EXPERIMENTAL STUDIES IN THE INNERVATION OF THE SKIN.

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(*From the Research Laboratories of University College Hospital Medical School.*)

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INTRODUCTION.

IF we make a general survey of our present knowledge of cutaneous sensibility it is at once clear that, in spite of the very great amount of both brilliant and laborious work that has been done, many of the essential problems remain unsolved; and that many pieces of such work have merely yielded disconnected hypotheses incapable of being brought together into any generally acceptable body of theory. It would seem that the latter peculiarity of the case is in some degree dependent on the fact that the investigations have until recently always been made along two widely separate avenues of approach, by observers greatly differing in training and interests. On the one hand we have a great mass of work on the sensory capacity of the normal skin. This work, which we may call the positive or physiological, has been concerned with the enumeration and measurement of the various sensations which may originate in skin possessed of its full sensory functions; the results of the various workers along this path have been on the whole consistent or complementary to one another, and have been obtained by a characteristic group of methods which have undergone continuous development and are to-day of unshaken validity. The essential features of the method are based on the recognition that function in the normal skin is distributed in, and limited to, minute and sharply localised spots. This conception was first established by Blix, it was further elaborated by Goldscheider, and received its final extension to all forms of sensibility from von Frey.

On the other hand the problem has been approached from what we may call the negative or pathological side, an attempt being made to enumerate and measure the various forms of sensory loss shown by skin deprived of its nerve supply. The interest of investigators has always been directed more towards anatomical distribution than towards minutiæ of function, and in correspondence with this fact the methods

chosen have for the most part been strikingly different from those of the physiological school. The work has been dominated by the anatomical conception of definite sharply outlined areas of loss, and little or no attempt has been made until recently to apply the more delicate possibilities of detailed investigation. Work done with these grosser methods, while adding but little to our knowledge of function, has for the most part proved fairly adequate for anatomical purposes, and it is clear that under the circumstances in which it has been carried out but little could be hoped from the finer methods of the physiologist. The latter has always had in the making of his observations the advantage of using as a subject a person possessed of scientific training; the worker in the pathological field has had his material determined for him by disease or accident without reference to intelligence or training.

It was reserved for Henry Head first to conceive the possibility of combining the advantages of both schools, and of obtaining material for investigation on the negative side in a subject who could be selected for his known capacity as an observer instead of by the fact that he had had the misfortune to lose the function of a nerve. The advantages of the combination of methods were shown by the discovery of a number of phenomena that had previously escaped attention. The results obtained showed conclusively how much had been lost by the grosser methods of previous workers on the abnormal, but they were also to some extent in conflict with the physiological work founded upon methods which still seem to be unexceptionable. In regard to this latter want of correspondence it is important to remember that the work of Head presents certain special features. The actual pioneering part of it upon which the new conclusions were based was done upon a single subject and upon a single area of sensory loss.

There can be no doubt that the most satisfactory conditions would be obtained in observations made on several different areas in more than one subject; such observations must possess as evidence certain advantages which cannot be obtained in work upon a single area. After the section of a nerve some considerable time must be occupied in the organisation of methods and in the accustoming of the subject to recognise and to record with precision a large number of abnormal sensations which have the confusing quality of the completely new. Thus the time available for satisfactory examination of the area before change has begun may be considerably limited, possibly even to the extent of interfering with that repetition of testing which is so necessary. Again as soon as the process of regeneration has begun, the picture

presented by the area is a continually changing one, so that the extent to which new experience can be made use of in repeating previous observations in a modified form is much restricted; it is probable that this applies with a special significance to the appearance of the earliest stages of recovery. Unless the subject already knows what to expect we may suppose that it would be very easy for him altogether to overlook phenomena which are in essence so elusive and variable. There can be no doubt then that could technical difficulties be overcome, certain substantial advantages would be obtained if a number of different areas were accessible to examination one after the other, each being used to corroborate observations on the preceding and to study whatever new problems should have been suggested by the work already done. Naturally if material could be obtained in more than one subject the satisfactoriness of the results would be increased.

Such difficulties are twofold: on the one hand the obtaining of the material, and on the other those of the actual observations. It is clear that it is the difficulties in obtaining material that in the past have proved most serious, but it is equally clear that they are merely surgical. The essential requirements are to find with certainty the nerve it is proposed to divide, to carry out the operation without a serious amount of disturbance of the tissues or of the immediate subsequent function of the part, and to ensure complete repair. The trouble in obtaining material seemed to us as surgeons capable of being dealt with, and we felt therefore encouraged in attempting to overcome the other obstacles.

The difficulties of observation are questions of detail which must be discussed later, but a few general remarks may be made here on certain of them. In the first place it may be said at once that there is perhaps no other problem in research which requires the expenditure of so much time in actual personal observation. To examine and record for example the sensibility to cold of a fairly large area takes from 45 to 50 hours, and this in spite of the fact that cold is the easiest and most precise form of sensation to investigate. It is of course clear that such observations must be repeatedly made in each area. When the form of sensation is less precise or is painful, the time occupied may be very much longer. Again, much of the work must be unbearably tedious unless the subject himself is deeply interested, and this is perhaps the most powerful argument against the use of patients as subjects for such research. It is in this relation also that it becomes evident how desirable it is that the person who at any given time is making the

actual observations should know from his own experience how great are the difficulties of tedium and discomfort that the subject has to overcome. As might be expected in a matter involving so great a bulk of minute detail, occasions are unfortunately not infrequent when material laboriously collected is found to be inapplicable; for example at a certain stage of the work we were led to make and record in detail a series of 50,000 separate touches only to discover that the solution we had sought was not to be obtained by that method. It is then that the special interest imparted by the participation of each in both sides of the research is most valuable.

PART I. METHODS OF EXPERIMENTATION.

Material. For reasons already given we were convinced when we undertook this investigation that such work could be based only upon observations made under experimental conditions with a trained observer as subject. We propose therefore to publish here such observations only as we have made upon ourselves. The chief bulk of the material has been obtained through the division by operation of seven cutaneous nerves in one or the other of us, but this has been supplemented by certain other experimental work which it became necessary incidentally to undertake. For example various observations were made on the effect of the injection of adrenalin into the skin and upon the effects produced by the paralysis of a nerve trunk through the injection of a local anæsthetic.

The cutaneous nerves we divided were the following: first the internal saphenous at the knee; six weeks later the great auricular or a main branch of it at the posterior border of the sternomastoid; three months later the posterior division of the internal cutaneous of the arm just below the elbow; a month later the anterior division of the same nerve at the same level; and after a similar interval a branch of the same nerve lying between these two. A month after the division of the last-named, a branch of the middle cutaneous of the thigh was divided just below the sartorius in one of us. Finally after an interval of seven months the corresponding nerve was divided in the other.

The following were the reasons which determined the choice of the several nerves: the internal saphenous presented some anatomical interest as no case of isolated lesion of it had as far as we were aware been submitted to exact observation[1]. Moreover we then thought it advantageous to obtain as large an area of anæsthesia as was possible

from the section of a single cutaneous nerve. The proximity of the area supplied by the great auricular to that of the fifth cranial nerve gave the opportunity of furnishing observations complementary to the investigations of one [2] of us on the latter. The internal cutaneous seemed to present a most favourable opportunity for the section in succession of two nerves which certainly supplied adjacent areas. After the posterior and anterior division had been cut, it was found that there was an intermediate area which still retained sensibility; this was supplied by a third branch of the internal cutaneous, section of which gave us a compact area of anæsthesia made up of three components the distribution of each of which we knew. The desire to make a second observation of a like character led us to divide one of the branches of the middle cutaneous in the thigh. So far it has not proved necessary to deal with the second branch of this nerve. The observations made upon the areas supplied by these six nerves had yielded information which seemed to us to be worthy of reliance, and in some directions to be fairly complete. It had been collected, however, during a period in which the methods of investigation used had been undergoing a more or less continuous development. We felt therefore that although the facts seemed clear they should be submitted to a crucial experiment in which we could employ the more thoroughly systematised methods of investigation that experience had yielded. It was for this reason that after an interval of seven months from the section of the sixth nerve of the series, the second middle cutaneous was divided, this particular nerve being chosen because the resulting area of altered sensibility is very conveniently situated for examination and causes very slight disability.

By a number of dissections on the dead body we attempted at first to establish rules whereby we could find with certainty various cutaneous nerves. It soon appeared, however, that the range of variability was so great that this was impossible without the use of incisions of much greater length than we were prepared to regard as desirable. In casting about for a more satisfactory method we found that when a finely pointed electrode of a faradic battery is applied exactly over a cutaneous nerve which is external to the deep fascia, a characteristic fluttering sensation is produced in the extreme peripheral part of the area which will be rendered anæsthetic by section of the nerve. This sensation is extremely easily recognised, quite distinct from the concentrically radiating and more or less painful sensation produced by faradisation of the skin, and is never felt unless the electrode is exactly over the nerve. By using this method we found that we could define the

position of a given nerve with absolute certainty and if necessary trace its course. That the method was adequate in practice is shown by the fact that in the six cases—namely all except that of the first nerve divided—in which we used it, we invariably found the nerve immediately under the spot marked. An incision of half an inch would always have been adequate for the finding of the nerve; in fact, however, we generally allowed ourselves as much as an inch to an inch and a half to permit of sufficient freeing to render the suturing satisfactory.

All the operations were done under local analgesia with eucaine and adrenalin. An interval of half an hour was allowed to elapse between the injection and the making of the incision, and the anæsthetic proved in all cases to be thoroughly efficient not only for the wounds but also for the nerves[1]. In each case the nerve was exposed, a piece of it a quarter of an inch long was excised and the ends sutured together.

It may be of interest to anyone contemplating similar work if we add a few words about such inconvenience as was entailed by these small operations. For from two to four hours after the operation in each case the wound was quite painless, then began the usual local pain which varied in intensity with the extent to which the patient used the part; it generally began to pass off in from four to five hours. With the appearance of local pain set in also pain in the areas of distribution of the nerve, due apparently to the suturing; it was usually quite severe for twenty-four hours, and during the next two or three days was confined to attacks generally traceable to pressure on the point of suture or to stretching of the nerve. In no case was the patient incapacitated from active work, although he was compelled for a week or ten days to be circumspect in the use of the part.

In all the operations we had the advantage of the assistance of our friend Dr R. G. Ellwell. His generosity in meeting the demands we made upon his skill and patience has never failed and has given us help of the utmost value.

[1] The solution used was 1 in 500 β-eucaine and 1 in 100,000 adrenalin chloride as recommended by Mr Arthur E. Barker. It is well known how much surgery has profited from the work done in the field of local anæsthesia by Mr Barker, and we gladly welcome this opportunity of acknowledging that, but for this, the present research could not have been undertaken. We should like to add that we both of us have had the especial advantage of learning from Mr Barker himself the technique, to the satisfactoriness of which each of us can testify both as surgeon and as patient.

Technique of observation.

General remarks. The obvious method of studying scientifically problems of sensation is to record and compare the effects of stimuli which are constant or directly measurable, and this is the principle which underlies the researches on which the physiology of sensation is based. It must not be assumed, however, that such a method is exhaustive in disclosing the finest changes which a lesion of a sensory nerve produces. Sensitiveness to the discrimination of stimuli will always have been rigidly conditioned by the practical value to the species of such capacities, that is to say, we may expect that a man's fineness of sensibility will bear a direct relation to the customariness of the stimuli by which it is tested and that the farther we depart from stimuli which are familiar to the subject and the appreciation of which will have been of value to his ancestors, the more likely are we to meet with anomalies or to overlook minor changes. A striking example of the direction of sensory capacity by these biological conditions is shown in the case of the sensations produced by stimulation of the skin with the faradic current. Von Frey [3] has shown that the sensation produced by such stimulation is twofold, containing an element of pain, and an element of touch. He has also demonstrated that the pain is produced on the pain spots by a current of less intensity than that which produces, on other appropriate spots, the sensation of touch. Clearly this relation of the thresholds for touch and pain renders sensibility to the electric current strikingly anomalous and of very slight value to the possessor of it, for we find that in the case of all other forms of stimulus capable of causing touch and pain, the touch sensation appears with a stimulus of less intensity than does the pain sensation. As von Frey himself says, "Es zeigt sich darin recht deutlich dass in der Organization des Körpers electrische Reizung nicht vorgesehen ist, oder mit anderen Worten, dass der electrische Reiz eigentlich ein unphysiologischer ist [4]." This possibility applies, however, not only to a form of stimulation so obviously unphysiological as the electric current, but also to certain methods of applying forms of stimulation which we are apt to look upon as quite natural; for example, the most satisfactory method we have of examining losses of sensibility to touch is undoubtedly that of the von Frey æsthesiometer, nevertheless it is fairly clear that the discrimination of touches given in this way cannot have been customary to the individual or have been specifically favoured by the processes of selection to which his ancestors have been subject. It is easy to realise how relatively

unphysiological is the von Frey æsthesiometer when we remember how rare in ordinary life is any practice in the discrimination of slight touches passively received, and how important a part is played in all fine discriminations by repeated comparisons of the sensations experienced.

It may be suspected therefore that forms of hypoæsthesia might occur which it would be impossible to detect by von Frey's method, that is to say, that two areas of skin may be to the subject distinguishably different as sources of sensation and yet give identical results when examined with the von Frey hairs. There is in fact then, in the nature of things, a difficulty in obtaining a stimulus which shall be measurable and to which the subject shall be maximally sensitive; hence for the determination of the slightest grades of hypoæsthesia it may be necessary to abandon the quantitative method and choose one which gives us qualitative results only. Such a qualitative method must deal with that form of stimulation sensitiveness to which will have been specifically encouraged by the selection to which the race has been subject. Sensation has developed in man to keep him precisely informed as to the nature of his customary environment. The most delicate measure of sensory loss will be obtained by determining whether or not such customary environmental stimuli applied to the suspected area produce sensations which are in any way unusual or different from those produced by stimulation of the normal surrounding skin. We may say at once that we have found the facts to be in accordance with these general considerations. When a person has lost the sensibility of a given region as a result of section of a nerve, it is invariably the case that the maximal extent of change is that obtained by getting him to mark out the area which feels in any way unnatural when he touches it himself. Furthermore, not only is this the largest area of detectable change but it is considerably larger than that outlined by the use of any of the quantitative methods.

We have already called attention to the fact that in most previous work upon the abnormal it has been assumed that the various forms of loss of sensibility could be marked out in compact areas, and to the fact that physiological work has shown that normal sensibility is always distributed in minute distinct units, so that it might have been supposed that there would be difficulties in outlining hypoæsthetic regions by a single definite boundary. Such in fact we found to be the case, and as the result of many early disappointments we were led to adopt the physiological method as the only one capable of yielding

accurate results in the abnormal. It is not of course implied that these laborious methods are necessary in clinical work, but it is most strongly held by us that they are indispensable in research.

