fracture of the skull, if a clot of blood or a layer of serous fluid be thrown out on the surface of the nervous structure, the immediate effect is deep and more or less protracted insensibility. It has long been known that if a part of the skull has been removed, and if the brain otherwise be healthy, consciousness can be taken away at pleasure by pressing on the brain surface with the finger. "Many cases of this kind are on record, one particularly by Haller, of a man who exhibited himself in Paris for money." * "It is certain," says Sir Henry Holland, "that the states of sleep and coma frequently graduate into each other in such a way as to show that the proximate physical conditions are nearly the same in both. Either name may be given to the state produced by moderate pressure on the brain when a portion of the cranium is removed. In a remarkable example of this kind which I saw in one of the English military hospitals at Santarem, when travelling in Portugal in 1812, there was cause from observation to infer that the patient went through every grade between these conditions, in proportion to the degree of pressure applied." †

Here then we have got one point in which a direct relationship can be proved to exist between a particular condition of the brain and the occurrence of unconsciousness. Doubtless, the coma produced by a clot of blood differs widely from ordinary sleep. But for the purpose of illustration or analogy it is not identity of condition

* "Edinburgh Medical and Surgical Journal," November 1818.
† "Chapters on Mental Physiology," p. 104.

we are to look for. In both cases we have one symptom —loss of consciousness—common to both. In one of them a cause is traceable. We cannot be more certain that a scale with a weight on it will be depressed if not balanced by an equal weight in the other, than we may be sure that no brain can continue an efficient organ of mind if its surface be subjected to a certain amount of pressure. The simple question therefore is: Can such a fact give us a clue to the direction in which to look for a possible explanation of loss of consciousness in ordinary sleep? This brings us back to a consideration of the physiological meaning of the modified circulation which we have found must, sooner or later, occur in the brain.

The altered balance of the circulation will interfere with the action of the brain in at least two ways: 1st, by the capillaries being drained to an extent with which activity of function is incompatible; and 2nd, by the brain itself being compressed. Both modes of inhibition are, I believe, necessary in the production of healthy sleep.

If it can be proved that an anæmic condition of the brain is present during sleep, it might at first sight be supposed that in such a state alone we have a sufficient explanation of the occurrence of unconsciousness. We can readily suppose nutrition—metabolic change—to be so far depressed, and the circulation therefore so reduced, as to render the organ unfit for duty, and many writers seem to be content with such a limited kind of explanation. Yet, it may be shown that it fails to cover all the facts of the case, and that it is inadequate as a theory of sleep.

From one point of view, the brain is a very composite organ. It contains centres for receiving impressions from the various organs of sense; it has centres for originating muscular movements; it provides the physical substratum required for the exercise of memory and the various mental faculties. Then, as the mental centre is constantly changing, we cannot for a moment suppose that all parts of the brain mass are at all times equally active. With every change in the mode of consciousness, some corresponding change must take place in the more immediately energising sphere of activity. When an individual is engrossed by some striking feature in the landscape, or in listening to music, his brain is differently affected than if he were engaged in solving a mathematical problem or in performing some gymnastic feat. In each case there is concentration of mental action, but we may be certain that the sphere more immediately concerned in liberating the necessary nervous energy is in every case different.

On the other hand, the brain may also be studied as a unit. From similarity and intimate union of structure and from acting under like physical conditions, there is such subtle sympathy and co-operation among different parts of its mass, that it is impossible to give a precise boundary to the part engaged in any particular operation. In ministering to a rapid succession of states or actions, therefore, we must regard the brain as a whole. As a whole it is active in wakefulness, when all its structures are raised to a state of tension and vascular erethism. Every part is then ready to respond to its appropriate stimulus, and to take on itself its own special duty. As a unit, too, it must go to rest in sleep. Whether it has been fatigued by purely mental work, or in exercising the muscles, or whether there may be simply a want of sufficient stimulus and interest, the ultimate physiological effect is the same,—the organ as a whole must be made to rest.

Now, this result would be less perfect if the occurrence of sleep depended on a diminished circulation alone. I, of course, assume that the molecular and vascular activities correlate and mutually condition one another, not only through the brain as a whole, but also wherever any ganglionic structure may exercise a localised function. Then, regarding the brain as a composite organ, we find that in many cases the immediately liberating sphere of activity may for a considerable time be comparatively limited. Thus the pedestrian may, for some hours in succession, plod along the road and be guiltless of anything like consecutive thinking; or the mathematician may for the same period be engrossed by figures and symbols, and have the minimum of muscular exercise. Each has earned his rest, and to both sleep may be equally sound and refreshing, but in each case the activity of a large part of the brain has been kept comparatively in abeyance. Yet this too must be put to rest during sleep. Our lives otherwise would be a constant dream. Activity would oscillate from one part of the brain to another, and the power of the will to concentrate itself for any length of time would be seriously interfered with.

To ensure rest to the whole brain, then, some factor in addition to diminished circulation is necessary, and that we have in the compression of the whole organ by hydrodynamic agency.

As an unsympathetic touch is sufficient to check the vibrations of a bell or glass and abruptly put a stop to the musical tone, so when the grey layer of the brain is subjected to pressure from without, the infinitely subtle vibrations or molecular motions in its tissue are checked. As the special function of the brain depended on these, that ceases to be exercised; the cerebrum fails to be the medium through which mental phenomena can be presented; sensation, thought, and voluntary motion are suspended; in a word, sleep is induced.

This pressure is no new force improvised for a special purpose. Through the whole series of vertebrate animals, a pressure, not simply passive like that of the cranial wall, but caused by moving fluid and therefore active in its nature, is unceasingly exerted on the brain's surface. It keeps the organ compact, and assists in intensifying the energy which is liberated. In the production of sleep, however, it overcomes for a time certain antagonistic forces. The stress or tension in the brain itself has become relaxed, the expansive force of its circulation has become weakened, and thus in the way repeatedly pointed out, the distending force within the veins bears with greater effect.

Perhaps I may be allowed to express what happens in a more fanciful manner. The membrane called the *pia mater* could not have been more appropriately named. Tender as a means of protection, it is rich and generous as a source of nourishment. In wakefulness it encourages and sympathises with every display of congenial energy in its charge; during sleep it is still the Pia Mater, soothing to rest by a closer embrace.

In the causation of sleep, then, we have not one or two, but a combination and succession of conditions inseparably linked together. The first change is a modified—a less energetic—movement in the molecules of the brain tissue; the last is compression of the whole organ. From lessened activity of the molecules spring a less active state of the capillary circulation and diminished stress through the cranial cavity. Next, we have a change in the balance of the encephalic circulation, in producing which the weight of the atmosphere, causing backward pressure in the cerebral veins, is an essential agent. The circulation in the brain itself is diminished; its vessels become comparatively empty, and to a corresponding extent the proportion of blood in the veins is increased. With the altered balance of the circulation there is a change in the balance of active pressure; it is less from within and more on the surface; it is less expansive and more compressing. With a certain amount of compression consciousness is suspended.

Such, then, is the hypothesis I would submit as to the causation of sleep. It remains to be seen whether a sufficient amount of confirmatory evidence can be got to enable us to raise it to the dignity of a theory. Does it fulfil all the conditions that should reasonably be expected in speculating on such a subject?

The occurrence of a change in the balance of the encephalic circulation may be regarded as the central point in the theory. Some modified molecular action is, of course, the primary cause of sleep and the foundation to build upon, but the altered balance of the circulation is the keystone which gives unity and stability to the superstructure. If this part of the theory fails, the whole must fall. We have therefore to consider whether any further evidence can be advanced in its support.

In the first place, then, let us consider how the brain circulation is likely to he affected when a state of unconsciousness is brought on abruptly, as in syncope or asphyxia.

If the arterial supply to the brain is at once and completely cut off, as in sudden decapitation, what must happen? Not necessarily that the circulation through the brain itself must cease too in a moment. The blood is moving with considerable momentum, and, as takes place in the general circulation after death, the capillary forces can draw onwards whatever remains in the arterial vessels. But *not a drop can be expelled from the head.* Here, then, there can be no doubt as to how the blood would at last be distributed. It can only be transmitted into the veins, and there it must remain.

If the supply of blood be simply diminished—if less is sent to the brain than is consistent with its activity—a similar altered balance will occur, although, of course, not so abruptly nor so completely.

There is no more certain or speedy means of producing the appearances of sleep than compression of the internal carotids. "It is sometimes difficult to catch the vessels accurately, but once fairly under the fingers, the effect is immediate and decided. There is felt a soft humming in the ears, a sense of tingling steals over the body, and in a few seconds complete unconsciousness and insensibility supervene, and continue so long as the pressure is maintained. On its removal there is confusion of thought, with return of the tingling sensation, and in a few seconds consciousness is restored." *

In an instance like this, or where syncope occurs

* Fleming, "British and Foreign Medical Chirurgical Review," April 1855. See Appendix F.

from hemorrhage or from failure of the heart's action, the mechanism of the disturbance of the intra-cranial circulation may again be readily traced. With a failure in the supply of blood the pressure within the arteries is at once weakened. But the stress through the whole cranial cavity must be kept equalised, and active pressure will have greatest effect in the direction of least resistance. Therefore if the outward distending impulse in the arteries fails, that in the veins must at once assert supremacy. At the moment of failure the capillaries were filled with a certain volume of blood, but this they cannot longer retain. As not more blood can leave the intra-cranial veins than is simultaneously being admitted by the arteries, *more blood will be transmitted into the former than will be discharged from them.* They will thus become speedily distended, and reacting on the brain, they will give a check to those molecular changes on which the liberation of nervous energy depends.

In the insensibility that results from asphyxia, the sequence of change differs from that of ordinary sleep in the circumstance that the first step is an altered state of the blood, rather than a change in the molecules of the structure. The union of oxygen with the elements of the tissue is among the most absolute of all the conditions for the liberation of nervous energy. If carbonic acid, therefore, accumulates in the blood, or if oxygen is replaced by some subtle agent like chloroform, the interchange or attraction between the blood and the tissue is suspended or is less active. From this point the sequence of physiological change is the same as in ordinary sleep. With less active interchange the capillary circulation becomes languid, and it therefore presents a less potent resistance to the tendency which the atmospheric pressure has to retard that in the veins, and to cause these vessels to become distended.

Important evidence in favour of an altered balance of the circulation being present during sleep is afforded by the revelations of the ophthalmoscope. The veins of the retina belong to the same system of vessels as those of the brain. They empty into the cavernous sinus, and are thus subject to the same conditions of atmospheric pressure. If the circulation of the retina, therefore, presents marked and constant differences in the waking and in the sleeping states, we may with some probability infer as to the condition of the intra-cranial circulation itself during these states.

Most interesting observations have been made on this point by Dr Hughlings Jackson.* He made examinations of the retina during sleep, on three occasions in one case, and on other three occasions in a second case. The results of these examinations (which I have numbered in the order in which they were made) were as follows:—

(1.) "I found the optic disc itself whiter, the arteries a little smaller, and the veins large. The veins were

* "Medical Times and Gazette," December 6, 1862.

thick and almost plum coloured. The neighbourhood of the retina was also more anæmic."

(2.) "The arteries are certainly smaller and the veins larger. The other parts of the optic disc are whiter, and the neighbouring part of the fundus is whiter."

(3.) "The optic disc was not so red, the arteries were certainly smaller, and on this occasion, I think, the veins were no larger, and about the same as during the day."

(4.) "All I can say is that the disc was rather paler in sleep."

(5.) "I feel convinced that the arteries are a little smaller, and the veins larger."

(6.) "The disc was whiter and the arteries smaller."

It will be noticed that in every instance the retina was found to have its capillary circulation diminished, and in only one case does the author hesitate to say that the veins were not fuller than in the waking state. If these observations do not amount to a demonstration as to the state of the whole encephalic circulation during sleep, they are surely as near an approach to it as any experimental testing is likely to show.

In the details of a state of trance, where the unconsciousness was profound and protracted, the following is the description of the condition of the retina as given by Dr Jamieson:—"There was a marked contrast in size between the retinal veins and arteries. Compared with their appearance after the attack had quite passed away, the veins were larger and the arteries smaller, and at the time this was especially distinct, the veins standing out boldly against the white background afforded by the disc and orange-coloured choroid, while the arteries were fine and hair-like." *

In a case of "Abnormal disposition to sleep," published by Professor Gairdner,† it was found that "the retinal veins were congested and rather tortuous; the arteries diminished in calibre, and barely visible."

A case of poisoning by the fumes of charcoal has been reported by Dr J. Hawtrey Benson.‡ The patient was "deeply comatose;" and here "the ophthalmoscope shewed extreme congestion of the venous, and emptiness of the arterial, system of the fundus of the eye."

The following case occurred in the Edinburgh City Parish Workhouse, in my own practice, a few years ago. Its history is from the notes of Dr Charu Chandra Bose, who was at the time Resident Medical Officer. "I. H., age 18, servant, was admitted to the hospital at Craiglockhart, for erysipelas of face and head. From this she made a good recovery, but has remained in the hospital on account of epileptic fits, to which she had been subject for some months previously. When at service she received a blow on the forehead. This was followed shortly afterwards by attacks of *petit mal*, on account of which she had to leave her situation. Pre-

* "Edinburgh Medical Journal," July 1871.
† "British Medical Journal," October 30, 1875.
‡ Ibid., July 5, 1873.

viously of cheerful disposition and active habits, she now became absent-minded, and for hours would sit looking at a book or paper in her hand, but without reading a word. Nine months after receiving the blow she got another shock on seeing her niece knocked down and run over by a cab. Since then she has been subject to epileptic seizures. Before the fit an *aura epileptica* begins near the umbilicus. She describes it as a cold, tingling sensation, which creeps upwards to the head, and then she becomes unconscious. The convulsion is almost restricted to the right side of the body. After it has passed off, and the breathing and the circulation have become quiet, a state of deep unconsciousness is left, and sometimes lasts a whole day. From this state no noise will rouse her. On being shaken, or pinched, or pricked, or if the strongest ammonia is held to the nostril, not the slightest evidence of sensibility is given.

"At Dr Cappie's suggestion, Dr Bose made an ophthalmoscopic examination of the eye when she was well and awake, in order, at the earliest opportunity, to contrast its appearance with that of the comatose condition. Fig. 1 (*frontispiece*) gives the appearance of the retinal circulation then observed.