It is clear that in the investigation of the problem of sensation by any method whatsoever, the value of the observations is never free from the serious qualification that no objective measure or record of a sensation can be made. The practical consequences of this are, first to render the comparison of sensations due to stimuli in different parts uncertain, and secondly to make still more uncertain the identification of sensations experienced by two persons. We have throughout been greatly impressed by these difficulties, and in no part of the field has the need for circumspection seemed greater than in connection with sensations of pain and the minor thermal sensations. Scepticism is more than ever necessary when one is dealing with abnormal sensations, because these seem to be more numerous and more variable than the normal as well as being unfamiliar. As a very important part of the work was concerned with conclusions based on the comparisons of abnormal sensations in two different individuals, it may be useful if we attempt to summarise such sensory peculiarities of these two subjects as we have observed and are able in any way to define.

Before the nerve sections were begun, and from time to time since, we have made a number of comparative observations on the two of us with a view to estimating our relative normal sensory capacity. In A, the normal touch threshold, for the skin of the limbs at any rate, is slightly but distinctly higher than it is in B. With this should certainly be correlated the fact that in A's skin the hairs are fine and less closely set than they are in B's; that is, the more hairy skin, while obviously thicker and less delicate than the less hairy, is *more* sensitive to touch. The more sensitive skin shows the goose-skin reflex, it may be added, more frequently and in a more marked degree than the less sensitive.

In a long series of observations with Weber's compass test a constant and striking difference was shown. As is well known the subject when being tested for the discrimination of two points may make mistakes in one of two directions; not only may he describe a contact with two points as single, but he may describe a contact with one point as double. It is convenient to denote the incorrect answer given by a subject when he is touched with two points as a *single-two*, and the incorrect answer when he is touched with one point as a *double-one*. Now B always gave fewer of these double-ones than he did single-twos, whereas A gave a strikingly larger number of double-ones than

single-twos. Thus, when all the results were lumped together, it appeared that A was definitely less sensitive to this form of testing than B; analysis, however, showed that his excess of error was entirely confined to double-ones, and that in the discrimination of two points he was constantly slightly better than B. For example, in a series of observations on normal skin in which each subject received on corresponding parts 3120 touches (1560 single, 1560 double) B failed to feel two points as distinct 409 times, while A made the same mistake only 382 times; on the other hand, while B felt a single point as double 274 times, A made this mistake no less than 512 times. Into the significance of these very remarkable results we have not had the opportunity of making an exhaustive investigation. It would seem, however, to be probable that the excess of error shown by A cannot be regarded as due in any ordinary sense to an inferior sensorial capacity.

With regard to the more general aspects of the question of sensorial acuity, we may say that sensations to A seem on the whole to be more definite and more easily recognisable than they are to B, in whom recognition and discrimination are much more subject to doubt; sometimes such doubts have been justified and at other times they disappeared with practice. In general, new sensations felt and described by the one have been experienced sooner or later by the other. It is in respect to pain and temperature that most of these new sensations have been felt.

Touch. In the investigation of the losses of sensation to touch we have used three methods, one qualitative and two quantitative. The qualitative method makes use of the facts that the customariness of the stimulus and the possibilities of frequent comparison are of great importance in the detection of minute changes; in consequence of the delicacy it thus gains it always gives the maximal area of altered sensibility. We have described the method and given some of the clinical applications of it elsewhere [5], so that we need not now give any detailed description. Briefly it consists of the outlining by the subject of the area which feels to him in any way abnormal. This is best done by gentle stroking touches with the finger, the boundary of change being approached from the normal. For exact work the part should be shaved. The change of quality noticed is not always the same in all parts of the boundary, so that the standard we adopt is to mark any change whatever. The results given are surprisingly constant. As will be shown later this area of minimal change persists unaltered long after the process of regeneration has begun; yet during all these months

it can be marked out by the stroking method with the greatest precision.

Of the quantitative methods which we have used we have come to rely entirely upon that of von Frey for detailed work, and we do not regard an area as having been satisfactorily examined as to its sensibility to touch, until we have determined the threshold stimulus of every touch spot. It is convenient, however, to employ under special circumstances quantitative methods which are somewhat less laborious, such for example as the methods making use of a fixed minimal pressure. Cotton wool, as recommended by Head, we have found to be somewhat awkward and unmanageable in detailed work, and we therefore use for the same purpose a fine camel's hair brush[1]. The principle is the same as that which underlies the use of cotton wool, namely that the pressure exercised is always below the threshold of deep sensation. The outline obtained by some such stimulus is a convenient one because it does represent a line of considerable change of sensibility. We may say with a sufficient approach to accuracy, that the line corresponds with the external boundary of that grade of anæsthesia which feels to the subject distinctly numb, and with the internal boundary of that grade of hypoæsthesia in which a large number of the touch spots have a threshold not far from normal.

Weber's Test. For making any extensive series of tests of the capacity to discriminate two points we have found the ordinary pair of compasses to be unsatisfactory on account of the difficulty of applying one point with promptitude and neatness when the two points of the compass are at all near together. We have therefore used a light wooden instrument with three adjustable arms so that it is not necessary to use for the single touches one of the points which is being used for the double touches. It is most convenient to use the instrument with the arm which is used for the single touches at about a right angle to those that are set for double touches, so that the stimulus can be changed by a movement of simple rotation of the observer's wrist.

Such other special features of technique as there are to which we desire to call attention will be conveniently dealt with along with the description of the various modifications of function in the investigation of which they were used.

[1] This consists of a pencil of the finest camel's hair half a centimetre in length and forming a bundle not more than half a millimetre in diameter at the base. In the rest of this paper the word "brush" is used to avoid frequent repetition of the longer and not more descriptive phrase—"camel's hair brush."

Temperature. For the application of various temperatures to the skin we have used copper cylinders of 6 mm. diameter terminating in a short process 1 mm. in diameter. The temperatures most commonly used are 50° C. and 0° C. The cylinders are readily heated to the former temperature in beakers over a sand bath, whilst for temperatures ranging downwards from about 20° C. we have used a felt-lined box containing a series of Dewar's flasks in separate compartments.

A few words may appropriately be added here on one of the difficulties of testing. At the beginning of a series of tests it often happens that there is a period during which no clear sensation of temperature is obtained. Of all thermal sensations that of true heat is the one which most commonly cannot be appreciated. This disability is usually not of long duration but occasionally, for some reason we have not been able fully to trace, it is more lasting, so that the investigation has for the time to be abandoned. It is therefore a practical point of some importance to begin any series of observations by ascertaining by some preliminary tests upon the skin surrounding the affected area whether the subject can appreciate normally the form of stimulus which is being used.

The investigation of thermal sensibility is one of the most difficult tasks which the study of the sensory functions presents. It is very often impossible to estimate precisely the significance of previous work on account of the want of definition of terms, the confusion of temperatures with sensations of temperature and the fact which has been so largely ignored that the sensations themselves are frequently so baffling and elusive to appreciate and describe. Moreover, from the very nature of the function of this form of sensibility, the results of observations under different conditions of external temperature are very variable or even contradictory. It will be necessary therefore for us to enter somewhat fully into preliminary considerations.

The various thermal sensations which can be elicited from normal skin form two series, heat and cold. Each of these has at the one end a characteristic maximal sensation, and at the other sensations of diminishing intensity finally fading into indifference. If the skin be tested with decreasing temperatures from 50° C. downwards, the series of sensations produced is not a continuous one but is interrupted as soon as the temperature of the testing cylinder gets to within 5 or 6 degrees of the temperature of the skin, and is not resumed until the similar distance below the skin temperature is reached. Temperatures of this intermediate region are felt as indifferent, and moreover the sensations

elicited by temperatures bordering on this region are of very slight intensity and shade gradually into the indifferent without there being abruptly marked off minimal sensations. It is of great importance to the understanding of the state of affairs when thermo-hypoæsthesia exists, to realise that the skin is normally insensitive to temperatures of a certain intermediate range, that in the series of sensations from hot to cold there is a gap of anæsthesia. Such of course might have been expected to exist when it is clearly understood that the function of the temperature sense is to appreciate temperatures differing from that of the general surface, and that therefore sensitiveness to temperatures near that of the skin is of no value. The adjustment of the capacities of the temperature sense to the needs of the organism goes further, for as is well known the relation of the intermediate group of indifferent temperatures to the thermometric scale is not an absolute one but varies according to the temperature of the skin at the moment. By warming or cooling the skin the normal intermediate thermo-anæsthesia can be shifted upwards or downwards respectively in relation to the thermometric scale. This elasticity of the temperature sense is clearly an expression of the importance of the organism being able to derive sensations from objects differing in temperature from the body surface. The series of sensations experienced during testing with decreasing temperatures may be described as hot, warm, indifferent warm, indifferent, indifferent cool, cool, cold, intense cold. Further increase of the stimulus in either direction will cause pain. The sensations warm and cool, it is important to note, are not sharply cut off from the indifferent, whereas the maximal sensations hot and cold are extremely precise. Of two grades of the sensation of warmth it cannot be said that there is anything in the one which is not in the other, the difference is one purely of intensity; on the other hand, between the sensation of heat and the most marked warmth there is a distinct difference of quality—heat possesses a certain abruptness and, so to say, brightness which warmth lacks. The sensation of heat consequently forms a very satisfactory standard of normal sensibility, whereas warmth shading as it does imperceptibly into the indifferent cannot be used for testing purposes. If an attempt is made to make use of it, the subject finds himself very soon in difficulties on account of the impossibility of maintaining the distinction between warmth and indifference. It is very remarkable that a sensation, which in the normal we are so accustomed to regard as being very definite, should prove in the presence of hypoæsthesia extremely vague and elusive. The difficulty is further

increased by the fact that what appear to be unmistakable sensations of warmth are frequently elicited from areas which there are strong reasons for believing to be thermo-anæsthetic. The reasons for believing these sensations to be hallucinatory are, that they are elicited with ice just as much as with hot objects; that in regions yielding hallucinatory warmth it is not possible to discriminate temperatures of 0° C. and 50° C.; that the results obtained are very variable, a spot which at one time gives distinct warmth to ice, at another time will give indifference, and finally that such sensations may often be elicited from the midst of an area the rest of which is unquestionably thermo-anæsthetic. (See Appendix II.)

The possibility then that any given response of warmth may really indicate thermo-anæsthesia is of very great practical importance in the estimation of sensibility to temperature. The most obvious corollary of the fact is that heat cannot be used as the stimulus for outlining the areas of complete thermo-anæsthesia, because sensations introspectively indistinguishable from true warmth may be felt by the subject when spots far within the true thermo-anæsthesia line are being tested.

This leads naturally to the problem of the effect of hypoæsthesia upon thermal sensibility and the methods by which alterations in the latter are to be estimated.

When a temperature spot has its sensitiveness reduced, the sensations roused by the appropriate temperatures are reduced in intensity, so that for example on a heat spot a temperature which gave before a sensation of warmth now gives indifferent warmth or indifference; while on a cold spot a temperature which gave cool now gives indifferent cool or indifference. The same of course applies to the maximal sensation in each case, warmth is felt instead of heat, cool instead of cold. Thus the characteristic change of thermo-hypoæsthesia is the disappearance of the maximal and minimal sensations. The disappearance of the minimal sensations will lead to an extension of the range of temperatures which are felt as indifferent, and will appear as an anæsthesia to intermediate temperatures, or rather an increase of the normal intermediate thermo-anæsthesia, while the disappearance of the maximal sensation is quite likely to escape notice, for the given spot still reacts to heat or cold as the case may be, giving a sensation quite distinctly recognisable but of diminished intensity. It is obvious that unless the facts we have just been considering are taken into account in organising the technique of observation, the nature of the change in areas showing thermo-hypoæsthesia may be misunderstood. For example, such an area may

be described consistently with the facts as "reacting" to extremes of temperature while being anæsthetic to intermediate temperatures, and a misleading conception of the actual state of affairs be given.

Clearly, therefore, the first essential is the precise definition of what is meant by a spot responding or reacting to a given temperature. The fact that a sensation of the heat or cold series is experienced must be supplemented by information as to its intensity. For example, suppose a given area to yield sensations only of warmth when tested with 50° C., it may be described as responding to this temperature and therefore of normal sensibility to heat, yet it may in fact be thermo-anæsthetic, for the "response" may be one of hallucinatory warmth; or it may be thermo-hypoæsthetic, for the response may be without the element of true heat.

To obtain the outer limit of thermo-hypoæsthesia, therefore, it is necessary to find the inner boundary at which true heat or cold can be felt. The actual spots where the responses are obtained must be marked and the whole region must be tested, for the boundary is not a uniform line but merely a zone where the spots become sparsely scattered and cease. Such examination it is important to make with both heat and cold as we shall see later in considering regeneration.

The outer boundary of complete thermo-anæsthesia can, as we have already pointed out, be obtained only from the use of cold as a stimulus, because of the occurrence of hallucinatory warmth. In this case all sensations having any quality belonging to the cold series must be responded to and the spots where they are elicited marked.

Discrimination tests are not in general of much value. They are very laborious to carry out and must be done in very large numbers to give results on which any reliance can be placed. They are chiefly of use in distinguishing between true and hallucinatory warmth and as an aid in determining thermo-anæsthesia, where, seeing that the work is entirely in minimal sensations, repeated standardisation is necessary.

The subjoined scheme has been added to bring out more clearly the relation of the normal series of thermal sensations to the hypoæsthetic series. It will be seen that in the latter case all sensations are reduced while the minor ones are abolished. The temperatures in the two columns to the right have been added to give a general idea of the relation of the various sensations to the thermometric scale. We wish, however, very emphatically to state that the relations given here are true only in the most general way, for they depend upon the temperature of the skin at the time of testing and upon the conductivity and specific

heat of the object with which the tests are made. The true significance of such thermometric relations can best be realised if it is remembered that the function of thermal sensibility is to register not temperatures but the rate of loss or gain of heat.

Series of sensations obtainable from normal skin		Series of sensations obtainable from hypoæsthetic skin		Approximate thermometric relations	
Position in series	Sensation	Sensation	Position in series		
Supermaximal	Pain	Pain	Supermaximal	140° F.	60° C.
Maximal	Hot	Warm	Maximal	120° F.	50° C.
	Warm	Indifferent warm	Minimal	100° F.	38° C.
Minimal	Indifferent warm	Indifferent	Intermediate anæsthesia	95° F.	35° C.
Intermediate anæsthesia	Indifferent	Indifferent	,, ,,	90° F.	32° C.
,, ,,	Indifferent	Indifferent	,, ,,	85° F.	30° C.
Minimal	Indifferent cool	Indifferent	,, ,,	80° F.	27° C.
	Cool	Indifferent cool	Minimal	70° F.	21° C.
Maximal	Cold	Cool	Maximal	60° F.	15° C.

Pain. In the clinical examination of alterations of sensibility to pain and in such experimental work on the human subject as has been previously done, it seems to have been assumed that no special precautions were necessary for ensuring invariability of the stimulus and that any method that gave fairly similar excitations must be satisfactory. Of these qualitative methods the most usual have been pricking with a needle and the use of the faradic current. In the earlier part of our work we used both of these extensively. The disadvantages of the latter were soon evident and sufficiently serious to render it of very little value to us. They lay in the variability of the results, due, as far as we could ascertain, to the difficulty in ensuring such uniform moistening of the skin as to give uniform conductivity. This difficulty was especially great in a part covered with records in paint of other investigations which it was necessary to preserve. Ultimately moreover, finding that so much of the work was concerned with the comparison of the various sensations of pain, we found that a very much higher standard of uniformity in the stimulus was necessary than could be obtained with pricks given with the needle in the ordinary way. We were led therefore to adopt, except for the very roughest examinations, methods in which could be ensured according to circumstances either exact constancy or precise graduation of the stimulus. Stimulation by pin-prick has certain advantages of which the chief is exact localisation. It therefore was desirable to be able to make use of

this method, and this we did by devising a little arrangement in which the force pressing the needle against the skin was applied by the bending of one or the other of a set of von Frey hairs (Fig. 1). It is not claimed for the instrument that it gives absolutely exact results, and it must be used with a certain expertness or it will prove misleading; with these qualifications we may say that we have found it in practice of great value. It undoubtedly gives a stimulus of much greater uniformity than the old method, with practically no increase of the expenditure of time. There are, however, certain general disadvantages which apply to any modification of the method of pin-pricks. One of the most

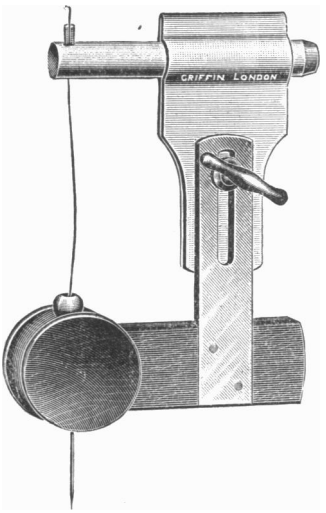


Fig. 1. Hair Algometer.

The broad horizontal bar is made of wood and bears at one end the metal upright to which can be fixed in any desired position the clamp holding the von Frey hair; at the other end of the bar is the vertical socket in which the needle fits. An ordinary fine and rather short sewing needle is used; to the eye end of it is fixed a small globule of lead in the top of which is made a conical pit for the lodgement of the tip of the von Frey hair.

When the instrument is being used it is important that the needle should be applied vertically to the surface of the skin, and for this purpose thumb pieces are provided so that the bar can be conveniently held at the situation of the needle. The socket allows the needle to run more smoothly if a little French chalk is rubbed into it.

In the figure the instrument is shown ready for use with one of the von Frey hairs in position. The point of the needle is to be put against the skin and the whole instrument depressed until the head of the needle has risen for about a quarter of an inch.

serious of these is the difficulty of finding again pain spots which have previously been identified. Such spots are extremely minute and may very easily fail to be detected even after repeated prickings in the neighbourhood of them. This makes it desirable to have a form of stimulus which can be applied over a considerable area. Another disadvantage is that in comparative work it may be necessary to stimulate the same spot repeatedly and if, as frequently happens in a markedly hypoalgesic area, considerable force is necessary to elicit the characteristic sensation, the spot becomes so damaged as to cease to respond at all. A form of stimulation therefore is necessary by which pain spots can be repeatedly excited without being injured. Both these requirements are satisfied by the use of heat as the source of pain, and this method has the additional recommendation of allowing very exact graduation.

Methods of recording. It was clear to us from the outset that, if results of any exact value were to be obtained, altogether special methods would have to be devised to obtain records of the various changes sufficiently precise to allow of exact comparison over considerable intervals of time. At first we thought that outlines of the various limbs obtained from photographs giving a known reduction in size would be of value. Such we had prepared[1], but difficulties of fore-shortening rendered them practically useless and we gave up the attempt to record minutiæ of detail in connection with the outline of the limb. We now use two methods. First for displaying general features of distribution of a nerve we employ photographs of the actual part with the various features it is desired to record marked on it. Secondly, for detailed work, the area is marked with various coloured inks and different signs; these are then traced off with thin tracing paper applied to the limb in narrow strips so as to allow of exact fitting, and then the result is combined in a flat surface chart which gives all the details in such a way that they can be readily studied and compared with other similar records. When it is important to obtain still more precise data for comparison we mark the surface of the skin with silver nitrate[2]. In this way we have kept in many instances features marked out for periods of several months, so that we have been able to detect the earliest phenomena of regeneration without difficulty.

[1] The photographs were kindly taken for us by Mr Higham Cooper, Radiographer to University College Hospital.

[2] A 30 % solution of silver nitrate we have found to be the most satisfactory strength. It is painted on and allowed to dry, and is then moistened with a solution of pyrogallic acid to ensure immediate and complete reduction.

For the recording of changes in the area of the great auricular nerve a special method was devised. A mask of wire netting of about 1 cm. in the mesh was moulded to the side of the neck and head so that it could always be applied and fixed in exactly the same position. A photograph was taken with the mask applied, and from this diagrams were constructed showing the various strands of the mask superposed upon the face. When a given series of observations had been marked on the face the mask was applied, and with this as a guide it was possible to copy down the marks made on the skin on to one of the diagrams previously mentioned. From this they could readily be transferred by tracing to an exactly similar outline of the face without the mask.

PART II. RESULTS OF NERVE SECTION.

In this part we shall limit ourselves to a description of the results which we have observed to follow the section of the seven cutaneous nerves which were divided.

Section 1. *Sensory.*

In the consideration of the effects of the loss of sensibility naturally the first question which presents itself is, to what extent does the subject notice the loss, and how much does he miss the capacities of which he has been deprived? In answer to this we may say at once that one of the most surprising experiences we have met has been how extremely unobtrusive to the subject areas of anæsthesia may be, even when quite large. 280 square centimetres of anæsthesia on the inner side of the leg, including the ankle, produced in the subject under ordinary conditions no special consciousness of their presence, the rubbing of the clothing, and even of the boot, passed unnoticed from the first. At rest it was impossible for the subject to know by any feeling he experienced at the time that the sensibility of the leg was not absolutely normal. A similar immunity from anything approaching a consciousness of the defect was experienced with the 188 square centimetres on the ulnar side of the forearm. It was different however with the anæsthesia of the external ear produced by section of the great auricular. Slight accidental contacts with the coat collar gave rise to much discomfort, and this did not diminish with custom. The discomfort lay in the feeling of a dead appendage attached to the living body, and was not unlike that accompanying the production of local

anæsthesia by infiltration, when one seems to possess a block of inanimate material set in the midst of the living flesh. It is interesting, however, to note that the anæsthesia of the cheek never produced the slightest embarrassment during the act of shaving.

Touch. Qualitative Examination. Investigation of any given affected area was always begun by the use of the method of stroking touches. The external line obtained in this way is that of the limit of any change

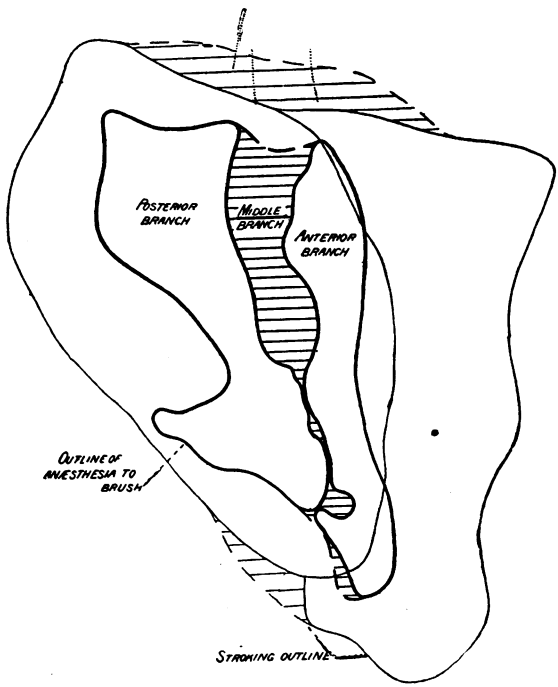


Fig. 2. Tracing of areas of altered sensibility produced by section of all three branches of the internal cutaneous nerve of the left forearm. Reduced by $\frac{2}{3}$.

The thick lines show the areas of anæsthesia to the brush.

The thick continuous lines enclose the areas of the anterior and posterior branches.

The thick broken line and heavy shading mark the area of the increase in anæsthesia which followed section of the middle branch.

The thin lines show the areas of minimal hypoæsthesia, i.e. the 'stroking outline.'

The complete oval outline is the 'stroking outline' which followed section of the posterior branch.

The large addition to the oval on the right of the diagram shows the increase in the 'stroking outline' which followed section of the anterior branch.

The thin broken line and fine shading show the additions to the 'stroking outline' produced by division of the middle branch.

of sensation which can be detected by the patient. It is always much larger than the anæsthesia to the brush, and than the area of distribution usually recognised as normal for the given nerve. The form of the outline corresponds roughly with that of the much smaller area of anæsthesia it contains. It shows no abrupt irregularities, but this peculiarity may be dependent on the way in which it is obtained, which does not lend itself to the direction of minutiæ of outline (Fig. 2). The nature of the change occurring at this boundary was for a long time a source of much difficulty to us. The change is not always the same, but usually it is from normal skin to one of two sensations which are somewhat difficult to define. The commoner of these is best described as feeling as if the skin had become smoother as the line was crossed; the other feels like a very faint soreness of the skin within the boundary. This sensation we have come to describe as "sharpness," and we have both found that the word expresses it very happily. The former of these changes is probably to be connected with another which is very characteristic, namely a considerable reduction in the ease with which the sensation of "tickle" can be elicited. Not only however is the change at the boundary line not everywhere the same, but the contained area always displays a marked want of homogeneity. In the central part is the area of anæsthesia to the brush, giving when tested by the stroking method, a marked sense of numbness. The area, conveniently called the marginal zone, contained between the stroking outline and the brush outline, is itself not homogeneous to the stroking method, but can usually be divided up into areas of varying degrees of smoothness, sharpness or numbness. The outline of anæsthesia to the brush is usually fairly abruptly marked to stroking touches, but it is not at all infrequent for considerable extension of numbness to be found in the marginal zone; that is to say, regions which are sensitive to the brush may feel to the subject distinctly numb. Investigation of the marginal zone by quantitative methods shows a distinct hypoæsthesia in the parts near to the brush line; but the parts near the external line are much less definitely abnormal. We have not been able to establish very definite relations between the qualities elicited by stroking touch and grades of hypoæsthesia determined quantitatively, but we are able to say that, as might be expected, the less normal an area feels to the subject the more hypoæsthetic will it prove to be, and that areas in which any degree of numbness is felt are always decidedly hypoæsthetic.

Quantitative Examination. Satisfactory quantitative examination of sensibility to touch depends on the recognition of the fact long known

that this form of sensibility is distributed in small spots, and of the fact proved by von Frey that these spots are localised in the hair bulbs. We have thus a ready means of showing that a given touch spot has been stimulated, for when pressure is made upon a hair bulb the corresponding hair moves. It is thus possible to examine sensibility to touch in the hairy parts with great precision and to determine exactly the threshold stimulus for each touch spot. In a part however, where the hairs are very fine and therefore mostly invisible even with the use of a lens, the whole surface must be stimulated with each hair and nowhere can the observer be sure whether an absence of response is due to a touch spot not having been stimulated or to the stimulus having fallen below the threshold of the spot. The consequence is that the results in such regions are much more vague and less reliable than the results on hairy parts. For example, on the thigh where every hair can be distinctly seen and therefore all the touch spots readily localised, the different grades of loss of sensibility appear to be much more sharply marked off from one another than on the front of the forearm, where the hairs are practically invisible. As might be expected, moreover, in the latter region in spite of the great fineness of the skin normal sensibility to touch seems to be distinctly less acute than in the former region. We may here add that quantitative results may be obtained on the hairless parts without the use of the enormously laborious method of determining the threshold of every place on the surface. We have found that a very satisfactory measure of the sensibility of such a part may be obtained by finding out which of the von Frey hairs elicits a certain number of responses in a known area. The method we now use in estimating hypoæsthesia on the front of the forearm is to mark out the area in square centimetres and to find out which is the lowest of the von Frey hairs which elicits ten or a dozen responses in each square.

The tactile sensory changes produced in an area of skin by dividing the corresponding cutaneous nerve may in the most general way be described as a hypoæsthesia, extremely slight at the periphery and gradually deepening, as the centre of the affected area is approached, into tactile anæsthesia. The transition however from minimal hypoæsthesia to anæsthesia is not equally distributed over the part, but is concentrated in certain zones and gradual in others. This characteristic cannot be demonstrated by the use of the minimal pressure methods such as cotton wool. When examined with adequate minuteness the series of changes from periphery to centre in such an area can be numerically expressed. The external boundary of hypoæsthesia, corre-

sponding with the stroking touch outline, is the most difficult of all the transitions to express exactly and cannot be detected except with the very lightest of the von Frey hairs; even with these it may be that the only difference is that touches inside the line are felt as less distinct than touches outside[1]. In examining the more hypoæsthetic zones the observer is liable to make mistakes if it is not clearly understood that contact with the heavier von Frey hairs may be answered to by the subject without his having felt any true sensation of touch. It is clearly therefore of great importance in testing defects of sensibility to touch, that the subject should be able to specify precisely what sensation he is answering to, so that the fact that he can recognise that he is being stimulated shall not be accepted as proof as to the nature of the sensation he experiences. Now when he is touched by one of the heavier von Frey hairs, careful introspection will enable the subject to detect the fact that he may experience three sensations which are perfectly distinct, namely pain, touch and pressure[2]. The confusions that may arise with the first of these we shall deal with later, but we must first enter at some length into the discussion of the relation to one another of the last two.

According to current views touch sensations are produced by contacts too light to produce sensations of pressure and are due to stimulation of nerve endings in the skin as distinct from those in the deeper parts, so that if the surface be stimulated with increasing pressures those of the latter which compress the skin only, will give rise to sensations of touch, while those which compress the subcutaneous tissues also will give rise to sensations of pressure, the stimuli forming a continuous series throughout and not differing from one another in anything but degree. It naturally follows from this conception that the only method of testing sensibility to touch, that is to say, of testing the sensibility of the skin to compression, is to use a stimulus so light that its effects shall not be transmitted to the subcutaneous tissues, hence we have the minimal pressure methods in the best known of which cotton wool is employed as the stimulus. We have come to regard these views as being inconsistent with the facts and the cause of much confusion. When the area of tactile hypoæsthesia is being investigated with von Frey hairs the subject cannot fail to notice the broad fact that he experiences two sensations which are remarkably distinct from one

[1] For the facts of observation upon which this conclusion is based see Appendix I.