"On 6th September she had a fit, followed by the usual condition of coma. Advantage was then taken to examine the fundus of the eye, the pupil having been previously dilated by atropine. Fig. 2 correctly represents the appearance of the retinal circulation now presented, and contrasts strikingly with that of the waking state. The whole disc is paler, the arteries are smaller, indeed sometimes scarcely visible, the veins are larger, more tortuous, and apparently distended to their full."

In injuries of the skull involving exposure of the brain, there is seldom an opportunity for examining the circulation through the pia mater. Either the dura mater is entire, or, if it be ruptured, the pia mater also, as well as some of the brain texture, is usually torn. In the following case, however, reported by Dr Kennedy, the pia mater was exposed and entire. The observations made on its circulation give important evidence confirmatory of the views I have been advancing.

"It was briefly as follows:—A man of middle age, whilst drunk, had his skull severely burnt at a lime-kiln, where he had fallen asleep. In a short time very urgent symptoms of pressure appeared, and he was trephined over the centre of the parietal bone. Subsequently, the opening was enlarged in one direction, and the result of the whole was to cause an opening of considerable size, and in shape like a comet. The brain was quite exposed, the dura mater having been removed to allow free vent to the pus. Whilst in this state I had the dressing of the case for several weeks, and plenty of opportunities for seeing the patient both asleep and awake, and I never saw him asleep that I did not observe marked congestion of the vessels, more particularly what seemed to be the veins, whilst all the vessels visible assumed a dark hue, and when the patient awoke, it was very interesting to observe, first an increase in the rapidity of the circulation, and then a change in the colour of the blood, and it sometimes seemed as if even new vessels, or at least some not seen before, had made their appearance." *

No theory of sleep can be accepted which does not allow for infinitesimal gradation in its production and amount, or which does not afford a ready means for restoring consciousness. "It is important," says Sir Henry Holland, "in all our reasonings, practical and theoretical, upon sleep, to keep in mind that it is not a unity of state with which we are dealing, but a series of fluctuating conditions, of which no two minutes are strictly alike."

Now, according to my theory the degree of compressing force is strictly correlated to the molecular motions. These still constitute the supreme conditioning factor. The pressure, therefore, is permissive and mild, or it is imperative and irresistible, according to circumstances. Usually, if there be a strong stimulus from without, or if the adjustment of the molecules be improved, or their storage of energy naturally completed, the circulation is readily stimulated, tension is raised, the

* "Dublin Journal of Medical Science," June 1877.

surface pressure is overcome, and all the conditions of active function are restored with ease. On the other hand, if exertion has been long continued and exhaustion be great, the brain may with difficulty respond to ordinary stimuli, the breathing may be loudly stertorous, and the condition may approach that of coma.

In dreaming, the special molecular agitation which conditions consciousness is not entirely suspended, but the lines of vibration are contracted. The sphere of activity is localised, and the mental correlative is correspondingly narrow. The avenues of immediate perception are closed, but chinks in the storehouse of memory present themselves, and through these stream flickering pencils of light, which revive objects and actions in the mental camera, but combined in unheard-of association. The long past is mixed up with the present, and locality, objects, and actions change without any respect for the claims of physical possibility. Consciousness is helplessly passive. The immediate picture or idea engrosses and leads captive whatever mental energy is excited.

Dreaming is most likely to occur in one's early sleep, when the nervous tremors have not completely quieted down, or at the period when waking is about to take place. In the latter case it might naturally be expected that as the storage of energy becomes completed, molecular agitation will tend to establish itself. Impressions not sufficiently strong to rouse consciousness to alertness, yet set masses of grey matter vibrating; and in proportion as the lines of vibration are shortened, or are extended and free, is the dream likely to be fantastic or more coherent.

Another point which requires to be considered, and with the facts of which a theory of sleep must be consistent, is the facility or rapidity with which at times consciousness can be lost and regained. Every one has had experience of more or less complete unconsciousness alternating within short periods with waking. "I have frequently," says Sir Henry Holland, "when in a carriage, obtained proof that this alternation of loss and recovery of waking consciousness must have occurred three times within a minute by knowing the distance gone over while the observation was made."

The following is an experience with which the medical practitioner (at all events the accoucheur) is not unfamiliar. Having been disturbed perhaps several nights in succession, he is again called to the bed-side of a patient in labour, and he finds he must wait for some time. The feeling of drowsiness soon becomes strong, and the talk of the gossips does not prevent him from falling asleep while sitting on his chair. But with the slightest expression of suffering from his patient he is at once awake. He becomes quite alert, and can take a full survey of all the possible contingencies of his case. He may speak a word of encouragement to his patient, and then, when quietness has been restored, he again allows himself to yield to the drowsy feeling, and before half a minute he is sound asleep. This alternation may occur repeatedly within an hour.

In such cases, the mechanism of sleep as I have endeavoured to unravel it is perfectly consistent. It can allow the whole series of physiological conditions to be changed *at once.* The first effect of a stimulus to the sleeping brain is to cause vibration through the nervous centre, but no vibration of any physiological consequence can occur without the capillary circulation participating. And, within the skull, increased capillary and diminished venous circulation must be simultaneous. With an increase of the expansive force, that of compression is of necessity diminished. Then, of course, with the molecular and capillary forces in free action, we have the working capacity of the brain itself restored.

On the other hand, if we are to suppose, with some writers, that during sleep the diminished cerebral circulation is compensated by an increase of cerebro-spinal fluid, the mechanism by which it can be immediately thrown out or absorbed has yet to be pointed out. Sleep sometimes comes on abruptly,* and waking especially

* "The Indians have a wonderful faculty of going to sleep. They seem to shut themselves up at will, with a snap like slamming down the lid of a box with a spring, and are fast asleep in a second ; and there they will lie, snoring and shivering with cold, until you touch or call them, and then they are wide awake in an instant, as if they pressed some knob concealed in their internal mechanism, and flew suddenly open again." Earl of Dunraven, "Nineteenth Century," April 1880.

may appear to be instantaneous. But whether the fluid be in ventricular spaces or perivascular canals, its absorption or effusion must be the work of time. To the pathologist its presence, beyond a very limited quantity, is considered a very ominous condition.

Of the serious character of watery effusion within the cranium, even when there is no trace of inflammatory action, we have evidence in the stupor occasioned by intense cold. Here we have a mechanical cause interfering with the return of blood from the brain. The atmospheric pressure is intensified by the constringent effect of the cold. This drives the blood from the surface, and causes congestion of the internal organs. The blood in the encephalic veins is subjected to additional stress, and these vessels must become engorged to their full extent. So great is the strain on their walls that effusion of serous fluid occurs. No other pathological appearance is present. This condition, however, is not sleep. It is coma; and the result is not refreshing rest, but imminent danger to life.

VIII.

SOME POINTS IN MENTAL PHYSIOLOGY.

In considering the phenomena and physiological conditions of sleep, we had occasion to regard the brain as a unit; we will now be led to look at it as a cluster of organs. A consideration of the great variety of function which it subserves may convince us that there must be no inconsiderable division of labour in different parts of its mass. It has something to do with all the phenomena of conscious life. Its more or less receptive and responsive condition is an essential factor in all the forms of mental activity. It is the centre towards which an infinite variety of impressions are directed, and where they are interpreted and registered. The subtle agitation of its molecules ministers to the still subtler faculty of intelligence in all its various modes of feeling, judging, and acting.

For the purpose of our present essay it is, fortunately, not essential we should be able to indicate with precision the function to which individual portions of the brain are subservient. The system by which the phrenologist tried to give definite boundaries to the seat of various mental faculties has become seriously discredited. Where "veneration," "firmness," "conscientiousness," were supposed to exercise their stimulating or inhibitory functions, the physiologist now places a cluster of motor centres. Nevertheless, the fundamental ideas of subdivision of labour, and of capacity in proportion to the more or less favourable conditions afforded by texture, mass, and surroundings, will hold their ground. A motor centre will not discriminate the hues of the landscape, nor will a sensory centre decide as to the justice or iniquity of particular acts or feelings. When the consciousness is engrossed by a present sensation, or the contemplation of external phenomena, the organ, as a whole, will be differently affected than when former impressions are recalled, or when the mind is disturbed by the passions of grief or anger, or when the reason is adapting means to ends, or the volition is calling into play a particular set of muscles.

Assuming, then, that the brain is a composite organ, and that, while different parts of its mass have their own special function, they are so co-ordinated that each ministers to mental unity, we have now to consider how the peculiarities of the encephalic circulation may affect the mode or outcome of functional activity in the brain itself.

In considering the physiological conditions of sleep we found that the blood, apart altogether from its nourishing and stimulating properties, has an important bearing on the action of the brain as a whole through the purely mechanical effects of mass and movement. In studying the organ when functionally active we have still the same kind of factor to take account of. We have still to consider the question of *balance;* but now, instead of a balance between the arterial and capillary circulation on the one hand, and the venous system of vessels on the other, we have to consider it as presented in the circulation through the brain itself. How is the balance here maintained? What conditions are likely to disturb it? And what are the effects on cerebral function of any change in the equilibrium?

I again assume that the molecular activity is the dominant factor in determining the local distribution of blood through the brain mass, and therefore in maintaining or changing the equilibrium of the encephalic circulation. Some pathological conditions seem to point in the direction of a positive influence being exerted by the vaso-motor nerves, but I am not aware that any definite knowledge has been got as to their mode of action. It will be sufficient for our purpose if it be admitted that the molecular agitation and the capillary circulation are, on the whole, so intimately related, that any influence which interferes with the one, either in the way of favouring or opposing, will also correspondingly modify the other.

The first point on which we have here to lay emphasis is, that the immediate seat of activity must have its vascularity increased. The arguments already advanced to prove that the brain as a whole must contain a larger quantity of blood during the period of wakefulness than when its function is suspended, apply with equal force to limited portions of the organ. As in a furnace, other things being equal, the draught of air will be strongest toward those points where combustion is most active, so in the brain the circulation will be determined in greatest volume toward and through those portions of its mass where the molecular commotion is briskest. Therefore, when an impression is received from a nerve of sensation, when intellectual effort is sustained, or voluntary muscular actions are incited, that portion which is more immediately subservient to the particular operation must become the seat of vascular excitement. Not only as compared with its own previous condition, but as compared with that of similar surrounding tissue, the function of which is not equally active, the amount of blood contained in and transmitted through its vessels must be augmented.

Here, then, we have a means by which the balance of the circulation through the brain itself may be actively influenced. Keeping in mind that the mass of blood which can be drawn on is strictly limited, and that the enclosing space is rigidly fixed, some of the immediate *physical* consequences of any alteration in its distribution may be at once perceived. In the first place, no sooner will one portion of the brain become more vascular than some other must become less so. If the blood is determined more freely into the anterior cerebral arteries, the smaller can be the amount held by, or transmitted through, other vessels. The extent to which the circulation may be thus altered will be in proportion to the extent of tract involved, and the intensity of the action itself.

Secondly, a certain amount of *pressure* must be exerted on the surrounding tissues. If any set of vessels becomes more distended with blood, the part involved must, of course, take up more room than before; if there be no room for expansion, the *tension* of the centre must be increased by the more rapid movement of the blood current.

We thus perceive how one portion of the brain may influence the function of other parts—either stimulating or inhibiting that function—independently of any connection through commissural fibres. We need not here do more than allude to the important law according to which the functional capacity of the nervous structures is related to their vascularity. The more vascular, within certain limits, any organ is, the greater is the energy or facility with which its function may be exercised, and, therefore, any circumstance that interferes with the supply of blood must diminish—whatever favours the supply will increase—the functional vigour of the part.

As the simplest method to develop our subject further, we shall take some mental faculty or condition, and see whether these principles may throw any light on its modifications.

When the fully developed mind is in healthy activity, the succession of mental states is in accordance with certain psychical laws. We do not require to enter with any fulness on the consideration of these. Impressions quicken the consciousness and produce sensation; perception recognises the impressing object, and memory, comparison, and judgment give us more or less definite notions as to its properties. Other notions link themselves in succession, not accidentally, but in a definite order. Intelligence recognises the fitness of things or actions for some special purpose, and directs the will in putting them to use.

To every step in the endless variations which may thus present themselves, the working brain must be in intimate correlation. The mental and organic mechanisms must work in harmony, each acting and reacting on the other. For this purpose a certain quality of brain tissue, centres or tracts for special faculties, and a healthy quality of circulating fluid are necessary factors, but the consideration of these does not come within the scope of this essay. I restrict attention to the influence which may be exerted by the mode in which the circulation may for the time being be going on.

The first subjective condition we shall select for illustration is that of Attention. It is unnecessary here to enlarge on the psychical importance of this state or faculty. Like consciousness itself, it may be said to underlie every other form of mental activity. If consciousness be the atmosphere in which the faculties have their being, attention is the light which reveals and directs their modes of acting. It is required to convert sensation into that comprehensive grasp of particulars which constitutes perception; without it, meaningless reverie will take the place of coherent thought. Not unfrequently, it may be difficult to differentiate it from volition; and, certainly, we can hardly conceive of any act being strictly voluntary apart from its guidance.

To study it in its physiological aspect, we will take the well-known effect of attention in modifying the intensity of sensation.

If we take the brain at any time when the mind is in what may be called a state of indifference—when consciousness is awake but not particularly alert in any direction—we may presume that in such a condition the encephalic circulation will also have a certain balance. Every part of the brain will be flushed, but determination of blood will not be specially active toward any centre. The balance, however, must be so delicate that it may be altered by the slightest cause. If some more active condition is to be induced in the brain itself, the first necessity must be that the blood will be ready to surge to a required extent in whatever direction a demand for it may happen to be set up.

If now an impression be made on some sensory surface of sufficient strength to secure attention, it acts as a stimulus to the brain on the one hand, and to the consciousness on the other. But as, in the latter case, all the energies of the mind are not involved, so, in the former, all parts of the brain are not equally active. Those portions concerned in receiving and registering or interpreting the impression will be the more immediate seat of molecular excitement, and, therefore, of increased vascular activity.

The subjective effect of attention is to make all the aspects of the objective cause more precise. An impression is stronger, and details as to the characteristics of the impressing object are more completely gathered in, when the mind is intentionally concentrated on it. On the other hand, if the consciousness is engrossed in some other direction,—if absorbed in an interesting occupation or train of thought,—the impression which formerly produced so much effect is now felt obscurely or not at all. To account for this difference, we cannot be content with a simply metaphysical explanation. To say that the mind is so constituted that it cannot at one and the same moment entertain with distinctness dissimilar ideas is only one half of the truth. There must be a cerebral correlative, and some notion as to the nature of this must be got if we are to come nearer the whole truth.