[2] To avoid confusion we omit here from the text mention of the fact that stimulation with a von Frey hair occasionally produces a distinct sensation of cold.

another and have very definite characteristics. One of these, which we shall call true touch, has the special qualities that while it may be accompanied by pain it never feels heavy, that it gives the impression of being in essence superficial and is most satisfactorily described as being like a minute pat on the surface. A further important characteristic of it is that when produced with a von Frey hair it is felt to be a contact with a small well-defined surface and to be accurately localisable. As was shown by von Frey this sensation of true touch is produced at the moment when the contact is made and at the moment when the contact is interrupted, but not during the interval between these if the stimulating object is kept still: hence the sensation may well be called "moving contact." The second sensation which the subject learns to distinguish, which we shall call that of true pressure or "static contact," is characteristically vague in the information it gives as to the situation and extent of the place touched and invariably possesses a quality of pronounced heaviness; this heaviness increases with the duration of the stimulus without any increase in the force of the stimulus, and tends to persist so that a few contacts may make the subject feel sure that a large part of the limb is being exposed to some formidable pressure. The contrast then of the two sensations is very striking. Touch is light, well localised, distinctly related to the form of the stimulating object and limited in time to the moment of stimulation. Pressure is heavy, vague, gives little or no information as to the form of the stimulating object and is not closely related to the duration of the stimulus. Some experience in the investigation of hypoæsthesia enables one to add certain important characteristics to those already enumerated; of these the most striking is that while modifications in the stimulus may produce variations in the intensity of pressure sensations no such continuous series of intensities can be produced with touch. Short of the fully-developed superficial pat which is a touch, the only sensation the subject can get is a vague tickling or creeping and this as a rule only in parts where there are hairs projecting above the surface. Thus we may say that with true touch if the stimulus fails to produce a perfectly distinct, fully-developed sensation it is not felt at all. The only way, therefore, in which a true tactile hypoæsthesia manifests itself is in the fact that a stimulus stronger than normal is necessary to produce a sensation, for when the sensation is produced it is indistinguishable from a normal touch. For example, on a hypoæsthetic area it may be that no sense of touch is elicited with a bristle of less than 3000 milligrammes pressure, yet if it is elicited, it is identical with the

light pat which a hair of 70 milligrammes produces on a normal touch spot. All these facts have led us to the conclusion that a fundamental distinction must be made between the two forms of sensation we have been defining and that they cannot be regarded as forming a continuous series with the sole distinction of degree in the force of the stimulus.

Until we had formulated this conception we found the investigation of hypoæsthesia to touch difficult and confusing. It was very soon clear that the theoretical objections to the use of a constant pressure stimulus (such as cotton wool) as a standard for the determination of tactile anæsthesia were very great. It could be urged that the line given by cotton wool as the limit of tactile anæsthesia was an arbitrary one, for there was no collateral evidence to show that because an area did not respond to cotton wool it was therefore totally incapable of yielding sensations of touch to a stronger stimulus. But as long as touch and pressure were regarded as forming a continuous series the use of a stronger stimulus than cotton wool was always open to the objection that responses obtained were due to deep sensibility. It was thus plain that even if zones of tactile hypoæsthesia existed they could not on these assumptions be demonstrated, because it could never be known at what point the sensations experienced were due to stimulation of structures deeper than the skin. Whereas when it is recognised that an absolute distinction between touch and pressure can be established from the qualities of the sensations, the investigation of tactile hypoæsthesia becomes not only possible but easy. As defined by us, then, a region of tactile hypoæsthesia is one in which touch sensations can be elicited only by the use of stimuli above the threshold normal for the part, and regions of tactile anæsthesia are such as do not yield the characteristic touch sensation to any stimulus however strong. Finally we may repeat that the touch sensation produced by stimulation of a hypoæsthetic area with a very heavy hair is in all respects identical with the touch sensation produced by stimulation of normal skin with its threshold hair.

We may now return to some consideration of the precautions which have to be taken in the investigation of regions where tactile hypoæsthesia is at all marked. Such investigations of course can be carried out only with the von Frey æsthesiometer. Now any given stimulus may produce a sensation of touch, of pressure or of pain. As the centre of the area under examination is approached and in consequence of deepening hypoæsthesia heavier hairs have to be used to elicit a sensation of touch, it will be found that a region is reached where touch

is no longer felt. Nevertheless the subject may continue to be clearly conscious of each contact, and unless he is alive to the distinction of touch from pressure he may go on responding and so mislead the investigator. To those who accept the current views as to the nature of touch it will seem at least remarkable that we think it necessary to discuss the distinction between touch and pain, nevertheless in defining the innermost limit of the region in which true touch can be elicited it may be necessary to use hairs so heavy that they produce considerable pain. Touch occurring alone is of course easily distinguishable from pain occurring alone, but when a stimulus gives rise to these two sensations together difficulties may readily occur. The touch sensation is momentary, elusive and follows closely on the stimulus: pain develops more slowly and is a sensation altogether more conspicuous, so that it easily overwhelms in consciousness the evanescent touch which precedes it. It is therefore necessary for the subject when von Frey hairs which cause much pain are being used, to be very alert in the detection of a touch element at the beginning of each sensation experienced.

We may now attempt to give in a general way certain numerical values of the various grades of hypoæsthesia found between the outlines of change to stroking touch and the region of total tactile anæsthesia. The change at the former line as already stated cannot be expressed precisely. On a hairy part, such as the thigh or leg, it is as a rule not to be detected with a von Frey hair of 70 milligrammes pressure, that is to say the hair bulbs inside and outside the line respond equally well to this stimulus. For a variable distance within the stroking touch line there is practically no increase in hypoæsthesia; this region we call the zone of minimal hypoæsthesia, and it may be an inch or two in width. The defect in sensibility is so slight that it cannot be detected with cotton wool, even as a so-called relative anæsthesia. Like normal skin ninety per cent. of its hairs respond to 70 milligrammes and the remainder to 140 or 280 milligrammes (see Appendix I). Internally to this zone a rapid increase of hypoæsthesia occurs; each line of hair bulbs will need a stimulus of considerably heavier pressure than the preceding until the region is reached where no stimulus, however heavy, produces a sensation of touch. In general it may be said that when touch is not elicited by a bristle of three and a half grammes pressure no further increase in the stimulus will produce it. The line bounding the area usually described as that of tactile anæsthesia, the area that is to say which is insensitive to cotton wool or the brush and is distinctly numb to stroking touch, falls in that region where the increase of hypoæsthesia is most concen-

trated. It may be said roughly to be somewhere in a zone, not usually more than half an inch wide, where the change is so rapid that while the outer part may respond to 280 or less, the inner may scarcely respond to 800 milligrammes pressure. The various grades of hypoæsthesia may be conveniently classified into three groups according to the pressures which are necessary to elicit a sensation of touch. The first grade, which we call minimal hypoæsthesia, is scarcely distinguishable from normal sensibility. It will respond to hairs of pressures varying between 70 and 400 milligrammes according to the natural sensitiveness of the part, so that for example, if the threshold hair of the part has a pressure of 70 as in the thigh, areas of minimal hypoæsthesia will respond to this hair equally well and the difference between the normal and the minimal hypoæsthesia can only be detected by using hairs below the threshold. The second grade we call that of transitional hypoæsthesia; such a zone will respond to hairs of pressures between 500 and 1200 milligrammes. The third grade, that of maximal hypoæsthesia, responds to pressures between 1700 and 4000 milligrammes. Corresponding with these grades of hypoæsthesia the groups of hairs to which they respond may be referred to as light, medium and heavy respectively. The figures given above are to be regarded as approximations of no very precise accuracy and the groups as not being capable of abrupt delimitation. They are, however, undoubtedly objective realities and are, in our experience, invariably to be detected after section of a nerve (Fig. 3, see Plate I). The area of minimal hypoæsthesia seems to be more definitely than the others a stage rather than a region of transition. It will be noticed that in giving these numerical values we have departed from the usage of von Frey in not graduating the various von Frey hairs according to the pressure exerted upon unit area (square millimetre). There is reason to suppose that such a method is very misleading, while it possesses no advantage over that in which the value of the hair as stimulus is reckoned as the weight necessary to bend it[1].

Weber's test. We have found no specific loss of the capacity to discriminate two points, that is to say that whenever the compass can be felt, some power of appreciating the distinctness of the two contacts remains. In the larger areas of anæsthesia there has always been a

[1] We are not alone in objecting to the method of von Frey of describing the stimuli yielded by the various hairs of his æsthesiometer. See for example Nagel, *Arch. f. d. ges. Physiol.* LIX. S. 595. 1895. Quoted by Sherrington, *Schäfer's Physiology*, II. p. 985.

central region where even firm pressure could not be felt, naturally therefore discrimination of two points was impossible. Outside the area of anæsthesia to the brush discrimination is normal, between this and the central area, that is in the intermediate region of Head, we have found a definite reduction of the discriminatory capacity but by no means an abolition of it, so that an increase in the separation of the points of comparatively small amount was adequate to yield results which showed a distinct degree of sensitiveness to the stimulus. For example, in the case of the middle cutaneous of the thigh the normal surrounding skin responded fairly accurately to a separation of 25 mm.

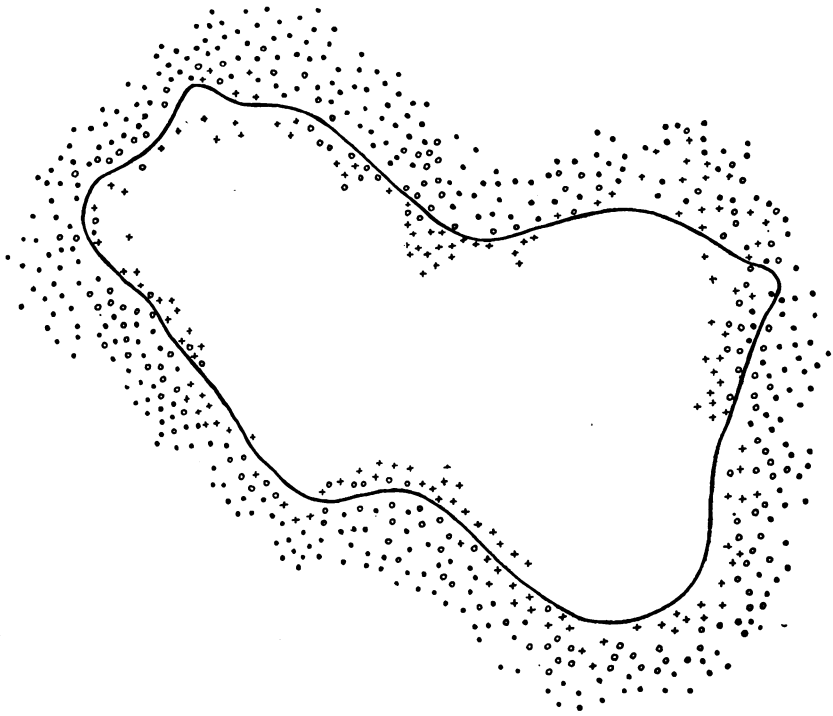


Fig. 4. Middle cutaneous: Left thigh. External branch. This and Figs. 5 to 10 inclusive are reduced by $\frac{1}{3}$rd linear.

26 days after section. Tracing of results of examination with von Frey hairs.

Touch spots marked • reacted to hair of pressure 280 milligrammes.

,, ,, O ,, ,, 800 ,,

,, ,, + ,, ,, 2280 ,,

The continuous line marks the limit within which there was anæsthesia to the camel's hair brush.

while in the intermediate zone the results with the same separation were very poor: with the points 50 mm. apart however, the intermediate zone yielded results nearly as good as those of the normal skin with 25 mm. Detailed examination showed that there was a gradual diminution of sensitiveness from the brush line towards the total anæsthesia.

To obtain these results a moderately firm pressure with the compass points is necessary for it is obvious that it is only occasionally that the points can light precisely upon two touch spots at the same time, and if the pressure is light enough only to excite such spots the points will not be discriminated. It is probable therefore that Weber's test depends upon the sensibility of the deeper layers of the skin and underlying parts. This is confirmed by the results of investigations we have made on the capacity to discriminate two simultaneous light touches. For this purpose we made a series of double von Frey hairs at distances from one another varying from 20 to 25 mm. With hairs of the lighter pressures although well above the touch threshold very little discrimination was possible, but with hairs of medium pressure, 500 mgrs. and upwards, discrimination was possible in some situations but not in others on normal skin. It seemed that thinness of the skin was of greater importance in relation to this sensibility than was tactile acuity. For example although tactile acuity on the front of the thigh is in general better than it is on the front of the forearm, discrimination in the latter place is much more accurate than in the former where the skin is of distinctly greater thickness.

We have found no evidence that sensibility to heavy pressure and to vibration is in any way affected by losses of sensibility confined to the skin.

Temperature. In investigating altered thermal sensibility we have found that there is a region of absolute anæsthesia and a region of partial anæsthesia. Experience has shown us that the most satisfactory method of finding these is the use of a temperature of 0° C. as a stimulus. Examination of the area with this will reveal an inner region within which the stimulus elicits either no sensation of temperature or what we have called hallucinatory warmth only; outside this thermo-anæsthetic area there is a zone within which the stimulus yields sensations of temperature which are quite distinctly recognisable, but do not possess the normal intensity,—the temperature of 0° C. being felt as cool. This thermo-hypoæsthetic zone varies in width considerably, but has certain fairly constant features of distribution. The outer limit lies

for the most part outside the line of anæsthesia to the brush and in the region where sensibility to touch is normal to any but the finest tests. The inner limit, that is to say the outer limit of thermo-anæsthesia, lies well within the brush line and just within the limit of complete tactile anæsthesia (Figs. 5 and 6). Within the thermo-hypoæsthetic zone the thermal sensibility of the part has the characters which, as we have already pointed out, are what might be expected in such an area, that is to say temperatures near that of the skin are less clearly appreciated than in the normal. The appreciation of such temperatures naturally varies somewhat with the temperature of the skin at the time

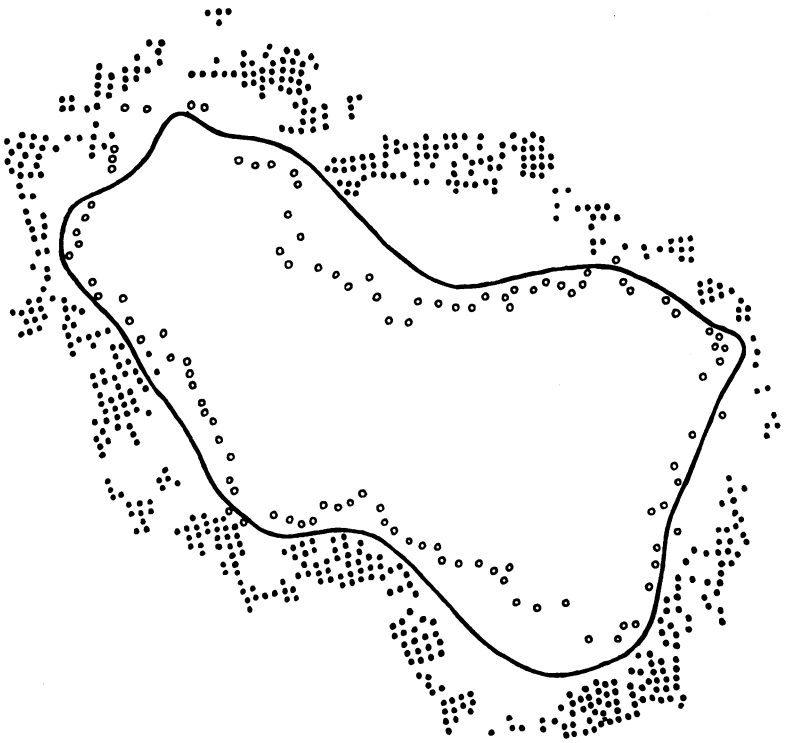


Fig. 5. Middle cutaneous. Left thigh. External branch.
21 days after section. Tracing of the results of examination with temperature of 0° C.
On spots marked • stimulus was felt as cold.
,, ,, ○ ,, ,, cool.
The blank area is that of thermal anæsthesia.
The continuous outline marks the limit within which there was anæsthesia to the camel's hair brush.

of testing, but on the whole we may say that the range of temperatures which cannot be felt is about fifteen to twenty degrees centigrade, and lies in that part of the thermometric scale which contains what have been called by Head "intermediate temperatures" (22° C. to 40° C.). The second character of the thermo-hypoæsthetic zone is that, as has been pointed out by Head, it is sensitive to temperatures higher and lower than these intermediate temperatures. A third characteristic however of this form of sensibility is that while extreme temperatures arouse sensations, these sensations are of a distinctly reduced intensity.