Two physiological factors, at least, may be specified as bearing on this problem. In the first place, when the consciousness is engrossed by an immediate sensation, the sphere of encephalic activity is, as we have seen, comparatively restricted. What that sphere may be in any particular instance, it is for anatomy and experiment to determine. For receiving the impression, for quickening the consciousness, and for completing its course as a definite perception, the tract involved may be wide and branching, but it does not include the whole brain.

In the second place, *the encephalic circulation will be focussed in the direction of activity.* The molecular commotion occasions at once a necessity and an attraction for more blood, and determination of this takes place all the more freely on account of the quiescence of the larger part of the brain. The latter has, as it were, loosened its hold on the circulation, and the impetus towards those parts which have an attraction for it is thus all the greater. This increased activity of the circulation reacts on the energies of the tissue, and the mental effect produced is therefore stronger.

If now we turn the picture, we find the lights and shadows have changed places. Let the mind be intent on solving some problem, or be engaged on some work requiring nicety of handling, and the impression which formerly so completely took possession of the consciousness may not now be felt in the least. Here, too, we have physiological conditions at work. The impression fails, not simply because the consciousness is otherwise engaged, but also because the track along which it is to travel, or the centre where it is to be recognised, is not now in a fit condition for responding to the stimulus. It is out of focus. The momentum of the circulation is now directed towards the centres of ideation and voluntary motion, and that implies derivation from, and consequent weakening of functional vigour in the sensory ganglia.

There is, however, another aspect in which the circulation is to be regarded as an important factor in modifying the action of the brain. It is the agent which has more immediately to do with the amount and direction of intra-cranial *pressure.*

In pneumatics, the pressure of the atmosphere may be studied as that of a fluid at rest, or as that of a fluid in motion. In the one instance we have it bearing equally over, it may be, a large part of the earth's surface. Its amount may be greater or less, but however powerful it may be in the aggregate, its presence need not be recognised. Its enormous energy is then potential. In the other case, the direction and force of the pressure may vary every moment, and reveal itself as the genial breeze, or as a destructive hurricane.

In like manner, the intra-cranial pressure may be considered in two aspects. In the first place, as the nerve structures are supported and everywhere permeated by fluids, the tension throughout the cranial cavity must be equal at every point, in accordance with the law of pressure in fluids; and, in the second place, we may have the disposition of the solid tissues determined by the volume, strength and direction of the blood currents.

I need not again go over the argument to prove that the brain when functionally active has necessarily an expanding tendency. The flow of blood through its capillaries is not that of a sluggish current creeping onwards by compulsion from behind. It is rather a seething impetuous movement, as of a current eager to burst through its restraining barriers. Under the influence of such commotion the bulk of the brain mass must be positively greater than when the organ is at rest.

To this expanding tendency there are, in ordinary circumstances, two limiting conditions. The more obvious of these is the rigid cranial wall, or, if this be defective at any point, the tough dura mater. However intensely the physiological forces be exercised, they must fail to overcome this solid environment.

A second and not unimportant check is the peculiar structure and relations of the pia mater. In this membrane, lying between the dura mater and the brain substance, two sets of vessels, as we have seen, are arranged side by side, or interlaced in a delicate network. The one set of vessels feeds, the other drains, the capillaries of the remarkably vascular nervous structures. Now, if the brain were to expand beyond a very limited extent, a process of self-strangulation would take place. The circulation itself would be stopped, and instant unconsciousness be produced. Indeed, when a cursory survey is made of the disposition of the blood-vessels, one is apt to wonder why such an untoward event is not of frequent occurrence. To prevent it, however, we find several safeguards. In the first place, the course of the arteries through the base of the skull is so contrived as to prevent the action of the heart from bearing too directly on the vessels within the cavity. A second precaution is the stress occasioned by the backward pressure of the atmosphere in the veins. Lastly, there is a delicate balance of check and counter-check (in which possibly the vaso-motor nerves may act an important part) between the tissue changes and the capillary circulation, in virtue of which the movement of blood is to a great extent correlated to metabolic change.

But to however slight an extent the brain expands, it must do so against opposing force, and this opposition will continue during the whole period of activity. The first effect of expansion must be somewhat to compress the veins, but the compression cannot be to a greater extent than will allow whatever amount of arterial blood which may enter the skull to be transmitted onwards. There is thus an increase of tension through the whole brain mass, and the blood pressure will be expended in more rapid movement. To this tension all the fluids and solids within the cranial cavity will be alike subjected. It will not be greater at one point than at another. We are compelled to infer, then, that when the brain is active, its function is exerted under a state of physical repression or stress. Such a condition, of course, is not peculiar to the nerve centres. This necessity for a barrier against the diffusion—and, therefore, waste—of energy, is a principle which we find operating throughout organic nature. The plant seed must have a firm envelope to enable the embryo to develop, and even the speck of protoplasm requires the restraint of the cell wall to enable it to evolve or exercise some special property or form of energy.

In physics we have abundant illustrations of the behaviour of energy under repression. Its tendency is to explosion, or, if liberated in a special direction, to produce intensity of discharge. The utility of the steam-engine, the rifle, or the telegraph, depends on our being able to control the liberation of certain forces under repression.

From the analogy of physics, then, may we not reasonably infer that whatever energy the brain is able to produce or liberate, it will be more concentrated and sustained—more readily or more completely directed into some special channel—than if it were at once diffused in all directions in its very production? Or, if we look at the mental correlative, we may assume that sensation is more acute — perception more exact— thought more coherently sustained—efforts to produce muscular movements stronger and more accurately directed, on account of the physical strain to which the organic substratum is subjected.

Perhaps I should here say a word to defend myself from what may appear a paradox. In a previous chapter I have tried to show that pressure inhibits the brain and suspends consciousness; I now insist that pressure is necessary to give accented force to brain function. To reconcile the two statements is a simple matter. In the former case—that of inhibition—the pressure is venous in its origin; it is from the outside—on the surface—of the brain, and it tends to empty the capillaries. In the other case, the pressure is capillary. It is the necessary accompaniment of molecular commotion, and is the immediate result and evidence of the activity itself. In both cases the pressure is equalised through the cranial cavity, but in each instance its active source, as well as the disposition of the solid nerve elements, is distinctly different.

Of course, if the brain as a whole requires some counterpoise to ensure a sufficient intensity in the discharge of its energy, the same rule must apply to individual portions of the organ. Each local or limited area of ganglionic structure which may have specific duties to perform, must receive a background of resistance or support from other structures. Each part of the brain will thus have what may be called a fulcrum function to every other part. Failure of the support so afforded will have a modifying effect on the discharge of function.

In speculating on any point in mental physiology, then, we have something more than the molecular action of the brain structure to consider. Three factors, at least, seem necessary for the successful liberation of nerve energy, and if cerebration is to be healthy, there must be harmonious action among them. In the first place, the molecular motions in the functioning centre must be free; secondly, the capillary circulation must have a correlated activity; and, as a third condition, the surroundings must afford such stable support as will secure the efficient "vibration" or "explosion," or whatever term may best express the immediate liberating action in the discharging centre.

It follows that any circumstance which renders the support of a nerve centre more efficient may have the effect of favouring its functional capacity. Its tension is thereby raised, and when this happens we may safely infer that its vibrating quality is made more sensitive, and may be better sustained. In illustration, we may refer to the effect which certain forms of muscular strain have in enabling attention to be more efficiently focussed. "If we take the simplest form of attention, that directed outward to an impression of the sense, it becomes obvious that the mental adjustment is effected, in part at least, by a muscular adjustment. Thus, in the case of expectant attention, when we are awaiting an impression of sight or of hearing, it is easy to recognise in the pose of the body, the movement of the head and eyes, the presence of a vigorous motor factor. This factor does not manifest itself in actual movement. One would rather say that the characteristic of this muscular exertion is fixation of body, limb, and sense-organ, by a balanced action of antagonist muscles, and by the inhibition generally of all diffused movement."* Here the nerve centre more immediately concerned in impressing the consciousness has its vibrating conditions made more favourable. The general intra-cranial stress occasioned by that in the motor centres assists the stress in the sensory; it makes the latter more acutely responsive, and enables it more readily to concentrate and sustain its discharge of energy.

Again, when a heavy weight is to be lifted, one motor centre after another is called into action, till a strain is thrown on the whole muscular system. This strain not only gives leverage steadiness to the osseous and muscular framework, but it prevents the energy of the principal discharging centre from being diffused,—the explosive force is more completely directed into the specially intended channel.

There is still another aspect, however, in which the

* J. Sully, "The Psycho-physical Process in Attention." Brain, Part II. 1890.

stress of an active centre may be regarded. As we have seen, there is in it not only action—molecular commotion and vascular turgescence,—but there is reaction—active pressure—on the surroundings, and this reaction may assert itself in various ways. The stress of one centre may be so raised, that the pressure radiated to other centres may stimulate the function of the latter, and thus another sphere of activity may be created. Nor have we far to go to find an illustration of this mode of action.

When a sensory centre is moderately impressed, the consciousness may be quickened without any outward physiological effect being produced. But when the sensation is of such intensity as to amount to acute pain, the tension of the centre is raised to a high pitch, and radiation of *physical* energy, the result of severe stress, is also produced. When the radiation thus produced involves the motor centres, these, in the first instance, are rendered more excitable,—the tendency to explosion in their cells becomes stronger, and they are ready to liberate whatever energy is stored up in their protoplasm. The continued strain acting as a stimulus, an explosive discharge occurs, through which various parts of the muscular system are thrown into violent action. Then follows what, I suppose, may be called the "final cause" of the muscular contractions. The discharging action in the motor centres tends by derivation to relieve the stress in the sensory centre. The circulation is partially diverted into other channels, and the intensity of the pain is thus positively lessened.

If the reasoning in this instance be at all plausible, it may possibly afford a clue to the direction for finding an explanation of other muscular movements, such as those which are the result of emotion, or even of those which are voluntary.

When emotional excitement occurs, some deep font of feeling is stirred, but instead of the outflow being in a steady stream, as occurs in ordinary volition, *eddies* are formed,—wavelets of impulse spread themselves around the seat of agitation. The commotion so produced reaching some other centre with its cells readily explosive, a discharge of energy takes place, and is shown in actions or muscular motions with which the volition may have little or nothing to do. We have thus the hearty laugh of pleased surprise or the sob of anguish, or the feeling may get vent in some pithy expletive or exclamation. The phrases thus given expression to may be meaningless, but they afford relief to some form of high-strung tension.

Even in voluntary movements there is perhaps always some such emotive impulse. Simply to *think* a movement is not sufficient,—the thinking must have a certain amount of emotive force. Psychologically, the will is essentially a prospective faculty. It must have a goal in view, whether a muscular movement, an effort of memory, or a process of reasoning be required to reach it. Some notion must precede action. Physiologically, the will exerts a focussing power over the energies of the brain. Intelligent action, therefore, implies an educated brain, where co-ordination has been established between various parts. How co-ordination may have arisen, it will be for the student of evolution to enlighten us; here, we have simply to do with it as an accomplished fact.

Ideation, the initiatory stage of volition, involves within a limited area molecular movement with corresponding vascular activity. If the tension of that area be sufficiently raised, radiation of energy must occur, and if cerebration be healthy, the aim of the will to give it a specific direction is carried out with precision. If radiation be toward a motor centre, we find in the latter all the conditions favourable for liberating its energy. In the waking state and in the absence of fatigue or disease, the centre requires little more than *permission* to do its work. All the potential conditions for discharge are already there,—inhibition has simply to be removed. The current of nerve force from the ideational centre communicated through commissural fibres, or the wave of impulse occasioned by simple pressure acting as a stimulus creates simultaneously molecular and vascular commotion. A condition of erethism is produced in the motor centre itself. This vascularity acts in two ways. In the first place, by derivation it removes the inhibitory action of other parts of the brain; and in the second place, it further stimulates the molecular motions. The final result will now depend on the condition of its surroundings. Turgescence implies outward pressure, and the general law in physics that action and reaction are equal and contrary, must here hold good. If the surroundings, then, be stable, natural relief will be got by the overflow or discharge of energy into a motor nerve, and precise contractions of the muscles will be the result,—the mandate of the will will be carried into effect. On the other hand, if the support afforded to the centre be insufficient, the vascular turgescence will to some extent spend itself in displacing the surrounding texture, and the intended movement will either not take place, or, resembling that of simple emotion, it will fail in precision or strength.

If reasoning as above be even approximately correct, it becomes a matter of detail to apply the principles in other directions.

If the cells of one centre, or class of centres, be too readily explosive, they may attract the blood so strongly as to inhibit the function of other parts by the comparatively anæmic condition these are thus left in. Of this we have an illustration in the phenomena of an epileptic seizure. Here we have the blood determined in such volume to the motor centres, that those which are more immediately related to sensation and intelligence have not sufficient left to enable them to sustain function with. Violent muscular contractions—more or less general convulsions—are produced, while consciousness is completely suspended.

On the other hand, if the attraction or regulative power of some centre is under the normal, the balance of the circulation may again be readily disturbed. A determination of blood toward other centres may from this cause be excessive, and thus the action of the whole encephalon may be modified.

The simplest illustration of this mode of action is the effect of darkness in causing the sense of hearing to be more acute, or, in some individuals, allowing certain notions to seize one rather strongly. If some unknown object is obscurely seen, or if the attention is strongly attracted by indistinct sounds, it may require a considerable effort of self-control to prevent the mind from being unpleasantly disturbed. If the whole brain be sluggish, as when there is an inclination to go to sleep, the mind is also in a condition of indifference, and the absence of light favours the induction of sleep. The stress in an important centre is lessened, and this favours the collapse of the whole brain. But if put suddenly and acutely on the alert by any circumstance likely to raise a feeling of anxiety or of fear, a state of mental tension is produced, and it becomes difficult to resist entertaining the notions that then rush on the imagination with extreme vividness. In such circumstances the fancy can frame in complete detail and with remarkable distinctness any object, or convert obscure sounds into

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any expressions that may suddenly suggest themselves. If these be associated with feelings of fear, self-possession may be completely lost.

Now, we have here a cause in operation by which the balance of the circulation may be disturbed. The centre for vision being largely composed of grey matter, and therefore extremely vascular, must in the ordinary waking condition exert no inconsiderable controlling influence on the cerebral circulation. But in the absence of the stimulus of light, a large portion of its structure has its function to some extent suspended. Its molecular activity and, as a consequence, its hold on the circulation are weakened. Therefore, when other centres are stimulated, the determination of blood to these is all the more free, and the effect on their functional capacity is increased in proportion. The sense of hearing becomes more acute, and the ideational centres are more actively disposed to form and retain images. Any notion suddenly suggesting itself is apt to take complete possession of the mind, and to prevent the usual discriminating power to be exercised. The obscure object assumes the form of some dangerous animal; a certainty is felt that the sounds can only arise from the stealthy tread or nefarious operations of the burglar. If a light be brought, not only is the judging faculty restored, but so completely do the phantoms vanish that the subject of the illusions finds it difficult to comprehend how they had previously seized on the imagination so strongly.

A condition on which some light may possibly be thrown by a consideration of disturbed balance of the brain circulation is that of hypnotism. We need not here enlarge on the mental peculiarities of this state. The sensational phenomena which the mesmerist professes to produce are well known. "Persons in a perfectly wakeful state . . . will be deprived of speech, hearing, sight. Their voluntary motions will be completely controlled so that they can neither rise up nor sit down except at the will of the operator; their memory will be taken away so that they will forget their own name and that of their most intimate friends; they will be made to stammer and to feel pain in any part of the body at the option of the operator; a walking stick will be made to appear a snake; the taste of water will be changed to vinegar, honey, coffee, milk, brandy, wormwood, lemonade, &c. These extraordinary experiments are really and truly performed without the aid of trick, collusion, or deception in the slightest possible degree."*

Such are the terms in which the professional mesmerist advertises his wonders. It is admitted that in a certain proportion of individuals who will submit to the ordeal, some or all of these remarkable phenomena will be manifested, and physiologists, I believe, agree in regarding them as essentially subjective. They arise

* Copy of Advertisement, quoted by Braid, "Edinburgh Medical Journal," June 1851.

from "dominant ideas," "paralysis of the will," "mental abstraction or concentration of the attention." The latest favourite term is "suggestion." Such a view is, of course, most important as enabling us to disregard other erroneous methods of explanation, such as the influence of "odyle force," or the streaming of a magnetic current from one individual to another. But it throws no light on the immediate mechanism, or the abnormal condition of the nervous system to which the phenomena are correlated. It will not be considered unimportant if even a small portion of the truth can be established in regard to its nature.

The first incident in inducing the hypnotic state is a steady, prolonged effort of volition. For a longer or shorter period the attention is concentrated in one—and that a very restricted—direction. The eyes, for example, are kept with a fixed strain on some minute object. No wandering of the eye or of the thoughts from one point to another is permitted. This strain is strongly opposed to natural inclination and habit, and we may safely infer that the sphere of brain involved is probably very circumscribed.

The immediate consequence is fatigue of the nerve centres concerned in keeping up the strain. The irritability of these is therefore diminished; their molecular motions become enfeebled from sheer exhaustion. They are thus reduced to a condition in which they cannot with ordinary facility respond to their accustomed stimuli. This condition probably approaches, if it is not identical with, that which is present during sleep, and a period of rest becomes necessary to enable the tissue to recover its ordinary tone and function.

The next physiological result is instability of the cerebral circulation. The balance of the latter, as we have said repeatedly, is to a great extent determined by the balance maintained in the metabolic changes in the brain tissue. In ordinary circumstances every portion attracts the blood towards it with a certain amount of force, and it thus exerts some control over the distribution to other parts. When the irritability of the molecular structure has been used up, this controlling power is lost. The attractive force which all parts of the brain exercise towards the circulating fluid then fails to be possessed in the usual relative proportion. The whole intra-cranial circulation is now in a condition analogous to that of the atmosphere with a low barometric pressure, —it is mobile and disposed to storms. Instead of quiet currents, we are apt to have irregular surging. Previously, the circulation was kept at high pressure in one direction under the stimulating action of molecular strain; but now, with the sudden collapse of the latter, a weak point has been developed that can influence the action of the whole encephalon.

If now no effort be made to rouse the function of any other part of the brain, the whole organ will collapse. We find it in a condition similar to that occasioned by the withdrawal of the stimulus of light. The tendency of the venous pressure on its surface will be to bear inwards with more effect, and if the veins of the pia mater once acquire a certain amount of fulness from this cause, sleep itself will be induced.

On the other hand, if, before the stage of complete unconsciousness has been reached, some stimulus calls into brisk functional activity any part of the brain whose irritability is unexhausted, then, in answer to the demand which is immediately occasioned, the determination of blood towards it will be greater than usual. The antagonism exerted by the rest of the brain is less than in ordinary circumstances, and a more abundant supply is thus permitted to the seat of activity. Then, the very momentum with which the blood surges in that special direction reacts on the molecular motions and intensifies function. If it be toward an ideational centre, some particular notion may so monopolise the consciousness, that discrimination and judgment are almost as completely in abeyance as in ordinary dreaming. An assertion boldly made to a hypnotised subject, therefore influences belief in opposition to former experience. If something bitter is put into his mouth and he is told it is sweet, the idea of sweetness becomes dominant because the circulation has been so strongly determined towards the ideational centres, that the gustatory tract or centre is thrown completely out of focus. It fails to respond to its ordinary stimulus, not simply because the attention is at fault, but also because a factor essential to normal action has failed to be present.

One might go over all the anomalies and perversions of memory, belief, and will which the mesmerist can produce, and find a similar explanation apply to each. The brain for the time being has lost its power of keeping the circulation in healthy equilibrium. A tendency to cyclones and anticyclones has been developed. The mind, therefore, is apt to be "tempest tossed." It is like a rudderless vessel drifted along by wind and wave. At one moment it glides bravely onwards under a puff of exaggerated sentiment or idea, and in the next it sinks into a trough of nescience and imbecility.

It has not been my aim to write an exhaustive treatise. My object has rather been to give prominence to certain facts and principles, which, as bearing immediately on details of adjustment and action, have been undeservedly overlooked as factors in the physiology of the nervous system. If the principles I have attempted, however imperfectly, to work out be sound, they can be further applied in various other nervous conditions, such as hysteria and some forms of insanity; but if I have been too sanguine in supposing they are of value, I have already said more than enough to illustrate their application to special conditions. I am very conscious they will require to be more fully elaborated, and to be stated with greater precision. But however defective my own treatment of them may be, their study has been prosecuted under a feeling of strong conviction that they certainly deserve attention. The topography and microscopic structure of the brain have, in recent years, been investigated with great zeal and success; if some of the same energy and perseverance be directed to the broader physical conditions of nervous action, I am confident that the physiology of the brain will be correspondingly benefited.

In the preceding pages I have had occasion to express opinions diametrically opposed to those held by eminent authorities. It would be uncourteous—it might be deemed pusillanimous—not to take special notice of these differences; and as any adequate statement of them in the text would have made my own argument to halt seriously, I have reserved for the Appendix the uncongenial task of facing the turmoil and risks of personal controversy. I trust, however, I shall do nothing that may expose me to the charge of hitting unfairly, while I do my best to weaken the position of writers opposed to myself, and, as opportunity offers, try further to fortify my own.

APPENDIX.

A.

KELLIE *VERSUS* BURROWS ON THE ENCEPHALIC CIRCULATION.

In the preceding essays I have assumed as correct the views of the encephalic circulation advanced by Monro (*secundus*), and supported by Dr Kellie of Leith, Dr Abercrombie, and others. As expressed by Dr Kellie these views were to the effect that it "does not appear very conceivable how any portion of the circulating fluid can ever be withdrawn from within the cranium without its place being simultaneously occupied by some equivalent, or how anything new or exuberant can be intruded without an equivalent displacement."

These views are considered erroneous by eminent authorities of the present day. "They have been completely overthrown by Dr George Burrows," says Sir Thomas Watson.* "By this refutation," he adds, "of a prevalent error not unlikely to warp or mislead our

* "Lectures on the Principles and Practice of Medicine," fifth edition, p. 322.

practice in cerebral disorders, Dr Burrows has done the science of medicine an essential service." Another writer alludes to them as the "Edinburgh dogma" which has been "demolished," "utterly refuted by the experiments and reasoning of Dr (now Sir George) Burrows."* As I firmly believe that a more common-sense dogma never was formulated, and that the assertions and reasonings of Dr Burrows have seriously impeded the progress of cerebral biology, I shall, at the risk of being tedious, detail with some fulness the early history of opinions on the disputed points.

As is well known, the first to formulate the so-called dogma or doctrine was Dr Alexander Monro (*secundus*). He wrote as follows:—

"The ends of the lateral sinuses perforate the cranium at some distance from the arteries, that the returning blood might as little as possible suffer interruption in its course toward the heart. For any alternate stop of it, especially when occasioned by the stroke of the corresponding artery, must have had a worse effect on the brain than on other organs; not merely on account of the delicacy of the brain and the thinness of its veins, but because, being enclosed in a case of bone, the blood must be continually flowing out by the veins, that room may be given to the blood which is entering by the arteries. For as the substance of the brain, like that of the other solids of our body, is nearly incompressible, the quantity of blood within the head must be the same, or very nearly the same, at all times, whether in health or disease, in life or after death, those cases only excepted in which water

* "On Passive Cerebral Pressure," by Dr Robert Turner. "Edinburgh Medical Journal," September 1876.

or other matter is effused or secreted from the blood vessels, for in these a quantity of blood equal in bulk to the effused matter will be pressed out of the cranium." *

The next writer on the subject was Dr Abercrombie. "Upon the principles of hydraulics," he says, "it seems probable that the vessels of the brain must always contain a considerable quantity of blood, even when other parts of the system are exhausted of it. This results from the peculiar situation of the brain,—its confinement in an uninterrupted cavity of bone, in which it is closely shut from atmospheric pressure. In such a cavity the blood probably cannot be diminished below a certain quantity, unless something entered to supply its place, and in the language of the old philosophy, to prevent a vacuum." †

Coming now to Dr Kellie, we find the most extraordinary misconceptions have been formed as to his views. The general impression among recent writers seems to be that he believed, and that he performed his celebrated experiments to prove, that the amount of blood within the skull must in all circumstances continue absolutely invariable. Now, it so happens that the occasion for Dr Kellie investigating his subject was the circumstance that in the post-mortem examination of two individuals who had died in one night from the effects of cold, he found from three to four ounces of

* "Observations on the Structure and Functions of the Nervous System," p. 5.

† "Edinburgh Medical and Surgical Journal," November 1818.

serous fluid in the ventricles and at the base of the brain; and his reflections on the probable production of this quantity of fluid within a few hours led him to the conclusion that an amount of blood equivalent to that of the serous fluid had been pressed out of the cerebral vessels. "When the cavity of the cranium is encroached upon by the depression of its own walls or by an effusion of fluid within its cavity, one of two things it is obvious must follow,—either the compression of its previous contents into less space, or the displacement and removal of an equivalent bulk of those contents." He then gives reasons why he considers it "highly improbable that in the course of a few short hours from three to four ounces of brain could be wasted or removed by absorption;" and continues, "it seems more probable that, in most cases of intrusion on the brain, compensation may be made at the expense of the circulating fluid within the head; or that less blood is then admitted and circulated within the cranium than before such encroachment on its capacity had been effected." *

It thus appears that to insist on the occurrence of a decrease of blood within the skull as a matter

* "Transactions of the Medico-Chirurgical Society of Edinburgh," vol. i., pp. 98, 99. The full title of Dr Kellie's paper was:—"An Account of the Appearances observed in the Dissection of two of three Individuals presumed to have perished in the Storm of the 3rd, and whose bodies were discovered in the vicinity of Leith on the morning of the 4th November 1821: with some Reflections on the Pathology of the Brain." It was read to the Society in two parts; the first on 6th February, and the second on 20th March 1822. It occupies eighty-five pages of the "Transactions."

of fact, was actually the starting-point of Dr Kellie's investigations!

Another fact which does not seem to be generally known, is the circumstance that Kellie's argument, so far as it is controversial, is directed against certain views of Dr Abercrombie. But such is the case, the immediate point of dispute being the pathology of certain forms of coma. In trying to explain the occurrence of "simple apoplexy," when no morbid condition of the brain could be discovered after death, Dr Abercrombie had written as follows:—

"The apoplectic state, as it occurred in these examples could neither depend upon increased quantity of blood, nor increase of its impulse, but simply upon *interrupted circulation;* and this principle, I think, will be found to accord with all the phenomena of simple apoplexy. By the term interruption, I here mean such a derangement of the circulation in the head that *more blood enters by the arteries than can be transmitted by the veins.* * Such derangement, it is evident, may take place from various causes. It may either depend upon a condition of the arteries connected with general plethora of the system, in which more than the usual quantity of blood is carried to the head; or upon causes impeding the return by the veins, the quantity entering by the arteries remaining unchanged."

"These (encephalic) vessels are enclosed in a cavity formed by the bones of the cranium, and the remainder of the cavity is exactly filled by an inelastic substance, the brain. They cannot, therefore, admit of much increase of the quantity of blood which enters them without deranging the circulation in

* The *italics* are mine.

the manner I have supposed. If the arteries were enlarged by plethora, the veins are prevented from a corresponding enlargement; hence a certain derangement of the circulation, producing, I imagine, the headache, throbbing, giddiness, tinnitus, and other analogous symptoms which mark the tendency to apoplexy. From increase of the same cause, or the addition of some incidental one, as an occasional increase of the impetus of the blood, the interruption at last reaches that point at which more blood enters by the arteries than can be transmitted by the veins—then occurs the paroxysm of simple apoplexy."