The outer limit of thermo-hypoæsthesia can be outlined with a high temperature (50° C.) as well as with ice, and the two boundaries correspond closely, allowance being made of course for the fact that cold spots and heat spots on the normal skin are grouped separately. When

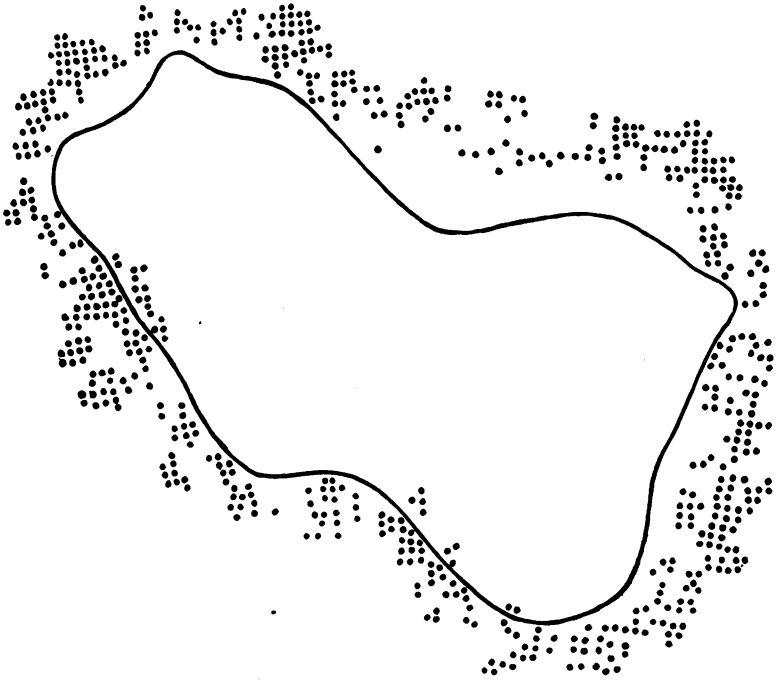


Fig. 6. Middle cutaneous. Left thigh. External branch.

30 days after section. Tracing of results of examination with a temperature of 50° C.

Spots marked are those which yielded a distinct sensation of heat.

The continuous line marks the limit within which there was anæsthesia to the camel's hair brush.

cold is used the outline marked is the line at which, working inwards from the normal skin, true cold ceases to be felt and a sensation of cool only is elicited. Similarly when 50° C. is used the line marked is where true heat ceases to be felt and is replaced by warmth.

As we have shown in discussing methods, heat cannot be used satisfactorily to determine the inner limit of thermo-hypoæsthesia. This is due in part to the close resemblance of the lesser sensations of warmth to sensations in which no element of temperature can be detected. It is very surprising how great may be the perplexity of the subject in deciding whether a given sensation contains warmth or no element of temperature at all. A series of sensations which at one time he will confidently label as having warmth, at another time he will equally confidently describe as indifferent, and this in spite of recognising the substantial identity of the two series (see Appendix II, Table I). This may result in a gradual deflection from the standard in one direction until for example the subject is led to answer "warm" to stimuli applied well within the thermo-anæsthetic area, or he may be reduced to a state of complete confusion in which he feels all responses are worthless. These difficulties apply to the borderland where thermo-hypoæsthesia is passing into thermo-anæsthesia and all the sensations are minimal. There is, however, a further and stronger objection which we feel to be so important that although we have referred to it already in the Introduction, we must make some mention of it here again. It consists in the appearance of what we have called hallucinatory warmth: this is not usually a vague sensation such as the minimal ones we have been referring to above but contains a distinct glow of what appears to be unmistakable warmth, although it never has, we may add, the brightness of true heat. Such hallucinations may be elicited from spots in the middle of areas undoubtedly thermo-anæsthetic. The clearness of the warmth experienced is independent of the temperature of the stimulating object, which may equally well be ice-cold, at the temperature of the skin, or at 50° C. Moreover the response of warmth is not constant and is frequently exchanged for indifference but never for anything else. (See Appendix II.)

Discrimination tests in the hypoæsthetic area do not yield further information about the nature of the change of sensibility. They confirm the observations that there is a considerable increase in the normal anæsthesia to temperatures near that of the skin and that this anæsthesia to intermediate temperatures is not sharply marked off by the temperatures to which it will or will not react.

Pain. The problems presented by the alterations in sensibility to pain we have found to be the most difficult which are encountered during the investigation of the results of the section of a nerve. The sensation concerned is in itself disconcerting and likely to interfere with the critical coolness which is so essential to accurate observation. Moreover the abnormal sensations of pain which may be elicited in an area of altered sensibility have to a great extent the quality of strangeness which proves a still further disturbing factor. In consequence of these and other difficulties which need not be enumerated here, we have found it very difficult to collect a consistent series of facts such as would justify general statements. Nerve after nerve had passed beyond the stage when we could be sure that none of the changes of regeneration had begun, before we had formulated precisely those points to which it is necessary to give attention and worked out a scheme for examination which would allow us to make the essential observations while maintaining that economy in the actual amount of examination which is indispensable if results worthy of reliance are to be obtained. In summarising the facts we have observed, we shall therefore follow to some extent the various aspects under which the problem presented itself to us at different periods.

We came to the problem in the full expectation of finding a central area of analgesia separated from the surrounding region of normal sensibility by a zone of hyperalgesia and this in fact is what in a general way we found. We could not however fail to be struck with the anomalous character of the production of an increased sensibility by what appeared to be a purely destructive lesion. It occurred to us that this hyperalgesia might be due to irregularities in the stimulus brought about by the fact, which is undoubtedly true, that the pain spots become fewer as the analgesia is approached. It was at any rate essential before we could accept the occurrence of a true hyperalgesia, that we should secure a means of applying constant or graduated stimuli. For this purpose we invented the algometer already described. Investigation of the affected area with this instrument did undoubtedly show that we had been accepting an exaggerated estimate of the extent of the increased sensibility to pain: certain spots which with the free-hand use of the needle had yielded abnormally unpleasant sensations of pain, now proved to be inexcitable by a stimulus fully capable of producing a distinct prick on many spots in normal skin. Still however, the fact remained beyond question that there were regions in which a pressure of the needle capable of barely eliciting a prick upon

the normal skin did produce an extremely painful sensation. The algometer therefore had shown us that there was a real hyperalgesia, but it had also shown that this hyperalgesia did not occupy a zone uniformly distributed around the analgesia but was arranged in patches which might, it is true, occur in the area described by Head as the intermediate zone, but might equally well occur beyond this or in the midst of the analgesia.

The next feature of importance which we noticed in relation to this hyperalgesia was that it differed from the other consequences of nerve section in not following immediately upon the operation. We found that the affected area was unduly sensitive for the first 24 or 48 hours and that then this sensitiveness disappeared. There was then a period of a week or more during which no abnormal sensitiveness was present. Between the tenth and twelfth days however, and as a rule rather suddenly, a very distinct hyperalgesia became evident. The most striking characteristic about this was its extent. It always lay in part outside the area of anæsthesia to the brush, extended usually up to the wound but never above it, and might often crop up in patches in the midst of regions which were otherwise profoundly analgesic.

Before tracing the further history of this last-mentioned hyperalgesia it is necessary to discuss the question of the origin of that which follows immediately upon the operation and clears up in a couple of days. It does not seem to us that this primary hyperalgesia is always of the same kind or due to the same cause. The experience that we have had has led us to regard as important three possible sources of pain and hypersensitiveness. These are, first the irritating effect of the nerve suture; secondly the bruising and local disturbance due to the infiltration and the dissection, and thirdly the possible occurrence of minor degrees of phlebitis as a result of the local injury and the slightly irritant character of the injection. The mode of action of the first-mentioned factor is shown in the following experience of one of us after the section of the middle cutaneous nerve of the thigh. He was walking home some hours after the operation when the effects of the local anæsthetic had completely passed off; the movement naturally produced traction on the nerve suture and consequent pain in the region of the external condyle. He got however the distinctest possible impression that the discomfort was due to extreme hypersensitiveness of the skin in this region and to the rubbing against it of the leg of the trousers and he was surprised to find that the most careful protection of the supposedly hyperalgesic region gave no relief whatever.

In relation to the second and third possibilities mentioned above, certain facts of some significance may be enumerated. The injection of adrenalin into normal skin produces a certain degree of soreness which persists for two or three days; this soreness however is distributed concentrically about the puncture through which the injection has been made, and it cannot therefore explain entirely the occurrence of primary hyperalgesia. Possibly however when the upper limit of diminished sensibility is close to the point of nerve section, as it was after all our operations on the forearm, some of the primary hyperalgesia may fairly be ascribed to the local injury.

A slight grade of phlebitis seems to us undoubtedly in some cases to have been the cause of the early hyperalgesia. These cases were those where a large vein ran close to the nerve which was divided; in them the tenderness and the attacks of spontaneous pain were associated with veins in the upper half or thereabouts of the area affected by the nerve section and at times we thought we could make out that the veins concerned were slightly indurated.

About the eleventh day after the operation the subject notices that the affected area of skin has begun to attract his attention once more through an unpleasant quality in the sensations produced by accidental touches. This increase of sensitiveness is quite distinct when the part is rubbed with the finger and tends to form a broad band surrounding the analgesic part and roughly corresponding with what we have called the zone of transitional tactile hypoæsthesia. Exact algometric observations now show that there is a definite reappearance of hyperalgesia, the sensations produced by pin-pricks being rather diffuse about the spot stimulated and having a character closely similar to that of the pain produced when a bruise is pinched. Even at this period the hyperalgesia is not uniformly distributed. In general it may be said for the most part to lie outside the line of anæsthesia to the brush, to extend for a less distance inside the line and to appear in detached islets in the midst of the analgesia. It does not however in our experience form a complete zone comparable with the zone of transitional hypoæsthesia, but may be altogether absent for considerable tracts which then merely show hypoalgesia gradually increasing from the periphery to the centre. It was this irregularity and intermingling of the arrangements of hypoalgesia and hyperalgesia which rendered the problem so confusing and prevented us from arriving at what we now consider to be a satisfactory generalisation of the facts until we had divided several nerves. The most valuable clue to the significance of

this was obtained from the observation that the hyperalgesia tended to be distributed in the neighbourhood of subcutaneous veins and especially of such veins as came exceptionally close to the surface. Each patch of hyperalgesia was associated with a particularly obvious vein and generally the skin over the vein itself was the most sensitive part of the patch. A pin-prick here would produce a severe burning

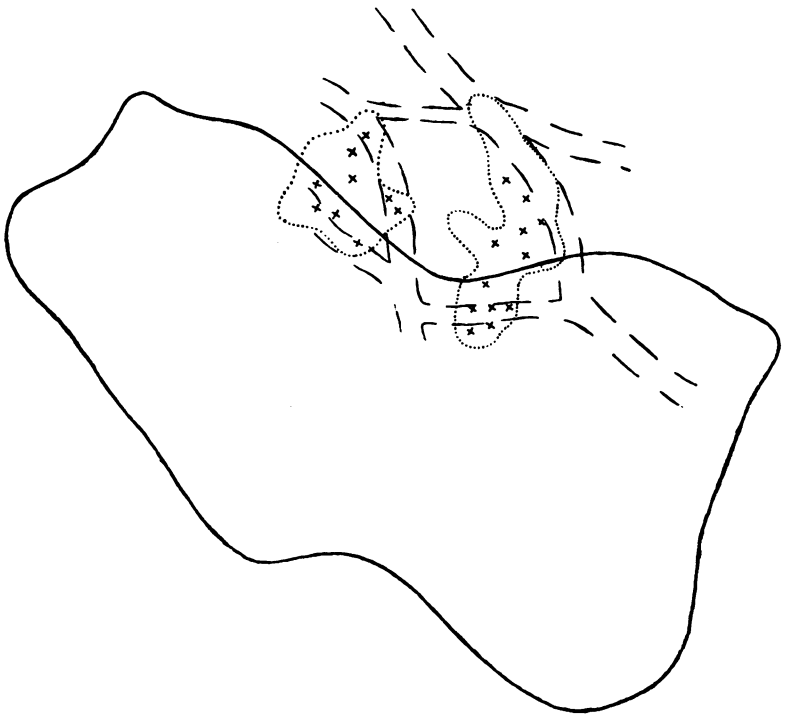


Fig. 7. Middle cutaneous. Left thigh. External branch.

34 days after section. Tracing to show a stage during subsidence of the hyperalgesia which follows nerve section.

The spots marked × were those of maximum sensitiveness to pin-pricks.

The dotted lines enclose the areas which were abnormally sensitive to pin-pricks.

The broken lines show the course of superficial veins.

Outside the dotted lines there was no hyperalgesia anywhere.

The continuous line marks the limit within which there was anæsthesia to the camel's hair brush.