"If any considerable quantity of blood (say ℥iv) has been extravasated on the surface of the brain, as in a case of injury of the head, coma is produced, and this is called compression of the brain. But in what manner does this compression operate? We have no reason to suppose that the brain itself is capable of being compressed into smaller compass, so as to make room for this extraneous mass. Something, however, must have yielded to make way for it, and this is most likely to be the vascular system of the brain. Less blood by ℥iv will now be contained in the vessels of the brain. If this diminution and quantity affected the arteries and veins equally, it probably would produce no urgent symptoms. But the quantity entering by the arteries is undiminished, or diminished only by the very trifling ratio which the quantity extravasated bears to the whole blood of the body, consequently the compression will chiefly or entirely act upon the veins. From the smaller impetus of blood in them, they are less capable than the arteries of resisting its effects; and from the situation of the greater part of them on the surface of the brain, they are more immediately exposed to it. Hence will arise a derangement of the circulation analogous to that I have supposed under a former article, more blood entering by the arteries than can be transmitted by the veins—the consequence is coma or simple apoplexy."

In regard to cases of what were called serous apoplexy he says :—

"*I object to the term entirely, and I think it extremely doubtful whether there really exists such a disease.** . . . It is not probable that serous effusion should accumulate in the brain with such rapidity as to produce the symptoms of an apoplectic attack. . . . When such a quantity of fluid exists in the brain, the blood circulating there must be diminished by the same quantity ; but however much it may be diminished, while it continues to circulate without interruption there will be no coma. . . . Pressure upon the surface of the brain I have supposed to produce coma, by diminishing the capacity of the veins, while the quantity of blood entering by the arteries remains undiminished ; if both arteries and veins were affected equally, I imagine there would be no interruption and no coma." †

In demurring to these views, Dr Kellie reasoned as follows :—

"I cannot conceive an interrupted circulation of blood within the brain while life is continued, nor can I admit that the derangement being once established, more blood can continue to be admitted by the arteries than is transmitted into the veins. . . . To whatever extent one set of vessels is becoming overcharged, to the same extent, it seems probable, is the other set becoming voided. But this derangement must have its limits, for were it repeated at every systole of the heart, one set of vessels would at length become entirely voided and compressed ; the circulation would then indeed be interrupted, and instant death rather than apoplexy be the consequence. While life continues, the effect of this derangement, whether in the case of *arterial* or *venous* congestion,

* The *italics* are Dr Abercrombie's.

† "Edinburgh Medical and Surgical Journal," November 1818.

will, in truth, be a retarded rather than an interrupted circulation of blood through the brain; for, in the one case, the diminished quantity of blood which is transmitted from the head by the narrowed veins will be the exact measure of that which at each systole of the heart can be forced into the plethoric and congested arteries; and, in the other, the quantity which the compressed or contracted arteries can admit will measure the quantity carried from the head by the enlarged and congested veins; or, the derangement once established, more blood cannot continue to be admitted by the one than is discharged by the other.

"The circulation within the head is, in truth, of a very peculiar description. The brain, itself little compressible, is contained within a firm and unyielding case of bone, which it exactly fills, and by which it is defended from the weight and pressure of the atmosphere,—a force constantly acting on every other part of the system,—a force, therefore, which must be constantly operating to maintain the plenitude of the vascular system within the head.

"If these premises be true, it does not then appear very conceivable how any portion of the circulating fluid can ever be withdrawn from within the cranium without its place being simultaneously occupied by some equivalent; or how anything new or exuberant can be intruded without an equivalent displacement.

"One of my oldest physiological recollections, indeed, is of this doctrine having been inculcated by my illustrious preceptor in anatomy, the second Monro—a doctrine which he used to illustrate by exhibiting a hollow glass ball, filled with water, and desiring his pupils to remark that not a drop of fluid escaped when inverted with its aperture downwards. . . .

"Is it then true and consistent with experience that we cannot lessen to any considerable extent the quantity of blood within the cranium by arteriotomy or venesection? . . . I believe it will be found nearly true that there are such obstacles as the hypothesis supposes to the free depletion of the vascular system within the head. . . . In animals bled to death the brain still retains much of its blood; the vessels on its surface are red, well filled, and sometimes exhibit the appearance even of turgidity and congestion. I had hoped, without any new cruelty, to have been able to determine the extent of this fact by a reference to the brains of the sheep and oxen which are daily slaughtered by bleeding in our markets. But it was objected that by the division of the intercostals and eighth pair of nerves in the way in which these animals are killed by the butcher, their death might be accelerated, and time not allowed for a more full and perfect depletion of the sanguiferous system."

Believing that it "is only by such an appeal to nature that the merits of the hypothesis are to be tried," he was induced to make the experiments, the details of which he proceeds to give. One sheep was bled from the carotid artery alone, another from the jugular veins, and two were slaughtered in the ordinary way by the butcher. Both carotids were tied in one sheep, and the jugular veins afterwards opened; in another, both jugular veins were ligatured, and then the carotid was opened. A dog was bled from both femoral arteries, another from the carotids, and a third from both jugular veins. Then, "to afford examples of brain not depleted by previous hæmorrhagy," he tied both carotids (including the pneumogastric nerves) in two dogs and allowed them to die, and a third dog was poisoned with prussic acid. In every case the condition of the brain was afterwards carefully examined.

In the majority of cases of bleeding to death, the brain did not appear to be seriously depleted; in no case was it at all exsanguined like the other parts of the body, but the appearances as indicated by the presence of "red blood" varied somewhat. Thus, in one of the sheep slaughtered by the butcher, where death occurred in two minutes, "the sinuses at the base of the brain were full of blood, the veins on the surface of the brain, cerebellum, and medulla oblongata were also filled. A fine web of vessels over the corpora striata was beautifully injected with florid blood. A very little serum was found in the ventricles." On the other hand, in the sheep where the carotid arteries were tied and the jugulars were opened, death did not take place till twenty-three minutes after the veins had been wounded, and for a time the blood flowed slowly and by occasional drops only. Here "the sinuses of the head were in their usual state; those at the basis of the brain contained less blood than we have hitherto found in them, and the veins on the hemispheres of the brain were less filled; the choroid plexus was pale and empty, the vessels on the basis of the cerebrum were better filled. Those ramifying on the basis cerebelli were minutely injected. There was a slight but very decided serous effusion within the ventricles."

In the dog poisoned with prussic acid, "the brain was everywhere turgid with blood. The veins and sinuses were loaded and congested; and it was quite evident that this brain contained, beyond all doubt or dispute, a much larger quantity of red blood than the brains of any of the animals which had been bled to death."

"The summary of these observations, in so far as they apply to our present subject of inquiry, may be thus stated, —that though we cannot, by any means of general depletion, entirely or nearly empty the vascular system of the brain, as we can the vessels of the other parts of the body, it is yet possible, by profuse hæmorrhagies, to drain it of a sensible portion of its red blood; that the place of this spoliation seems to be supplied both by extra- and intra- vascular serum, and that watery effusion within the head is a pretty constant concomitant or consequence of great sanguinous depletion."

He then alludes to the apparently almost bloodless condition of the brain found after death from anæmia. "In cases like this, when little or no red blood remains in any part of the system, it seems in no way surprising that the vessels of the brain should exhibit at least the appearance of great depletion, while they might, in fact, contain no small amount of serous fluid, or of the almost colourless blood which was circulated during life."

Proceeding with his argument, he remarks that—

"If the obstacle to the free depletion of its vessels depends mainly on the cerebral system being defended from the weight and pressure of the atmosphere by the solid and unyielding cranium, it seems probable that by removing a portion of the skull and allowing the atmosphere to gravitate upon the brain, we should succeed in producing a much greater depletion of the vessels by general blood-letting than can otherwise be effected."

To test this point he made other three experiments on dogs, by removing a portion of the cranium with the trephine, and the animals were then bled to death. On afterwards examining the brains the contrast in appearance to that of the former cases was very striking. Thus in one of them, "the vessels on its surface were reduced to mere hairs. The brain was remarkably pale, and the choroid plexus bloodless."

"Comparing, then, these with the observations made on animals bled to death by simple hemorrhage, it appears that when the head is entire the brain still contains a considerable quantity of blood,—when previously perforated, very little; the brain continues to fill the cranium in the one case, and subsides within it in the other."

Our author then remarks that "the same causes which maintain the plenitude of the cranium, and oppose the depletion of the vessels of the brain, may be presumed to present also natural and constant obstacles to the repletion of those vessels." To prove his case still further, therefore, he proceeds to an elaborate examination of some of those "occurrences and accidents in human life, and some diseases also incident to man, which bear on the question of repletion and congestion with all the force of direct experiment." He investigates the results on the brain circulation of death from suspension, suffocation, and drowning; the effects of stooping and other low positions of the head; the effects of some diseases of the heart and of the larger blood-vessels; and lastly, the effects of ligatures and tumours compressing the vessels of the neck so as to impede the free return of blood from the head. In concluding, he says:—

"I have thus passed in review the most important of those circumstances which, from the earliest era of medicine, have been presumed to have a powerful and undoubted tendency to force blood into, or to confine it within, the vessels of the brain, and so to produce a dangerous morbid congestion of that viscus,—circumstances which accordingly have very generally been enumerated by systematic physicians as the principal exciting causes of comatose diseases; and though I am aware of many objections—though I know but too well the unlucky *pour* and *contre* which embarrass us in almost every subject of medical inquiry—I think a case has fairly been made out, proving that the agency of such causes has been greatly overrated;—that nature has guarded with peculiar care the brain and its vessels against such accidents from repletion and depletion, as they must otherwise have been constantly exposed to; and that while the structure of this organ remains *healthy* and *unchanged*, and its *vessels sound*, those causes are little capable of occasioning plethora, congestion, effusions, or comatose diseases.

"The real causes of apoplexy are changes which take place in the brain itself—disorganisations and structural alterations of its own texture, and of its vessels and membranes."

We have, lastly, to refer again to the views of Dr Abercrombie, as these are given in his volume on "Diseases of the Brain." * Here we find Dr Kellie's views adopted without reservation. Instead of explain-

* Published in 1828, ten years after his paper in the "Medical and Surgical Journal."

ing simple apoplexy by an "interrupted circulation," he says, "the explanation is to be sought for in an interruption of the due relations which ought to exist between the arterial and venous systems of the brain."

> "Upon the whole, then, I think we may assume the position as in the highest degree probable that in the ordinary state of the parts no material change can take place in the absolute quantity of blood circulating in the vessels of the brain. But the blood circulating in these vessels must be divided in a certain ratio betwixt the arteries and veins of the brain; and it is probable that the healthy state of this organ will depend upon the nice adjustment of the circulation in these two systems. If we could suppose a case in which more than the usual quantity of blood was accumulated in the one system, the necessary effect would be a corresponding diminution in the other, because the whole mass of blood in the brain must, by the supposition, remain the same. Hence would arise a derangement of the circulation, such as could not occur in any other part of the body, because there is no other organ so situated as the brain."

We turn now to the indictment preferred against these views by the late Sir George Burrows. This author, "impressed with a conviction that some erroneous opinions in reference to the circulation within the cranium are very generally entertained, and that these errors obstruct our advances in the pathology of a most important organ," set himself to the task of establishing "more correct principles on this part of the physiology of the brain." *

* "On Disorders of the Cerebral Circulation," p. 2.

"Many physicians of high attainments have directed their attention to the peculiarities of the circulation within the cranium; and they, from experiments and reasonings founded on the mechanical construction of the cranium, have arrived at the conclusion that the absolute quantity of blood within the cranium is at all times nearly the same." He then undertakes to give a "concise account" of Dr Kellie's experiments, and adds: "As I proceed with this abstract I shall detail analogous experiments performed by myself. The physiological conclusion deduced from them will contrast very forcibly with the opinions on this peculiarity of the cerebral circulation which have been maintained by Dr Abercrombie, Dr Kellie, and other modern British authors."

The experiments of Dr Burrows were as follows:—(1.) A full-grown rabbit was killed by opening the jugular vein and carotid artery on one side of the throat, and another was strangled. In the brain of the former scarcely the trace of a blood-vessel was seen, and in the other every vessel was turgid with blood. (2.) Two rabbits were killed with prussic acid, and while their hearts were still pulsating, they were suspended for twenty-four hours, the one by the ears, and the other by the hind-legs. In the former, the internal and external parts of the head were in a state of complete anæmia, and in the other there was a most intense congestion of similar parts. (3.) Lastly, two were destroyed by placing ligatures around the trachea, and one of these was suspended by the ears immediately after death; the other was laid upon its side. In the former the blood-vessels of the head were depleted, and in the other the congestion produced by apnœa was uninfluenced.

The following are the inferences Dr Burrows drew from his experiments:—

1. "That it is not a fallacy, as some suppose, to assert that bleeding diminishes the actual quantity of blood in the cerebral vessels. By abstraction of blood, we not only diminish the momentum of blood in the cerebral arteries, and the quantity supplied to the brain in a given time, but we actually diminish the quantity of blood in the vessels." *

2. "That the principle of subsidence of fluids after death operates on the parts contained within the cranium as well as upon those situated within the thorax or abdomen." †

3. "That in the majority of instances, when death takes place from strangling, hanging, suffocation, drowning, and other means of causing apnœa, that a congestion of the cerebral vessels is found after death. The same condition is also found after death from those diseases which obstruct the return of venous blood from the brain." ‡

4. "That the results of experiments show that a diminution of the quantity of blood in one set of vessels is not necessarily accompanied by a state of repletion of the other system of vessels." §

In short, "I think that experiments and physiological considerations lead us to the conclusion that the quantity of blood within the cranium is extremely variable at different times, and under different circumstances." ||

* *Op. cit.*, p. 15. † *Ibid.*, p. 18. ‡ *Ibid.*, p. 28. § *Ibid.*, p. 31. || *Ibid.*, p. 32.

Before examining those propositions, let us see what "doctrine" Dr Burrows proposes to substitute for that of Dr Kellie.

"Those who have maintained this doctrine of the constant quantity of blood within the cranium have not, I believe, taken into due consideration that large proportion of the contents of the cranium which consists of extra-vascular serum. We know that in health the quantity which exists in the ventricles, membranes, and substance of the brain, is considerable. Regarding this serum as an important element of the contents of the cranium, I admit that the whole contents of the cranium, that is, the brain, the blood, and this serum together, must be at all times nearly a constant quantity." *

Now, we may unhesitatingly challenge any one to point out a single particular in which this doctrine differs from that of Dr Kellie. The latter refers repeatedly to the draining of red blood being compensated by an increase of serous fluid. On this point it is no difficult matter to convict Dr Burrows of the indiscretion of *suppressio veri*. For example, the following is quoted as the summary of results from Kellie's paper, and I have added within brackets the sentences that have been omitted.

"The summary of these observations is thus stated: that though we cannot entirely or nearly empty the

* *Op. cit.*, pp. 32, 33.

vessels of the brain as we can the vessels of other parts of the body, it is yet possible by profuse hemorrhage to drain it of a sensible portion of its red blood." [*That the place of this spoliation seems to be supplied both by extra- and intra- vascular serum, and that watery effusion is a pretty constant concomitant or consequence of great sanguinous depletion.*] "If instead of bleeding *usque ad mortem*, we were to bleed animals more sparingly but repeatedly, there is no doubt we should succeed in draining the brain of a much larger quantity of red blood, *although serous effusion would be increased.*"

Instead of the concluding part of the sentence which I have put in italics, Dr Kellie's words were :—

"*But in such experiments we should, I think, find a larger effusion of serum, and be satisfied that many vessels destined to circulate red blood were filled with serum only, and even the larger trunks with a very thin and diluted blood.*"

These quotations require no commentary.

Throughout his argument Dr Burrows overlooks the significance of the expression Dr Kellie so frequently uses, viz., "*red blood.*" Of course, in 1822, when the paper was published, the microscope was not the everyday instrument of research it is now, else we might have had more exact details as to the proportion of *red corpuscles.* It is well known that the effect of bleeding is largely to diminish the proportion of these corpuscles, and that in cases of persistent bleeding complete anæmia results. It appears to me, therefore, that the only experimental test that is necessary is to ascertain the state of the encephalic circulation after sudden decapitation. The brain may be examined as soon as bleeding from the vessels has ceased.

Again, the specific gravity of the corpuscles is greater than that of the serum, and when the circulation ceases they must tend to gravitate toward the lowest part of the body. When a dead animal, therefore, is suspended by the ears, the corpuscles will steadily gravitate from the venous sinuses of the skull, but an equal bulk of serum must ascend, otherwise a vacuum would be produced. Conversely, the veins within the head may become completely packed with red corpuscles by the displacement of the serum. Such facts are completely in accordance with the truth of the "Edinburgh dogma." The array of authorities quoted by Dr Burrows to prove that such a state as congestion of the brain occurs is quite beside the question. Our authors would have been the first to admit its frequent occurrence. For example, if interstitial wasting of brain tissue takes place from inflammatory or other form of diseased nutrition, increase of blood, or serum, or both, according to their views, becomes an absolute necessity.

"But," says Dr Burrows, "the principle of subsidence of *fluids* after death operates on the parts contained within the cranium as well as upon those situated in the thorax or abdomen." To this surprising statement we can only answer that if it occurs in the case of the rabbit, it simply shows that the rabbit's skull is not sufficiently rigid to resist the weight of the atmosphere.* His reasoning, however, requires closer examination. He says :—

"Does the anatomical structure of the human cranium warrant the opinion that it is a complete sphere capable of removing its contents from the influence of atmospheric pressure? I think not. The numerous fissures and foramina for the transmission of vessels and nerves through the bones of the cranium appear to me to do away with the idea of the cranium being a perfect sphere, like a glass globe, to which it has been compared by some writers. If there were not always an equilibrium of pressure on the parts within and without the cranium, very serious consequences would arise at the various foramina of the skull. Are then the contents of the cranium removed from the influence of the atmospheric pressure? I think not from other considerations. Atmospheric pressure is undoubtedly exerted on the blood in the vessels entering the cranium. This pressure, by a well-ascertained law in hydrostatics, must be transmitted in all directions through the fluid blood, and hence to the blood and other contents of the cranium."†

Instead of thus making indefinite queries and statements, it would surely have been more to the point if

* We may here remark that, while the experiments of Kellie were made on sheep and dogs, those of Burrows (also, all those by Kussmaul and Tenner) were made on rabbits. Now, if a perfect hecatomb of "such small deer" were made, and the results appeared to prove that the weight of the atmosphere can bear directly on the cranial contents—for that is really the question—we should yet prefer to abide by the decision of common-sense, which, very emphatically, is to the effect that in the adult cranium, the contents are not—cannot be—affected by any such influence.

† *Op. cit.*, p. 35.

Dr Burrows had enlightened us by specifying even *one* foramen through which the atmospheric pressure can directly bear on the interior of the completed cranium. To common-sense vision there is none. For example, the optic foramen, so large and obvious in the bare skull, is in the natural state of the parts made completely secure. If a tendency to the formation of a vacuum should occur within the cavity, the eyeball would only be more firmly pressed into the socket,—if the eyeball be removed, the fibrous adhesions of the optic nerve would have to give way before the cranial interior could be affected by pressure from without.

As to the serious consequences that would arise at the various foramina "if there were not always an equilibrium of pressure on the parts without and within the cranium," he answers himself in the next sentence. He there shows how a constant communication between the pressure outside and the organs within the skull is kept up through a fluid medium. So long as the circulation goes on, therefore, the means of preserving the strictest equilibrium are present.

In reading the latter remarks quoted above from Dr Burrows, the inference might fairly be made that previous writers had overlooked the circumstance that the weight of the atmosphere can affect the interior of the cranium through the blood-vessels, the truth being that this fact was an essential part of the argument of Monro and the other writers. Dr Burrows himself gives the following quotation from Abercrombie:—"The cranium is a complete sphere of bone, which is exactly filled by its contents, the brain, and by which the brain is closely shut up from atmospheric pressure, and all influences from without, *except what is communicated through the blood-vessels which enter it.*"

In the early part of his essay Dr Burrows says:—"I am more strongly induced to give an abstract of these (Dr Kellie's) experiments, because I suspect that most writers on the subject subsequent to Dr Abercrombie's publication have been satisfied with his allusions to the experiments of Dr Kellie, and that few have taken the trouble to analyse the original account of them." I have only to express the hope that any physiologist taking an interest in the subject of the encephalic circulation, may not be satisfied with the account of Dr Kellie's views and experiments as given by Dr Burrows. The more closely the essay on "Some Reflections on the Pathology of the Brain" is studied, the more must we admire the clear common-sense views of the author, and the cautious method of inference which he manifests at every step of his argument. In forsaking the track he so well entered on and prosecuted, biologists have been neglecting a field of inquiry which is not more interesting than it is certain to be fruitful.

The above was written several years ago without any reference to the review of Dr Burrows' volume by Dr John

Reid (" Edinburgh Monthly Journal of Medical Science," August 1846; also " Physiological and Pathological Researches"). The line of argument I had independently taken is in many respects similar to his. In Dr Reid's essay, however, many points to which I have not alluded are carefully considered. For example, the views of Dr Burrows on " compressibility," the " movements " of the brain, and, especially, his remarks on the appearances found in the brain after death by strangulation are acutely criticised. In regard to the cerebro-spinal fluid, Dr Reid writes as follows:—" We feel confident that our author has magnified the amount of influence which this fluid exercises upon the quantity of blood in the vessels within the cranium; at least there can be no question that he can adduce no proof of many of the statements he has advanced. It is well known that there is found very little of this cerebro-spinal fluid—in fact, in general, little more than what is sufficient to moisten the surface of the membranes—in the interior of the cranium, in healthy persons, up to the middle period of life. Under these circumstances, the quantity of cerebro-spinal fluid that could be displaced from the interior of the cranium must be trifling."

B.

MR DURHAM ON "THE PHYSIOLOGY OF SLEEP."

In Guy's Hospital Reports for 1860, an important essay on the Physiology of Sleep appeared from the pen of Mr Arthur E. Durham. The views expressed in this paper have largely influenced the opinions of other writers on the subject. The author gives the results of some experiments on animals to determine the condition of the brain during sleep. Similar experiments have been made by Dr William A. Hammond of New York. The conclusion arrived at by both these authors is, that during the continuance of sleep the whole mass of blood within the cranium is diminished. The following is Mr Durham's account of "one or two of the most successful" of his "numerous experiments and observations":—

"A dog having been thoroughly chloroformed, a portion of bone as large as a shilling was removed from the parietal region of the skull by means of the trephine, and the subjacent dura mater partially cut away. The portion of brain thus exposed seemed inclined to rise into the opening through the bone. The large veins over the surface were somewhat distended, and the smaller vessels of the pia mater seemed full of dark-coloured blood; no manifest difference in colour between the arteries and veins could be perceived. The longer the administration of chloroform was continued, the more distended did the veins become. As the effects of the chloroform passed off, the animal sank into a comparatively natural and healthy sleep. Corresponding changes took place in the appearance of the brain; its surface became pale, and sank down rather below the level of the bone; the veins were no longer distended; a few small vessels, containing blood of arterial hue, could be distinctly seen, and many which had before appeared congested, and full of dark blood, could scarcely be distinguished. After a time the animal was roused; a blush seemed to start over the surface of the brain, which again rose into the opening through the bone. As the animal was more and more excited, the pia mater became more and more injected, and the brain substance more and more turgid with blood; the surface was of a bright red colour; innumerable vessels, unseen while sleep continued, were now everywhere visible, and the blood seemed to be coursing through them rapidly; the veins, like the arteries and capillaries, were full and distended, but their difference of colour, as well as their size, rendered them clearly distinguishable. After a short time the animal was fed, and again allowed to sink into repose; the blood vessels gradually resumed their former dimensions and appearance, and the surface of the brain became pale as before. The animal slept in a perfectly natural manner. The contrast between the appearances of the brain during its period of functional activity and during its state of repose or sleep was most remarkable."

On these interesting experiments I may be allowed to remark, in the first place, that the facts immediately observed on the dura mater being cut away appear confirmatory of the views I have expressed in my essay. The circulation of the pia mater is venous, and the brain tissue is comparatively bloodless; that is to say, the balance of the circulation is proved to be altered.

The objection immediately presents itself, that the comatose condition induced by chloroform is not sleep. That is at once granted. The degree of unconsciousness is much greater, and the physical changes in the brain are likely to be more decided. But the immediate physiological conditions are perfectly analogous. In ordinary sleep there is a flagging interchange between the blood and the tissue, in consequence of the latter having a lessened attraction for the oxygen of the former; the effect of chloroform is to check the interchange by displacing the oxygen itself to a greater or less extent. The absence of sufficient reaction between the blood and the tissue molecules being the reason, in both cases, why the capillary circulation becomes weakened, the ultimate result—an altered balance of the circulation—less blood within the solid structures and a greater volume in the veins—must be the same in both. Any difference will be one of degree; just as in different sleepers, or in the same individual at different times, we have also great differences. In light, easily broken sleep, the venous distension may be very slight; while in those who sleep heavily and snore loudly, it is likely to be greater.

"But," says Mr Durham, "when the effects of the chloroform go off, and sleep becomes natural, all the vessels seen become contracted and almost emptied of blood, and the surface of the brain is pale." Against this observation I place the facts of a case of brain exposure, "in which accident has prepared the experiment for us," reported by Dr Kennedy, and which I have already quoted in a previous essay.* Here the opening in the skull was "of considerable size," and the case was under observation for several weeks. Dr Kennedy had frequent opportunity of seeing the patient asleep and awake; and "I never," he says, "saw him asleep that I did not observe *marked congestion of the vessels, more particularly what seemed to be the veins, whilst all the vessels visible assumed a dark hue.*"

At this point, therefore, I have no hesitation in at least asking a verdict of "not proven" on the issue submitted by Mr Durham, viz., that the veins of the pia mater, as well as the arterial and capillary vessels of the cerebral tissue, have less blood in them during sleep than during wakefulness. But a further serious objection remains to be urged. Facts, no doubt, are "stubborn things," but an inference that to the eye of common-sense is plainly deducible from a simple comprehension of correlated facts, is also stubborn. Such an inference is the one by Monro, that the quantity of blood within the cranium cannot be reduced unless an equivalent volume of some other material is simultaneously introduced. Now, if the whole intra-cranial system of vessels be so thoroughly drained, there must be a large vacant space, unless something is made to fill it. We become curious, therefore, to learn how Mr Durham meets this difficulty.

Dr Hammond never once alludes to the possibility

* See p. 103.

of such an objection being raised. In watching the exposed brain as sleep was coming on, he found that "its volume slowly decreased; many of its smaller blood-vessels became invisible, and, finally, it was so much contracted that its surface, pale and apparently deprived of blood, *was far below the level of the cranial wall;*"* and assuming it to be "sufficiently established" that "sleep is directly caused by the circulation of a less quantity of blood through the cerebral tissues than traverses them while we are awake," he passes on as if there was no difficulty in the way.

The following is the manner in which it is disposed of by Mr Durham:—

"It is obvious enough that the total contents of the cranium must be a constant quantity. Now, the variations I have described in the amount of blood in the encephalic vessels are accompanied by corresponding variations in the amount of cerebro-spinal fluid in the ventricles of the brain and in the sub-arachnoid spaces. That this is not only possible, but true, may be easily proved by experiment and by observation in cases of fractured base of the skull, in which accident has prepared the experiment for us.

"The rapidity with which the cerebro-spinal fluid can be absorbed and produced is established by the original investigations of Magendie, confirmed and extended by those of Hilton, Ecker, and other physiologists; the correctness of whose conclusions may readily be tested by the repetition of their experiments. It is evident from the anatomy of the parts that, as the encephalic vessels become distended, the fluid can easily pass from the ventricles to the base of the

* "On Wakefulness," p. 30. The *italics* are mine.

brain, and from the sub-arachnoid spaces within the cranium into that of the spinal canal. When, on the other hand, the amount of blood in the vessels undergoes diminution, the pressure of the atmosphere on the surface of the body (transmitted by the soft tissues) causes the re-ascent of an equivalent amount of cerebro-spinal fluid. The force thus exerted seems to have been overlooked by those who have been at a loss to account for the rise of the fluid from the vertebral canal.

"Again, when the distension of the blood-vessels is lessened, the pressure to which they are subject is also lessened to a corresponding extent, and thus the effusion of fresh serous fluid is promoted." *

In regard to the statement that "the fluid can easily pass from the ventricles to the base of the brain," it may be mentioned that this is denied by eminent anatomists. Dr Todd, for example, has the following observations on this point:—

"Does the internal fluid communicate with the sub-arachnoid space? Magendie affirms that a communication takes place by means of an opening which is situated at the inferior extremity of the fourth ventricle. I have not been able to satisfy myself of the existence of such an opening. . . . My own opinion is, that this orifice does not exist naturally, but that it is produced by the violence to which the brain is subject in its removal, or in the manipulations necessary for demonstrating it. It appears to me that the fourth ventricle is closed in the same way as the inferior horn of the lateral ventricles, namely, by the reflection of its proper membrane from its floor on to the adjacent pia mater." †

* "Guy's Hospital Reports for 1860," pp. 157, 158.