The diagram shows an advanced stage in the subsidence of hyperalgesia, and brings out the facts that this hyperalgesia may occur outside the camel's hair line and that it tends to persist longest in the neighbourhood of the veins. Apart from the areas enclosed by the dotted lines a hypoalgesia deepening towards the centre of the area of anæsthesia to the camel's hair brush was present.

pain which tended to persist for some time and to reappear spontaneously from time to time afterwards. When the vein was exceptionally sensitive, a touch over it with a light camel's hair brush would often be enough to precipitate an outburst of pain.

During the next week or two the hyperalgesic areas tend rapidly to diminish in extent and finally to disappear, maintaining however to the end the association with superficial veins (Fig. 7). At the end of six weeks scarcely any hyperalgesia can be detected, while at the end of two months it has completely disappeared and we then have a central area of analgesia surrounded by a gradual hypoalgesia, so that at this stage the defect of sensibility to pain is precisely similar in character and distribution to the defects in sensibility to cold, to heat and to touch (Fig. 8). When it is understood, as we shall show later, that regeneration may begin by the tenth week and always bring with it a definite

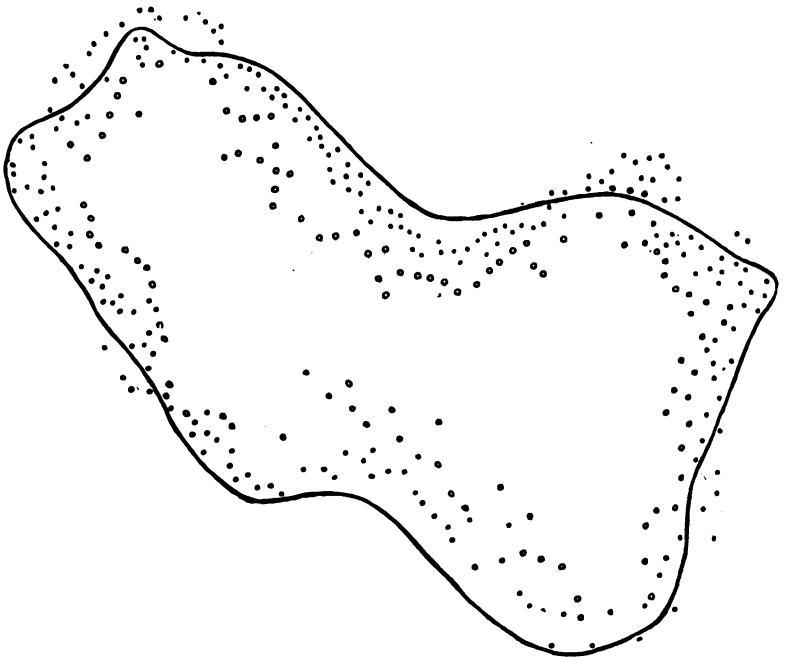


Fig. 8. Middle cutaneous. Left thigh. External branch.
23 days after section. Tracing of results of examination with algometer.
Spots marked • reacted to pressure of 1860 milligrammes (normal threshold).
„ ○ „ 2280 „
The continuous line marks the area within which there was anæsthesia to the camel's hair brush.

hyperalgesia, while this form of patchy hyperalgesia which we have just described may barely have disappeared by the eighth week, it will be comprehensible how easy it is for the fact to be overlooked, that there is a period following the section of a nerve when the defect of sensibility to pain forms no exception to the rule that the changes consequent upon depriving a piece of skin of its nerve supply are distributed in a central area of absolute loss surrounded by a zone of partial loss which is slight towards the periphery and deepens towards the centre.

Section 2. *Motor.*

Thus far we have been concerned solely with the effects of section of the afferent fibres in a cutaneous nerve; we must now deal with the effects of section of the efferent fibres. Such effects are extremely unobtrusive and this is probably the reason why they have attracted so little attention in man; on the other hand however they have this great advantage over the results of division of the afferent fibres in that they are susceptible of purely objective observation. It will serve to emphasise the inconspicuousness of such paralytic phenomena as are produced, when we say that our attention was not attracted to them in the areas of change following the earlier operations, except in one or two instances the full significance of which we did not at the time realise. When however we began deliberately to investigate these phenomena we found them most precise and easily observable.

So far as our experience goes, all cutaneous nerves contain efferent fibres of three kinds, vaso-motor, pilo-motor, sudo-motor; section of such a nerve is always followed by definite paralytic phenomena affecting these three functions.

Vaso-motor. A localised area of vaso-motor paralysis confined to the skin produces changes which are even at their maximum very inconspicuous, while their duration is so short that within a few weeks of the operation only the slightest changes may be observable even when special methods of examination are used. It may be stated with confidence that of all the changes produced by the section of a cutaneous nerve, the modifications of vaso-motor activity are the first to disappear. The effects of a vaso-motor paralysis of the skin are shown in three different ways. First, an alteration in the colour of the part; secondly, alterations in the temperature of the part; thirdly, variations in the reactions to stimulation of the circulatory conditions of the part. All

these changes are relatively minute and as might be expected may very easily be masked or overwhelmed by gross normal circulatory modifications in the whole limb. Under favourable circumstances however they are very definite.

Within a few hours of the operation the region of distribution of the nerve is found to be redder than the surrounding parts. This redness while not very pronounced is quite distinct and the area can be easily marked out. It is found to correspond very closely with that of anæsthesia to the brush. The redness is distinctly dusky and may in places be slightly mottled with a paler colour. These observations as to colour apply however only to the limbs. In the case of section of the great auricular the vaso-motor changes were noticeable only in the ear. This became of a bright red colour and showed no tendency to the duskiness which was observed elsewhere. The congestion of the part gradually becomes less noticeable and can scarcely be detected by about three weeks after the operation. The ear however differed from the rule also in this respect, for no abnormal redness was observable in it after a week.

Vaso-motor paralysis is also shown by the fact that the temperature of the part is less independent than normally on surrounding conditions. During the first two or three weeks if the area is exposed after having been covered up for some time it is found to be obviously warmer than the surrounding skin. After prolonged exposure however, or after the application of cold to the limb as a whole, the affected part is distinctly cooler than the surrounding skin. The latter peculiarity seems to persist longer than the evidences of congestion, though these after they have ceased to be observable under ordinary conditions may be rendered obvious by cooling the surface. We have found the increased dependence of the temperature of the affected skin upon surrounding conditions to be the most convenient test of the persistence of vaso-motor weakness.

When normal skin is irritated by scratching, certain changes in colour appear within a few seconds of the cessation of the stimulus; first along the line of the actual scratch there comes out a streak of redness and around this develops more slowly a distinct margin of whiteness from 5 to 15 millimetres in width. The skin in which the vaso-motor mechanism is paralysed shows a characteristic modification of this reaction. The streak of redness develops sooner, is narrower and of a brighter colour, whereas the surrounding whiteness is much less distinct and tends to be patchy, the whole condition suggesting

that the effects are produced directly upon the vessels without the modifying action of the normal nervous mechanism. These changes are the most evanescent of all the vaso-motor changes which are observed to follow the section of a cutaneous nerve. We have not observed them to persist for more than three weeks after the operation.

With regard to the relation of the size of the area of vaso-motor change to that of the areas of altered sensibility, it may be stated that the former tends to correspond with the latter in a general way, and with the outline of the hypoæsthesias rather than with that of the anæsthesias; for example, the congestion seen soon after the section is as large if not larger than the area insensitive to the brush.

Pilo-motor. It has often been noticed that after division of a cutaneous nerve the hairs in the anæsthetic region have lost their regular arrangement and lie at all angles to one another and to the surface. This has been attributed, for example by Head and Sherren, to what is called trophic disturbance. When however such hairs are carefully examined it is found that they are abnormally susceptible to passive movement and have less than the usual elasticity in regaining their positions after they have been displaced. At the same time the skin in which they are set is seen to be abnormally smooth and totally lacking in the slight prominences which mark the hair follicles of normal skin even in the absence of anything like an actual condition of goose-skin. The surface of such skin moreover can be felt to be unusually uniform. These conditions are due to a paralysis of the pilo-motor apparatus consequent upon the nerve section, as can very well be seen in a part which readily exhibits the condition of goose-skin. As each wave of this passes over the part an area in the affected region will be found invariably to remain unchanged. This area, unlike that of the vaso-motor paralysis, tends to conform with that of the anæsthesia rather than with that of the hypoæsthesia and to lie therefore within the boundary of insensibility to the brush (Fig. 9). As a rule it is surrounded by a margin in which goose-skin develops but feebly.

This paralysis of the pilo-motor mechanism is one of the most definite and least questionable of the results of nerve section; it needs however to be looked for with some care and the chief difficulty lies in the extremely capricious nature of the reflex, and the fact that in certain regions it is scarcely to be observed at all. For example, in the face and hand pilo-motor paralysis might very well escape notice altogether, while in the thigh and arm of a moderately hairy person it is much more obvious. To excite the reflex we have found large smooth

touches more efficient than cold. For the lower limbs at any rate the most satisfactory place to apply the stimulus is over the distribution of the posterior primary division of the lower spinal nerves, while for the arms local stimulation is remarkably efficient. Water seems to be the best medium to make the stimulus with and it does not seem to matter much whether it is hot or cold. As is well known the least amount of febrile disturbance greatly exaggerates the goose-skin reflex. We were fortunate in the fact that at the time when our attention was first

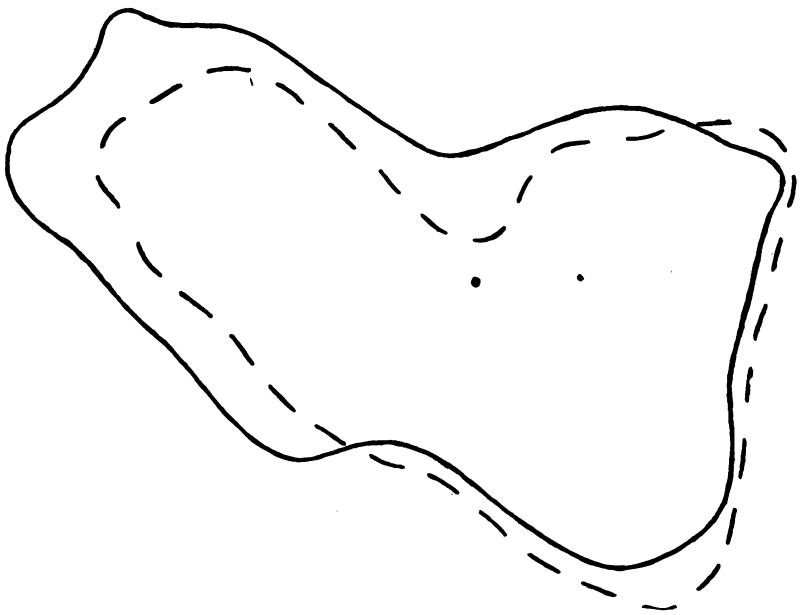


Fig. 9. Middle cutaneous. Left thigh. External branch.
23 days after section. Pilo-motor paralysis.
Broken line marks the area within which pilo-motor reflex was absent.
Continuous line marks the limit within which there was anæsthesia to the camel's hair brush.

attracted to this subject one of us happened to be suffering from influenza; the weather at the time was cold and as soon as the limb was exposed a series of waves of very pronounced goose-skin would begin to pass over it.

The researches of Elliot[6] and others have shown that adrenalin has a specific capacity for exciting locally the pilo-motor mechanism, and that when the sympathetic fibres to a part have been cut and

allowed to degenerate the action of the drug becomes more pronounced. These conclusions we have been able to confirm. If an area which includes normal skin and skin showing pilo-motor paralysis be injected with a weak solution of adrenalin in normal saline, marked goose-skin is produced throughout but is distinctly more pronounced in the paralysed area. It is a remarkable fact that in skin in which there has been no activity whatever of the pilo-motor mechanism for many months the local apparatus remains absolutely intact and capable of responding energetically when appropriately stimulated.

It is not necessary however to have recourse to adrenalin in order to demonstrate the integrity of the normal local pilo-motor mechanism. A contraction of the muscles of the hair bulbs can be produced in two ways, as a reflex or as the result of direct stimulation. The reflex is best induced by light stimulation covering a large area and involves considerable parts of the surface at a time. The local reaction can be produced by a more energetic stimulus such as scratching or

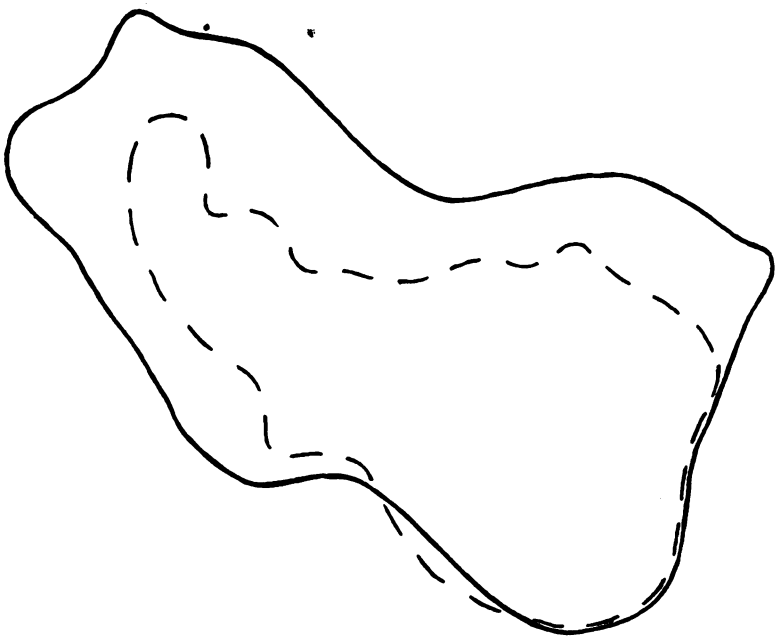


Fig. 10. Middle cutaneous. Left thigh. External branch.
33 days after section. Sudo-motor paralysis.
Broken line shows area within which sweating did not occur.
Continuous line marks the limit within which there was anæsthesia to the camel's hair brush.

rubbing and is always limited to the part actually stimulated, showing no tendency to spread as does the reflexly excited goose-skin. This local pilo-motor activity is in no way interfered with by section of cutaneous nerves[1].

Sudo-motor. The most convenient method of investigating the activity of the function of sweating is the use of the Turkish bath, and this we have exclusively employed. We chose it in preference to pilocarpine as being more physiological in its action and because of the extremely capricious action of the drug when used as a means of determining the limits of defective sweating.

Section of a cutaneous nerve abolishes sweating over a very well-defined area. This area corresponds in extent in a general way with the anæsthesias, and in fact seems to be the least extensive of the alterations in function produced by the section (Fig. 10). The area of total loss is surrounded by an indefinitely marked zone in which sweating while quite evident is less pronounced than normal.