† "Cyclopædia of Anatomy and Physiology," vol. iii., pp. 640, 641.

Such a statement from so accurate an observer, should at least convince us that the passage of fluid from the ventricle into the sub-arachnoid space, or *vice versa*, must be slow. Dr Todd believes it can only occur by a process of endosmose.

But supposing the communication to be as free as Mr Durham could desire, we are still at a loss to know what becomes of so much fluid. How is it that after death the quantity found is really very small indeed? Let it be remembered that the brain, in proportion to its size, receives more blood than any other organ of the body,—that, indeed, it is computed that one-fifth of the entire mass of blood is sent to the intra-cranial vessels. Then, judging from the description of appearances as given by Mr Durham and Dr Hammond, and assuming that the whole brain is affected to an extent similar to what they have observed at the trephined opening, it would surely be a moderate calculation to say that one half of the blood must be drained from its vessels during sleep. Therefore, a space equivalent to one-tenth—or, to give a large margin, say one-twentieth—of the whole blood in the body must be taken up with serous fluid. Now, what becomes of it all? Why does it not begin to well out profusely whenever the membranes of the brain are punctured? In most cases the quantity is so small that its presence is easily overlooked. In young subjects very little is found even when it is looked for. In hypertrophy of the brain there may not be a drop of extra-vascular serum; yet we are told that "there is nothing special in the cerebral symptoms which could lead us to the diagnosis of this particular form of malady."* A true theory of sleep must, of course, apply to all classes of cases, but, if Mr Durham's physiology be correct, the subjects of brain hypertrophy should be absolutely sleepless.

Again, if the quantity of serous fluid be increased at the base of the brain, the latter must be pushed upwards. Now, if this happens to even a moderate extent, the nerves in that locality must always be seriously stretched when sleep supervenes. Thus, instead of being a means "to protect the larger vessels and nerves situate there from the unequal pressure of neighbouring parts," it would become a constant source of positive danger. This circumstance alone should show that there are serious fallacies in Mr Durham's argument.

Nor is he at all happy in his explanation of the mechanism by which the fluid can be raised from the spinal canal. "When, on the other hand, the amount of blood in the vessels undergoes diminution, the pressure of the atmosphere on the surface of the body (transmitted by the soft tissues) causes the re-ascent of an equivalent amount of cerebro-spinal fluid." On reading this sentence we are certainly brought to a stand-still. We in vain try to recollect what are the "soft tissues" through which the atmospheric pressure

* Reynolds' "System of Medicine," vol. ii. p. 484

can bear on the serous fluid within the spinal canal. We had supposed that the latter cavity was as much removed from the direct effects of external pressure as are the contents of the cranium. Our first impulse, therefore, is to say that the ascent of cerebro-spinal fluid, by the aid of the atmospheric pressure, is simply a physical impossibility.

It would certainly have been satisfactory if Mr Durham had pointed out with more detail the mechanism he here insists on. The cavity of the vertebral canal is one of fixed capacity, and it cannot be altered by atmospheric pressure. Its contained serous fluid can be raised to the cavity of the cranium only by its absolute quantity being increased, or by some immediate engorgement of the spinal veins. In the case of the encephalic veins, we are able to trace how, through the "soft tissues" of the neck, the jugular veins may be subjected to the influence of atmospheric or any other form of pressure; how, according to a simple law in hydrostatics, the force so occasioned must be communicated through the sinuses of the dura mater to the blood flowing in the veins of the pia mater; and I have ventured to infer that if vascular pressure within the brain itself be lessened, distension to a greater or less extent in these veins becomes a *physical necessity*. But I can see neither necessity nor probability for the opinion that lessened vascular pressure within the cranium could cause engorgement of the spinal veins. Are the lumbar, or intercostal, or any of the other venous channels by which blood is returned from the canal, more directly exposed to the pressure of the atmosphere than the internal jugular? Would artificial pressure from without assist in the least degree to raise a single drop of either venous or serous fluid from the spinal canal into the cranial cavity? I cannot believe it, unless, as in spina bifida, a deficiency has occurred in the bony covering of the cord. Until Mr Durham, therefore, shall point out with some detail the mechanism by which the atmospheric pressure can cause the ascent of the fluid, we may insist that such ascent, if not a physical impossibility, is, to say the least, a physiological improbability.

Mr Durham proceeds: "Again, when the distension of the blood vessels is lessened, the pressure to which they are subject is also lessened to a corresponding extent, and thus the effusion of fresh serous fluid is promoted." Now, in what circumstances do we actually find an accumulation of serous fluid within the head? Is it not in those cases in which we may with confidence predicate increased pressure within the vessels, or diminished support outside of them? For example, it occurs in inflammatory diseases,—is there lessened pressure in these? Would lessened pressure cause the sutures of the cranial bones to be opened up even after they have seemed to be fairly knit? Effusion is also found in the cases of coma that have been brought on by exposure to intense cold,—is there not decidedly increased pressure in these? It is, further, to be met with in old age, when the cerebral tissue has become atrophied, and when, in consequence, we may suppose the external support of the vessels has become weakened.

Mr Durham lays great stress on the fact, and he repeatedly alludes to it, that in cases of fracture at the base of the skull "the cerebro-spinal fluid does not flow at all, or flows very slowly, from the ear during sleep, but begins to flow afresh as the patient wakens up. This fact," he says, "affords striking confirmation of the hypothesis advanced in the present paper." It appears to me that the fact tells just as decidedly in the opposite direction. If the atmospheric pressure causes the spinal fluid to well up into the cranium during sleep, why should it just at that particular period cease to flow from the ear? If it came with a sudden spurt on the patient waking up, and then as suddenly ceased, the drift of the argument could be understood; but if it goes on during the period of wakefulness, it simply shows that the flaw in the uniform support which the vessels usually receive on their external surface permits direct effusion to occur more abundantly when the increased vascular pressure which accompanies functional activity has set in.

Mr Durham's further speculations on the physiology of sleep are of great interest. I do not require, however, to enter on the consideration of these. I have wished to restrict myself to those points on which our views are hopelessly antagonistic, and I now leave it for others to determine on which side the greater amount of probability may lie.

C.

DR PLAYFAIR ON SLEEP AND SOME OF ITS CONCOMITANT PHENOMENA.

AMONG the various theories that have been formulated as to the induction of sleep, one which has been undeservedly overlooked by physiologists is that submitted by Dr (now Sir Lyon) Playfair.* The title of his paper is "On the Function of Oxygen in Relation to Sleep and some of its Concomitant Phenomena." It is an elaborate essay, and deserves the attention of all who are interested in the physiology of the brain.

After an introduction on the general importance of oxygen in the system in a number of what would now be called katabolic changes, he proceeds :—

"The great distinction between animal and vegetable life is volition. Vegetables not being possessed of volition, are constantly engaged in increasing their fabric ; and therefore when volition ceases in the animal, it is aptly said to have a

* "Northern Journal of Medicine," January 1844. Also, "Phrenological Journal," October 1844. The latter is the source from which my extracts have been taken.

vegetative life,—for the vital powers are wholly employed in increasing the mass of the body. Sleep is the time when an animal becomes assimilated to a vegetable. Physiologists have shown that the two most marked points during sleep are, diminished respiration and decreased circulation. They are agreed that, towards the evening, or at the lapse of a certain number of hours of work, the involuntary organs—the heart and lungs—lose their wonted activity, and suffer a periodical diminution of action. Blumenbach describes the case of a patient trepanned, in whom the brain was observed to sink during sleep and enlarge on waking, obviously arising from the circulation being diminished in the former state, and increased in the latter. The consequence of this diminution is, that less oxygen is taken into the system. Hence the proportion of venous blood is increased, and the waste caused by arterial blood is diminished. The skull, being a close cavity, must contain a larger proportion of venous, if there be a diminution of arterial blood in the body. It is the latter alone which can cause the waste of the brain,—for venous blood has already parted with its oxygen to materials met with in its course.

"Matter in a state of inertia can never manifest the existence of a power. Its motion alone shows that some power is in operation. If the portion of matter used as the organ of manifestation be placed in such a condition as to render that manifestation impossible, there is no evidence to the external world that power was exerted. It has been perfectly demonstrated, that every manifestation of power in the voluntary organs is accompanied by a change in the matter of which they consist. The changed matter being now unfit for vital structures is separated from the body. Müller and all other eminent physiologists are of opinion, that the same change takes place in the brain—the organ of the mind. In fact, the contrary opinion involves such violation of analogy, that its adoption, unless founded on the strongest grounds, is inadmissible. We look upon a spot attentively; it gradually waxes dimmer until it finally disappears. We think upon a particular subject; in time our thoughts are less clear, soon they become strangely confused, and we are obliged to give up the attempt at concentration, by thinking on a subject quite different from that which first engaged our thoughts. This, of course, implies that the organs of manifestation have become in part destroyed, and that the mind cannot manifest itself to the world, until the impaired organs have attained their proper integrity; for it cannot be conceived that the mind, disconnected with matter, could suffer exhaustion. This involves, it is true, the idea that different parts of the brain are employed in different manifestations; but we know that as far as sensation and intellect are concerned, this is the case, and probability indicates a still more minute division. If, therefore, the brain suffer changes, as do the other organs of the body by their exercise, there is as much necessity for repose in the action of the brain as there is for a vegetative state of existence to reinstate, in their full integrity, the organs of volition. Hence the necessity for that quiescent state of the mind known as sleep, when its manifestations cease. The waste of cerebral substance could only have been occasioned by oxygen, which is the only ultimate cause of waste, as far as we are aware, in the animal economy. A deficiency in its supply would, therefore, retard waste, and allow vitality to remodel its impaired structures.

"Such, then, is the state into which the body is thrown by the periodical diminution in the action of the heart and lungs. The less rapidly that the heart beats, the less rapidly can the blood be aërated, and the oxygen-bearing fluid can be supplied to the brain. The slower that the lungs act, the slower must oxygen enter the system to supply the diminished circulation. And as the brain in sleep is not in a state in which it can change, from a deficiency in the supply of oxygen, the consequence is (if it be admitted that the manifestation of thought and sensation is accompanied by changes in the material substance of the brain), that the manifestations of the mind are prevented, and it becomes no longer apparent to the external world.

"This, then, is Sleep. But if the theory be correct, it must be able to explain the various circumstances which occasion or act as predisposing causes to the production of this state, and if it fail in the explanation of any of these, then is the theory imperfect; but if it explain more of them than the other theories usually received, such as those of Cullen, Blumenbach, Park, and others, it deserves to be considered as a nearer approximation to the truth, and the cases which it fails to comprehend may be included as our knowledge advances."

In support of these views the author refers to a number of conditions which appear to favour the induction of sleep by interfering with the free supply of oxygen. He considers the recumbent posture favourable to sleep, because having thus "acquired a retarded flow, the blood now comes less rapidly in contact with the organs of respiration, on which the same posture has produced a diminished action, and thus the quantity of arterial blood in the body becomes diminished. Though, therefore, all the vessels in the brain remain as full as they did before, yet, by the deficient supply of oxygen, or, in other words, of arterial blood, and by the retarded circulation of that which does exist in the cavity of the skull, the causes of waste are diminished; and, therefore, according to the theory, sleep is produced."

He then proceeds, at some length, to illustrate his views by a reference to various facts in pathology and natural history. He is thus led to detail many points of interest which, he believes, show that "the tendency to sleep in different animals is in inverse proportion to the amount of oxygen consumed by them, and to the amount of carbonic acid produced."

The theory of Dr Playfair appears to fail principally in the way of short-coming. Its scope is too narrow and too purely chemical. Indeed, the author himself admits that "chemists are too apt to fall into the sad error of converting the animal body into a laboratory." But it is impossible to over-rate the importance of oxygen as a factor in nervous action. His thesis that "anything which removes oxygen from the blood will cause sleep" is indisputable. If the effects of chloroform or ether had been known when the paper was written, they would have afforded an important argument in favour of his views,—as, in all probability, these effects are produced by the agent being able to displace the oxygen in the blood to an extent incompatible with the proper exercise of function.

All the author's illustrations bear on points that imply a *deficiency in the supply* of oxygen to the brain, but not a little might be said in favour of the view that, in the production of *healthy* sleep, the initiatory step is rather a *diminished attraction* for that element on the part of the brain molecules.

In the body of this work I have argued that neither diminished molecular action alone, nor decreased circulation alone, nor these two conditions combined, are adequate to give a sufficiently comprehensive theory of sleep. The same line of argument will apply to a simple deficiency in the supply of oxygen. Any one of these conditions, if carried to a certain extent, will most assuredly produce a state of unconsciousness. But something more than such a fact is required to make the theory of sleep *totus, teres et rotundus.* It must make provision for the thousand and one modifications in regard to facility, depth, duration, &c., which varying circumstances may induce or require.

D.

MR CHARLES H. MOORE "ON GOING TO SLEEP."

THE little volume by Mr Moore is a remarkably pleasing and instructive work. His detailed observations on the phenomena of sleep, and on the requirements of any theory of its mechanism, are very ingenious and interesting. His own views, intended apparently as a complement to those of Mr Durham, ascribe an important office in the ganglionic nerves in inducing sleep. These are supposed to act on the arterial vessels, causing their contraction, and so lessening the circulation of the brain to an extent inconsistent with activity of function.

"The mechanism of sleep is no mere weariness of the brain itself, no chemical process for clearing its texture, no voluntary suspension or gradual causeless subsidence of its activity; it acts with power, putting the functions of the brain into compulsory abeyance, and depriving the subsidiary organs of their sense.

"Compulsion like this is clearly not exercised by the parts which sleep and wake, but by a separate mechanism. . . . Now, the functional repose of the brain would be secured by a sufficient but not an excessive reduction of its arterial circulation. . . . It may be taken without question that the reduction of the quantity of arterial blood in the brain is effected by contraction of the arteries themselves.

"If now it be considered reasonable to conclude that the contraction of the arteries conveying blood to the brain is the immediate cause of sleep, the question may next be entertained, under what control this contraction takes place? Assuredly, that power is not left with the brain itself. . . . The cause of the contraction of the arteries is not far to seek,—since it cannot be cerebral, it must be ganglionic. The brain does not send nerves to its own arteries. They are supplied from the sympathetic system. Around the carotids is a large number of them, proceeding from the first great ganglion in the neck. The vertebrals receive their endowments in less abundance, and chiefly from the second and third cervical ganglia. . . . If ganglia can produce contraction of the blood-vessels of a gland, with the effect of arresting its secretion, they may by the same means interrupt the activity of even so mighty an organ as the brain."

"Wakefulness opens the arteries, superseding the influence of the ganglion over them. . . . The first power, that of the brain, overwhelms the less, which is that of the ganglion. Let the first moderate, the influence of the second rises. It is not necessary to conceive this latter as more than an automatic action—a resumption by the ganglion of its natural energy—

which is forthwith expended upon the muscle with which it is connected. Be the brain, therefore, weary or bewildered out of its attention, or soothed by a monotonous sound, or simply unoccupied, straightway the ganglia, set free for separate action, usurp supremacy, not over the brain, but over the arteries. The exact proportion of activity between the brain and the cervical ganglia, which is requisite for setting the latter free, is a matter of degree only, and is, from the nature of the case, undefinable and possibly variable. . . . At any moment, when the attention of the brain is unconcentrated, instantly the ganglia become uncontrolled and primary nervous centres, and reduce the size of the arteries." *

We need not long be detained by any criticism of these views. Of course, I shall not be expected to agree with the author when he says, "it may be taken without question that the reduction of the arterial blood in the brain is affected by contraction of the arteries themselves." As I have already pointed out, the exit of blood from the cranium takes place under the opposing pressure of the atmosphere. This opposition has effect backwards through the sinuses of the dura mater to the minute venous radicles of the pia mater. It tends to prevent more blood from entering these from the capillaries, and it reacts against the internal surface of the veins through their whole extent. To accomplish the movement of blood, therefore, active internal forces are necessary. The action of the heart affords the primary condition of a supply of arterial blood; the molecular

* "On Going to Sleep."

affinities between the blood and the tissue constitute, more immediately, a direct, active, antagonistic force. Let the rapid and powerful affinities that accompany activity of function be weakened, either from exhaustion on the part of the tissue, or from a less stimulating quality of blood being supplied, and an altered balance of the circulation becomes inevitable, although the arterial vessels were to continue as dilatable as before. This argument, however, has already been stated oftener than once, and its details need not be repeated here.

Still, I am by no means inclined to question that the ganglionic nerves may have an important influence in favouring the contraction or dilatation of the arterial vessels. But before that influence can be made the foundation for a theory of sleep, we would require to have much more definite information as to its mode of operation, and its analogous action in other organs, especially in those whose function is periodic. It will be observed that Mr Moore restricts attention to the inhibitory action of the ganglia, but if we look a little further, we are just as much impressed with their stimulating action. When the stomach is quiescent, would it be considered a philosophical explanation to say that the secretion of gastric juice is suspended on account of the positive energy of the ganglionic nerves being exerted to keep the gastric arteries contracted? Or, when the secretion of milk begins, is it sufficient to say that the inhibitory action of the sympathetic system on the vessels of the mammary gland has been overcome? If difficulties stand in the way of such explanations being received in these instances, it is not likely that Mr Moore's theory of the causation of sleep can be accepted without considerable qualification.

But let us suppose that this view is, nevertheless, correct, and that the action of the ganglionic nerves to produce contraction of the cerebral arteries is an essential condition of sleep being induced. Such an admission would still give only a limited view of its causation. In illustration, we may recall the circumstance that, as we have seen, Dr Lyon Playfair regarded sleep to be constituted by a diminished combustion of the cerebral tissue. Now, no one denies that, during its continuance, the affinities between the oxygen of the blood and the molecules of nervous substance are less powerfully exercised than in wakefulness, but that does not explain the mechanism of sleep. It is an important fact among the necessary factors, but not a solution of the problem. It ignores the mass of anatomical and physiological detail which surrounds the question. So, if the action of the ganglionic nerves were proved to be as powerful as Mr Moore believes, it would still be only one item among the essential conditions. By itself it would be insufficient to cover all the phenomena involved. An altered balance of the cerebral circulation would still be imperative, and would more completely fulfil what Mr Moore insists to be necessary—

"Compulsion not exercised by the parts which sleep and wake, but by a separate mechanism." Indeed, it may safely be asserted that no theory which leaves out of view the physical surroundings of the brain, and the almost self-evident deductions from these as to the peculiarities of its circulation, is likely to give more than a limited and unsatisfactory explanation of the more important workings of the brain, whether in the sleeping or in the waking state.

E.

DR MARSHALL HALL'S THEORY OF SLEEP.

As a contrast to the views of Mr Durham, and going to the opposite extreme, I may simply allude to the theory of Dr Marshall Hall. According to this writer, sleep is allied to epilepsy, and has a like causation.

"I am of opinion that a state of contraction of certain muscles of the neck takes place, analogous to that of the orbicularis palpebræ, as sleep comes on,—that certain veins are compressed,—that congestion of the brain takes place,—and, lastly, as a consequence of this last, *sleep*. . . . In sleep, the entire encephalon is in a state of congestion, the medulla oblongata included." *

This state of congestion included the capillary vessels (or *blood channels*, as Dr Hall preferred to call them).

* "Practical Observations and Suggestions in Medicine." Second series.

As I believe this view is discarded by all physiologists, I do not require to criticise the mechanism by which the condition is supposed to be brought about. It is, however, an interesting item in the history of opinions on the question.

F.

ON COMPRESSION OF THE CAROTIDS.

In connection with Dr Fleming's experiments on compression of the carotid arteries, it may be interesting to give the following curious observations from Bell's "Anatomy of the Human Body."

"The carotid arteries are also named the Arteriæ Cerebri, as if they were the sole arteries of the brain, and the ancients, either ignorant or forgetful of there being any other arteries for the brain, or not observing that the vertebral arteries might convey blood enough for the functions of the brain, did actually name the carotids the Arteriæ Soporiferæ, believing that, if they were tied, the person must fall asleep. The name which we use, viz., that of carotids, is synonymous in Greek with Arteriæ Soparales. How a person might die from having the great arteries of the head tied, I can most readily conceive; but how he should rather fall asleep, and not die, is quite beyond my comprehension; and yet many of the best anatomists, in the best age of anatomy, have abused their time repeating these experiments.

"Valsalva, Van Swieten, Pechlinus, Lower, and especially Drelincurtius in his 'Experimenta Canicidia,' and many others, spent days and weeks in tying up the carotids of dogs. What does all this imply? Surely a strong belief in tales which would disgrace the Arabian Nights,—tales concerning a manner of tying a cord round the neck of a She-goat, or even of a young Man, so that, without hurting them, they should be made to sleep or wake, according to the bidding of the spectators.

"Costæus first tells this tale:—'Circumforaneous mountebanks (says he) often perform this miracle. They tie a ligature round the jugular veins of a She-goat, and they tighten it and relax it from time to time, so that, at their pleasure, the animal falls down motionless and stupid, and at their bidding leaps up again with great vigour.' The most incredible tales soon followed, and soon crept into otherwise good and useful books. Even Hoffman seems not unwilling to believe that the Assyrians had been in use of tying up the jugular veins in their young men before circumcision, that they might feel less pain. A serious operation, God-wot! for so slight a cause. Even Morgagni talks more seriously of the She-goat, and of this snibbing of the young men of Assyria, than one could wish in respect of the character of one so truly great as Morgagni. But the person the most celebrated in this affair was Realdus Columbus; and the wildest and most barefaced tale that ever was told, is that delivered by his pupil Valverda, in his 'Anatomy of the Human Body.'

"'The carotid arteries (says Valverda) being tied up, or anyhow obstructed, the person grows stupid, and falls presently into a profound sleep. This experiment I saw at Pisa in the year 1554. It was performed upon a young man by the celebrated Columbus in the presence of a great many gentlemen and strangers, with no less misery to them than amusement to us (the pupils), who, though we knew the cause, ascribed it altogether to the black art.' But if any one word of this were true, Valverda would have told us, and been proud to tell us, by what particular operation, ligature, or pressure, this strange thing was performed; and Columbus himself, the author of this new amusement, would surely have dropped some hints about it in some place or other of his works. But from the modest silence of the master, and the secrecy of the pupil, we have reason to believe it is untrue; and if Columbus ever did venture to exhibit such a mean piece of legerdemain, he put himself quite upon the level with the quack and his She-goat. The quack, indeed, was much beyond him in point of merit, since it must have been far easier to teach a clever young man to fall down or start up than to teach all this to a She-goat."*

G.

COMA FROM DEPRESSED BONE.

As illustrating the effects of compression of the brain we may give in detail a case reported by Sir Astley Cooper, where consciousness was restored by trephining the skull, after a state of coma had continued for many months.

"It is a case which, whether we regard it in a physiological or surgical point of view, is perhaps one of the most extraordinary that ever occurred; and as connected with surgery and physiology, I am surprised it has not made a greater impression on the public mind than it appears to have done. A man was pressed on board one of His Majesty's ships, early in the late Revolutionary War. While on board this vessel in the Mediterranean, he received a fall from the yard-arm,

* "The Anatomy and Physiology of the Human Body." By John and Charles Bell. Vol. ii. pp. 88-90.

and when he was picked up he was found to be insensible. The vessel soon after making Gibraltar he was deposited in a hospital in that place, where he remained for some months still insensible; and some time after, he was brought from Gibraltar on board the *Dolphin* frigate, to a depôt for sailors at Deptford. While at Deptford, the surgeon under whose care he was, was visited by Mr Davy, who was then an apprentice at this hospital. The surgeon said to Mr Davy, 'I have a case which I think you would like to see. It is a man who has been insensible for many months; he lies on his back, with very few signs of life; he breathes, indeed, has a pulse, and some motion in his fingers; but in all other respects he is apparently deprived of all the powers of mind, volition, or sensation.' Mr Davy went to see the case, and on examining the patient, found there was a slight depression on one part of the head. Being informed of the accident which had occasioned this depression, he recommended the man to be sent to St Thomas's Hospital. He was placed under the care of Mr Cline; and when he was first admitted to this hospital, I saw him lying on his back, breathing without any great difficulty, his pulse regular, his arms extended, and his fingers moving to and fro to the motion of his heart, so that you could count his pulse by the motion of his fingers. If he wanted food, he had the power of moving his lips and tongue, and this action of his mouth was the signal to his attendants for supplying this want.

" Mr Cline, on examining his head, found an obvious depression; and thirteen months and a few days after the accident, he was carried into the operating theatre and there trephined. The depressed portion of bone was elevated from the skull. While he was lying on the table the motion of the fingers went on during the operation, but no sooner was the portion of bone raised than it ceased. The operation was performed at one o'clock in the afternoon, and at four o'clock, as I was walking through the ward, I went up to the man's bed-side, and was surprised to see him sitting up in bed. He had raised himself on his pillow. I asked him if he felt any pain, and he immediately put his hand to his head. This showed that volition and sensation were returning. In four days from that time the man was able to get out of bed, and began to converse; and in a few days more he was able to tell us where he had come from. He recollected the circumstance of his having been pressed and carried down to Plymouth or Falmouth; but from that moment up to the time when the operation was performed (that is, for a period of thirteen months and some days), his mind remained in a state of perfect oblivion. He had drunk, as it were, the cup of Lethe; he had suffered complete death as far as regarded his mental and almost all his bodily powers; but by removing a small portion of the bone with the saw, he was at once restored to all the functions of his mind, and all the powers of the body." *

H.

DR B. W. RICHARDSON ON A CASE OF DEATH DURING THE ADMINISTRATION OF ETHER.

In the *Lancet* for July 3, 1875, there is an interesting report of a case of death, with escape of blood into the trachea, during the administration of ether, for an operation on the tongue, from Mr G. H. Bailey, Anæsthetist to the Cancer Hospital and to the Dental Hospital of London. Appended to the report is the following note by Dr Benjamin W. Richardson, F.R.S., who assisted at

* "Lectures on Surgery," Lect.

the *post-mortem* examination. I give it here as supplementary evidence in favour of the view that an altered balance of the cerebral circulation may take place in certain conditions.

"The case recorded by Mr Bailey is one of extreme interest. The mode of death seems to me, from all the facts I gathered from the different observers, to have been as follows. From the deep narcotism induced by the ether, the respiration for a moment became reduced in power, as is not unfrequent under this mode of general anæsthesia. During the artificial respiration, a little blood escaped into the glottis and impeded the efforts of the operators in re-establishing natural respiration. They filled the lungs with air, but did not establish a return current, so the death became pronounced from asphyxia. The heart, as is common under such circumstances (when the lungs remain inflated), continued to beat until it collapsed from deficiency of arterialised blood.

"I have no doubt the man would have recovered under the artificial respiration had the trachea been free of obstruction; and the practical lesson taught in the case is, that in future, whenever the respiration fails during an operation on the mouth and throat, the artificial respiration should be made with double-acting bellows from an opening in the trachea, with the head of the patient brought very low, so as to allow fluid to gravitate from the bronchial tract.

"Physiologically, the case is of interest in that it has, unfortunately, enabled us to see, for the first time in the human subject, the precise conditions induced in the organism by ether administered to complete insensibility. The appearances are identical with those I have seen in the lower animals after death by ether. The blood fluid, the arterial blood dark, the cerebral arteries and veins charged with dark blood, the mucous membranes injected, and the pia mater of the brain, medulla, and cord intensely injected, but the cerebral mass itself white and bloodless. Long ago I classified ether with alcohol, amyl nitrite, and others of the same series, as an agent which by its action on the organic nervous supply of the minute circulation reduces the arterial tension, and produces narcotism by congestion of vessels and suspension of circulation through the cerebral mass. The case before us is a case in point. The whole external vascular mechanism of the cerebrum, cerebellum and cord was distended with blood; the whole of the internal nervous mechanism was bloodless. The facts have a further and important bearing on the suggestive researches and ingenious theories of Dr Cappie upon the cause of the phenomenon of sleep. But the most interesting fact of all taught by the case is, that a perfectly bloodless condition of brain substance may co-exist with intense vascular congestion of the membranous vascular network, the same as co-exists with that empty and contracted state of the vascular network which is induced by chloroform and other narcotic agents of the chloride series. This is a new truth which must not be forgotten in future research."

TURNBULL AND SPEARS, PRINTERS, EDINBURGH.