The central area of total loss roughly corresponds with the area of maximal anæsthesia, the area that is to say in which it may be supposed that the whole thickness of the skin, with possibly the subcutaneous tissue also, has been completely deprived of its nerve supply. This correspondence might very well have been expected because as is well known the sweat glands lie in the subcutaneous tissue and not in the skin itself. Loss of sweating in such an area is absolutely complete, the affected skin remaining perfectly dry while the whole of the rest of the body is sweating profusely[2].

PART III. PHENOMENA OF RECOVERY.

Section 1. *Sensory.*

Peripheral and other forms of reference. After the complete disappearance of hyperalgesia at about the sixth to the eighth week,

[1] Before leaving this subject we may mention an observation which as far as we are aware has not been made before. It is that when the pronounced form of goose-skin induced by the injection of adrenalin has passed off, that is by about an hour after the injection, the part affected by the drug shows a complete pilo-motor paralysis which lasts for three or four days. Clearly the prolonged activity produced by adrenalin exhausts the peripheral neuro-muscular mechanism in a way that can never be effected by the normal goose-skin reflex which is so characteristically transient.

[2] We are much indebted to the manager of the Hammam Turkish Baths, Jermyn Street, for very courteously allowing us the use of the establishment outside the usual hours and providing us with every facility.

the area affected by a nerve section passes into a quiescent condition. In this state it attracts the attention of the subject less and less and might very well be forgotten if it were not for the periodical examination. We wish particularly to insist upon the complete absence of any unpleasant sensation or sensitiveness in the part at this stage.

At some period however, between the tenth and fourteenth weeks after the operation, a remarkable change becomes observable near the proximal boundary of the area. Up till now a touch with the finger here has produced a numb and vague sensation of pressure only, and the change consists in the fact that this is now accompanied by a distinct sensation having the characteristics of true touch which is felt, however, not locally but in the most peripheral part of the anæsthetic area. This peculiar phenomenon, which we call *peripheral reference*, is a constant and characteristic accompaniment of returning sensibility, and must therefore be dealt with in some detail. In the first place it is necessary to say that while peripheral reference is invariably present in an early stage of recovery, it does not, except possibly in the very earliest stages of all, accompany the sensations elicited by stimulation of every reappearing sensitive spot of the area. As we shall see there are certain qualities which do invariably accompany sensations elicited from every such spot and these qualities also are shared by the spots which give peripheral reference.

This reference of sensation being a very striking phenomenon, which can scarcely escape the notice of the least educated observer, is by far the most valuable and least equivocal of all the evidences of regeneration. When a spot which has developed peripheral reference is touched, one of two possibilities may occur; either the touch is felt locally, and is referred as well, or nothing is felt locally and the touch is felt in the area of peripheral reference. The region in which the referred touch is felt is always at the edge of the most peripheral part of the anæsthesia. As long as no attempt is made to outline it with the finger it seems perfectly definite; as soon however as such an attempt is made and the region of reference is touched, the referred sensation becomes vague and disappears. There are few experiences during regeneration so surprising as this contrast between the difficulty of recognising by touch the part involved and the precision with which it can be described.

These referred sensations although felt, it may be, more than a foot away from the spot actually touched, resemble normal touches so remarkably that the subject frequently mistakes them for such.

They do however present certain peculiarities. They may appear less closely upon the stimulus than do normal touches; they often seem like a minute trickling within the substance of the skin, and when they are called forth in bulk by, for example, rubbing the recovering area with the whole hand the sensation produced is almost exactly like that of a faradic current of a strength just below the pain threshold. On spots which give both peripheral and local sensations it can generally be shown that the former is elicited less readily than the latter; such a spot for example when touched with a certain von Frey hair may yield a local sensation only, whereas when it is tapped repeatedly with the same hair the referred sensation may be produced.

Touch however is not the only form of sensation in connection with which peripheral reference occurs. It is in fact sensations of cold which show the phenomenon in its most striking form. When an appropriate spot in a regenerating area is touched with a metal cylinder at a temperature of 0° C. nothing may be felt locally, but after a latent period, usually somewhat prolonged, there is felt in the area of peripheral reference a sudden trickle of cold of amazing intensity. This referred cold is perhaps the most definite and unmistakable sensation that it is possible to experience. No one who has heard the most imperfect description of it can fail at once to recognise the phenomenon when he experiences it in fact. Peripheral reference of cold reveals certain qualities which are either not present or are only imperfectly developed in peripheral reference of touch. The most striking of these is the intensity of the sensation. There can be no question that it is much more intense than any sensation of cold which can be elicited from normal skin by an object of equal size. As is well known the intensity of temperature sensations is dependent on three factors, the temperature and the conductivity of the exciting object and the size of the area of skin which is stimulated. Now the intensity of referred cold produced by a cylinder of 1 mm. in diameter is as great as that produced by a much larger object on normal skin. For example in an area showing very well-marked peripheral reference the sensation elicited by the 1 mm. cylinder at 0° C. was as intense as that produced on a corresponding normal part by a metal object 25 mm. in diameter at the same temperature.

Another measure of the intensity of the referred sensation is the fact that if the temperature of the testing cylinder be gradually raised, a sensation of icy coldness is quite definitely produced even as high as 20° C. (68° F.).

It has already been said that the interval between the stimulus and the sensation may be unusually long. This is not always the case, but on the whole may be said to be the rule. As with touch the local sensation may or may not be felt. It may precede or follow the referred sensation, usually the former, and, at any rate in early stages of regeneration, is practically always the less conspicuous of the two. Reference of cold is not confined to the maximal sensation, for sub-maximal sensations may also be referred. This however is a phenomenon much less striking and much more easily overlooked than the abrupt, intense and startling reference of cold. A fact no doubt closely associated with the intensity of the sensation is the tendency of this referred cold to persist. A succession of stimuli applied to an area which is giving referred cold induces a prolonged sensation which, for a time, renders testing impossible.

Peripheral reference occurs also with pain. As with touch and cold the sensation may be local and referred or referred only, and the referred sensation is as a rule more pronounced than the local. The delay in the appearance of the sensation which occurs with cold may also occur with pain. The referred pain shows three well-marked qualities: it is, proportionately to the stimulus, very intense; it does not reproduce a normal sensation with the exactitude found in the case of touch or cold but has a special quality of strangeness and unpleasantness such as no pin-prick on normal skin can give; finally it produces an almost irresistible desire on the part of the subject to rub or scratch the region in which it is felt. When this region is rubbed considerable relief is experienced, and the pain which would otherwise have shown a marked persistence ceases. After many pin-pricks this rubbing ceases to afford relief and the part acquires a continuous soreness which may last for an hour or more. It is interesting to notice that the subject has no desire to touch the part to which the stimulus has been applied but only that to which the sensation has been referred. Moreover it must be added that it is not exactly the region of reference which must be rubbed, for that is anæsthetic, but rather the skin possessing sensibility bordering immediately thereon. The peculiar unpleasantness of peripherally referred pain is well shown by its mental effects; after an hour or so of investigation of the sensibility to pain on a recovering area the subject becomes quite incapable of carrying on the observations and may show an amount of distress quite incomprehensible to anyone who has not himself experienced how great is the disproportion

between the discomfort felt and the trifling nature of the stimulus which calls it forth.

The very precise way in which sensations of touch, of cold and of pain are referred might have prepared one to expect that sensations of heat would be referred in the same way. In fact however peripheral reference of heat never occurs. Occasionally, when temperatures which would produce a distinct sense of heat on normal skin are being used, a faint and diffuse sense of warmth may be felt in the peripheral reference area. Like all sensations of warmth however its significance is very slight and no importance can be attached to it, so that it does not in any way modify the striking difference in their behaviour towards peripheral reference, of sensations of heat on the one hand and of touch, cold and pain on the other.

A word more must be added here to emphasise the fact that peripheral reference always has a very precise relation with the anatomical distribution of the nerve. We have already said that it is felt at the edge of the peripheral part of the anæsthesia and to this we must add that it seems always to be felt in the line of the nerve trunk and in the place where the characteristic fluttering is produced when the normal nerve is faradised. The region of peripheral reference is for each nerve very constant. In the forearm for example where we had two nerves which supplied contiguous areas regenerating together, it was always possible to distinguish peripheral reference in the anterior branch from that in the posterior. As might have been expected, recovering sensibility, and therefore the possibility of peripheral reference, begins to appear first in the neighbourhood of the nerve trunk; first actually over the nerve and then in the previously anæsthetic skin on each side. Moreover, when tactile, painful and cold stimuli are applied over the actual nerve trunk between the point of section and the proximal limit of the anæsthesia, peripherally referred sensations of touch, pain and cold respectively are felt. In addition of course, corresponding normal sensations are felt locally, for the skin through which the stimulus is being applied to the nerve is of normal sensibility. As the proximal limit of the anæsthesia is usually quite close to the point of section of the nerve, so that there is a very small length of the nerve trunk between these two, it was some time before we were able to observe with precision this very remarkable acquisition by a nerve trunk of what appears to be specific sensibility. Fortunately however in the case of one middle cutaneous of the thigh, a distance of no less than six inches was present between the point of section and

the upper limit of the anæsthesia, and this allowed the phenomenon to be demonstrated with unmistakable clearness.

As recovery proceeds two changes occur simultaneously, the local factor in sensation becomes more distinct and the abnormal quality of both local and peripheral sensation fades. While peripheral reference is the earliest phenomenon of recovery it persists until recovery is so far advanced that hypoæsthesia is scarcely detectable by any quantitative methods.

So far we have treated referred sensation during recovery as if it occurred towards the periphery only; this however is not the case. Peripheral reference is by far the most striking and the most constant form of reference and occurs from a much larger part of a recovering area than any other. From parts however in the distal regions of recovering areas, a reference of sensation in the opposite direction is observed. This is just as precise as peripheral and has similar characters with the single exception that the referred sensation is felt along the nerve on the proximal side of the anæsthesia and usually at the point of section of the nerve.

A third form of reference we have found in the case of one nerve only, namely the great auricular. Here recovery began with peripheral reference but ultimately a state of affairs was reached in which touch was always referred more or less exactly to the margin of the anæsthesia opposite to the place stimulated: there was never any reference to the point of nerve section. We have thus three well-defined types of abnormal reference during recovery and they may be called the peripheral, the proximal and the diametric respectively.

Qualitative characteristics of sensation during recovery. It has already been said that not all the spots in a recovering area which respond to stimulation give peripheral or some other form of reference; it must now be added that these spots which do not give reference, that is which yield local sensations, yield sensations which have many of the special modifications of quality found in referred sensations. Thus it may be said that a leading characteristic of sensation produced by stimulation of a recovering area is that it is abnormal in quality.

In the case of spots which yield peripheral reference to touch there is as we have seen no considerable modification in the quality of the sensation, because such modification being principally an increase in intensity cannot affect a form of sensation the intensity of which does not normally vary according to the stimulus; moreover no doubt such modification as occurs is rendered easier to detect by the fact of

reference, and thus it happens that touches which are felt locally in a recovering area have a quality practically normal. Local sensations of cold show a modification almost as striking as referred cold. The sensation is extremely intense, delayed in appearance and strikingly persistent, so that careful testing can only be done very slowly. The only qualitative difference therefore from the referred sensation is that the local is without the extremely striking trickling character which has already been described. Local sensations of pain have practically all the characters of the referred; that is to say they are intense, peculiarly unpleasant, persistent and produce in the subject an imperative desire to rub the place where they are felt, in this case of course the point stimulated.

It is not until recovery is far advanced in an area that the sensation of heat begins to return. Up to this time cylinders with a diameter of 1 mm. and at a temperature of 50° C. (122° F.) give rise to pain only. The pain is a pure prick having the same characters as pain otherwise produced in the same region; it is totally without any quality of temperature whatever. At this stage therefore it is clear that there is no modification in the quality of heat similar to that which occurs in the quality of cold and pain. This state of recovery is a fairly stable one and an area may remain for a considerable time with the four primary sensations *qualitatively represented* as follows:—touch practically normal; cold and pain profoundly modified; heat unrecognisable (Figs. 11, 12, 13). It must be understood that this statement has no quantitative application, in fact considerable hypoæsthesia may be present. It is obvious that the return of sensibility to heat affords a remarkable exception in the process of recovery. It is at first represented by pure pain, that is to say, pain will be produced by a temperature which on a normal heat spot gives the unmistakable sensation which is not only completely painless but is actually pleasant. The next stage is that into the pricking pain there steals an element still without a definite temperature quality but having the character which can be called burning. Gradually the burning becomes predominant; one can say that one is being touched with an object either very hot or very cold but cannot say which. As recovery progresses and a true sense of heat appears, the pain element rapidly diminishes, and it may be laid down as an invariable rule that as long as a spot yields any sensation of pain, the accompanying sensation of heat will be imperfect, and that as soon as the sensation of heat is perfect the pain will have disappeared. These results can be generalised by saying that

Fig. 11.

Fig. 11. Left internal saphenous. Reduced by $\frac{1}{3}$rd.
11 months after section. To show a stage in recovery.
Tracing of results of examination with a temperature of 0° C.
Spots marked • gave a sensation of cold felt locally.
,, ↓ ,, ,, peripherally (just in front of internal malleolus).
,, ○ ,, ,, both locally and peripherally.
The continuous outline is that of minimal hypoæsthesia as determined by the 'stroking method.'
The broken outline is that of anæsthesia to the camel's hair brush.
The thermo-anæsthesia which followed section of the nerve roughly corresponded with the area which now shows peripheral reference of cold.
Recovery is most marked along the line of the nerve.
The original area of anæsthesia to the camel's hair brush is greatly reduced.

the skin is hypersensitive to heat and reacts to 50° C. as normal skin would to a temperature 15 or 20 degrees higher. When the temperature of the cylinder is lowered sufficiently to counteract this sensitiveness, there is no longer sufficient thermal difference between the skin and the cylinder to produce a sensation of heat.

Quantitative observations. So far we have dealt with the qualitative reappearance of sensibility; we must now enter upon the question as to whether the return to the normal standard is immediate or gradual. It will be clear from what has gone before that it is very unlikely that sensorial acuity of normal grade will be acquired as soon as the quality of each sensation can be recognised. When we speak of return of sensibility to touch we mean that there has been recovered the possibility of feeling that characteristic light superficial pat which has been totally lost within a certain part of the affected area. We do not mean, however, that it can be elicited by stimuli as light as those which elicit it on normal skin. We find in fact that sensibility to true touch may return to an area long before that area is capable of responding to stimuli of a strength and character which would readily elicit a response from normal skin, that is to say it may be capable of yielding this sensory quality sometime before it responds to cotton wool or the brush. In connection with the examination of recovering areas with cotton wool or the brush, we may point out here that the distribution of the reappearing sensibility in spots which may be very sparsely scattered and are usually of widely differing sensitiveness, renders the results given by these methods quite unreliable and may prevent any precise result being obtained on account of the baffling inconsistency of the subject's responses.

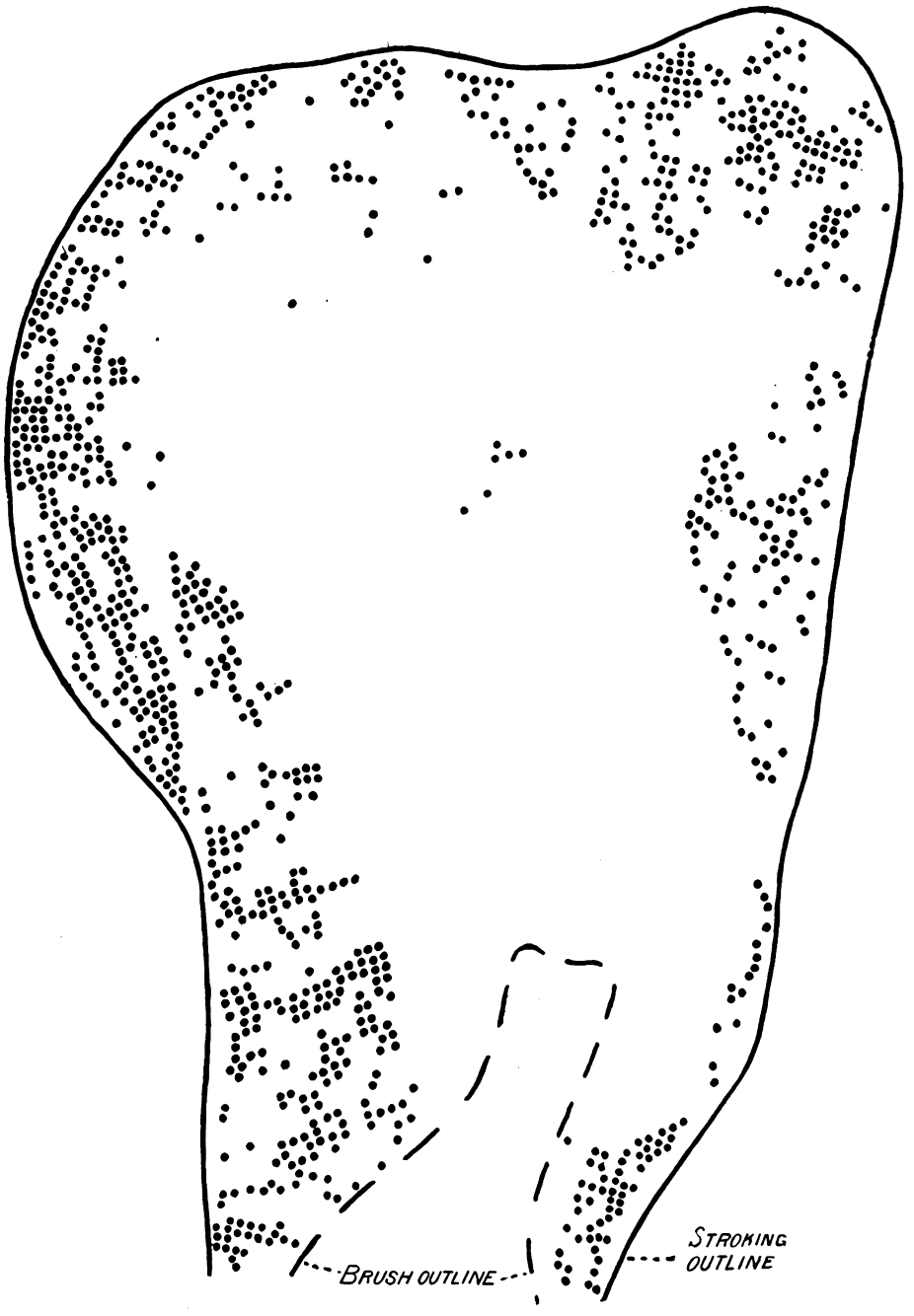


Fig. 12. Left internal saphenous.

11 months after section. To show delay in return of sensibility to heat at a time when recovery to cold was far advanced.

Tracing of results of examination with temperature of 50° C.

Spots marked gave a distinct sense of heat.

The outlines are the same as in Fig. 11.

Fig. 13. Left internal saphenous.
12 months after section.
To show distribution of hyperalgesia of recovery.
Spots marked were those which, tested with the algometer at a pressure of 1860 milligrammes (normal threshold) yielded intensified sensations of pain, for the most part referred.

In order to get a clear idea of the way in which sensibility returns, it is essential to realise that the course of the nerve, as might have been expected, forms the central line of advance. Along this will always be found the farthest outposts of change and about it will be grouped all such change as has occurred, making up a roughly wedge-shaped area, the axis of the wedge being the nerve and the base the proximal margin of the formerly anæsthetic part. As it is along the axis of the wedge that recovery begins, so it is there that recovery is most advanced, whereas along the sides the return is least complete. Thus for example the sides and apex of the area showing well-marked regeneration may contain spots which respond only to the heavier von Frey hairs of pressures from 2000 to 4000 milligrammes, while the axial parts contain spots which respond to pressure below 400. About the apex the sensitive spots are always sparse and usually give sensations which are either referred alone or if they are felt locally are referred as well, whereas in the axial parts the sensitive spots may have attained their normal density of distribution. It must be clearly understood that in speaking of responses obtained to the heavier von Frey hairs, we are referring only to such responses as have the characteristic quality of touch, a quality very easily to be distinguished from the sensation of pressure which with these hairs usually accompanies it. Such touches, it is interesting to note, although elicited by the bending of a formidable bristle which leaves a pit in the skin, give the same superficial pat as that which is produced by a fine horse-hair.

As to the precise order in which the various sensations return our observations have convinced us that touch, cold and pain all reappear about the same time and advance together. Probably touch, in a distinctly hypoæsthetic form of course, is the earliest, but within a week or two pain and cold are felt. Although it is the first to appear, tactile sensibility remains hypoæsthetic while the others soon develop a hypersensitiveness.

Section 2. *Motor.*

The vaso-motor changes which follow nerve section begin to show a diminution within a few days of the operation, and by the end of six weeks scarcely any abnormality of this function can be detected. It seems probable therefore that recovery occurs by some local compensatory mechanism rather than by an active regeneration of the vaso-motor nerve fibres. The area appears to recover as a whole and we have found

no evidence of it being invaded from the proximal end by a process of recovery, though of course the changes present even at the first are too vague to allow of very exact observation.

The case is different with the pilo-motor and sudo-motor functions. These reappear in a way which shows that recovery is due to regeneration of the nerve. The change begins at the proximal part of the area and gradually spreads throughout. The return of function occurs in stages so that a given region will first recover subnormal activity and this will be present for some time before full activity is attained. The time at which the change begins furnishes further evidence that a true regeneration is in progress. In a general way it may be said that pilo-motor and sudo-motor recovery begin about the same time as sensory recovery, showing that in both cases the time taken is probably due to the growth of the new fibres from the point of section to the paralysed area. Pilo-motor recovery does not progress so rapidly as sudo-motor and corresponds fairly closely with the improvement in sensibility to touch. Of all the six functions of the nerve the recovery of which is unquestionably due to a regeneration, sudo-motor function attains its complete activity first, and an area will show normal sweating while its sensibility to cold is very scattered and its sensibility to touch and heat very imperfect.

Figs. 14 to 28 contain the records of four stages observed in the area of the middle cutaneous of the thigh, namely soon after section, 4½ months, 6 months and 8 months later respectively. Fig. 14 is given on Plate I. These records may be taken as typical of what was found in the other nerve areas. It will be seen that at six months sudo-motor function was present all over the area though not in a fully active form, at a time when a very thin sprinkling of cold spots had reached the lower part, when no sensation of true heat could be felt, when sensibility to pain estimated with the normal threshold stimulus had returned in the upper two-thirds of the area and when touch was present all over, though in a markedly hypoæsthetic form. Pilo-motor function had recovered only in the part which did not show more than a moderate hypoæsthesia to touch. At eight months sensibility to heat was returning; touch had returned, but showed a moderate hypoæsthesia; cold and pain were almost complete; pilo-motor activity had returned in more than half the area and sweating was normal.

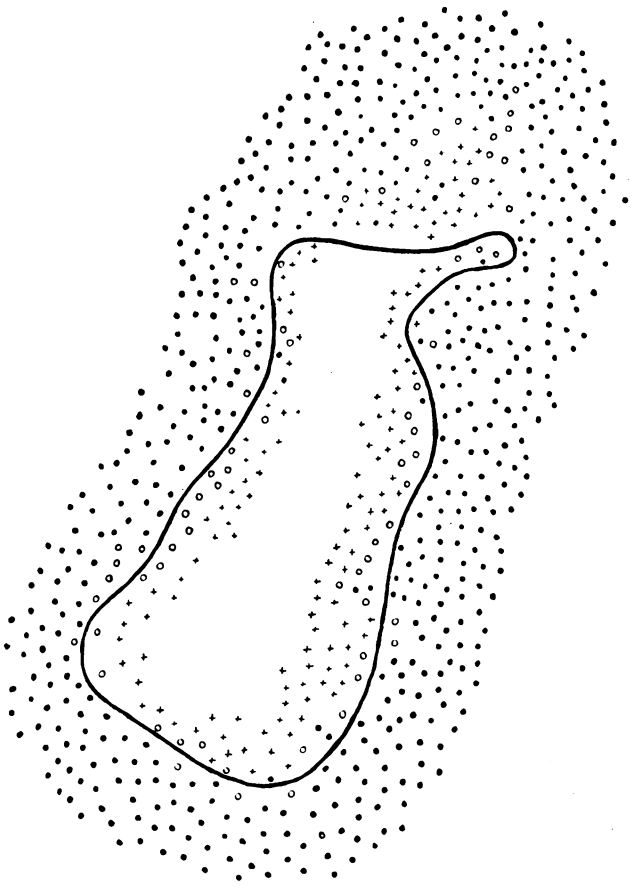


Fig. 15. Middle cutaneous. Right thigh. Outer branch. Sensibility to touch.

Tracing of results of examination with von Frey hairs 3½ months after nerve section. Reduced by ¼.

The spots marked • were touch spots which reacted to a hair of 280 mgs. pressure.

" ○ " " " 800 "

" + " " " 3480 "

The area at this time shows the definitive results of the nerve section; all hyperalgesia has disappeared; the defect of sensibility is scarcely noticeable by the subject except during the periodical examinations. Signs of recovery however are just about to appear.

The continuous line in this diagram and the rest of the series dealing with this nerve is the boundary of the area originally insensitive to the camel's hair brush, and at this time of course unmodified.

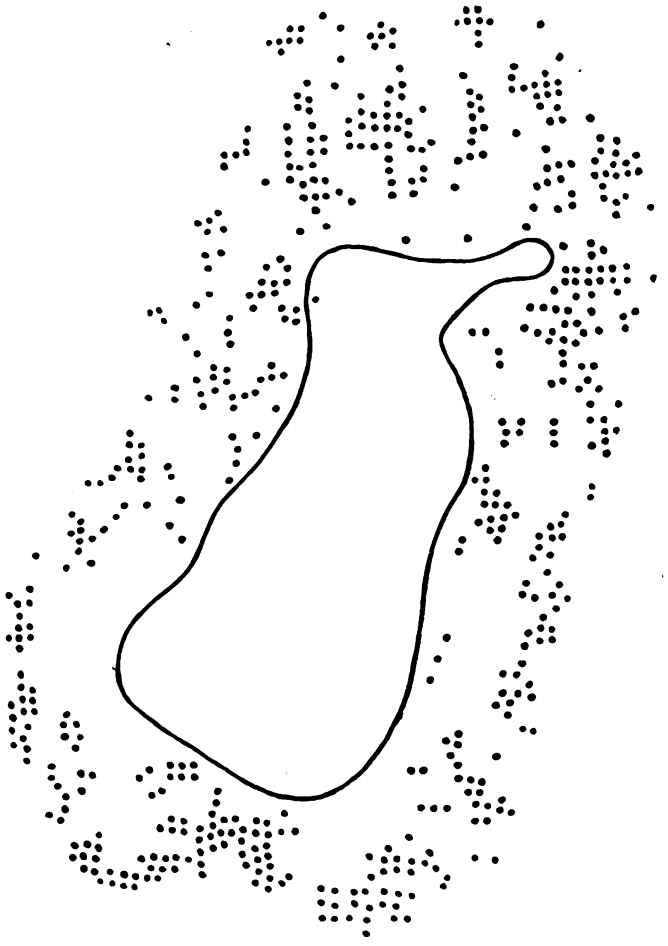


Fig. 16. Middle cutaneous. Right thigh. Outer branch. Sensibility to cold.
Tracing of results of examination with a temperature of 0° C. 3½ months after nerve section. Reduced by ¼.
No evidence of recovery.
The spots marked are those which yielded a distinct sense of cold.

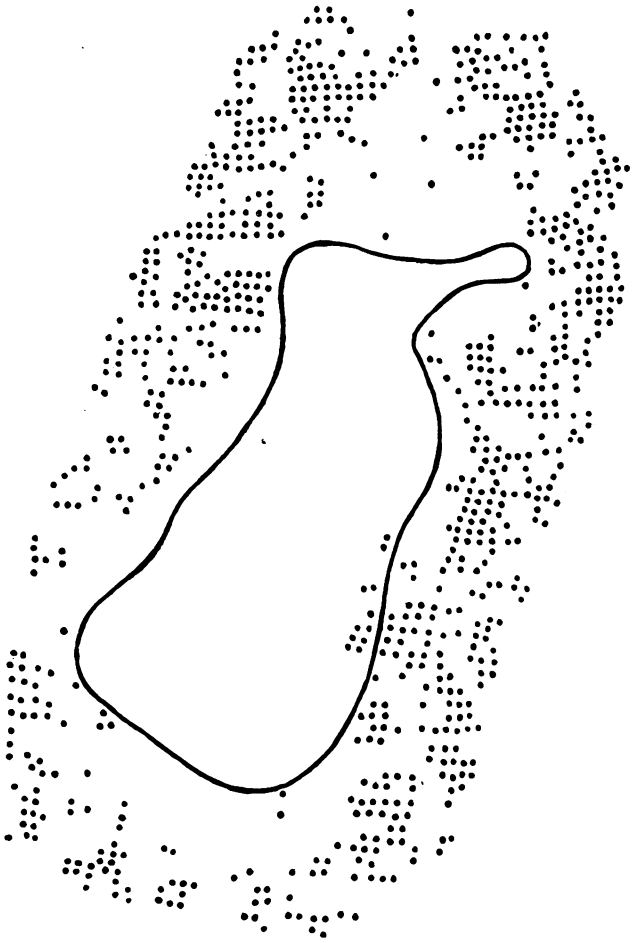


Fig. 17. Middle cutaneous. Right thigh. Outer branch. Sensibility to heat.
Tracing of results of examination with a temperature of 50° C. (122° F.) 3½ months after nerve section. Reduced by ¼. No evidence of recovery.
Spots marked are those which yielded the sensation "hot."

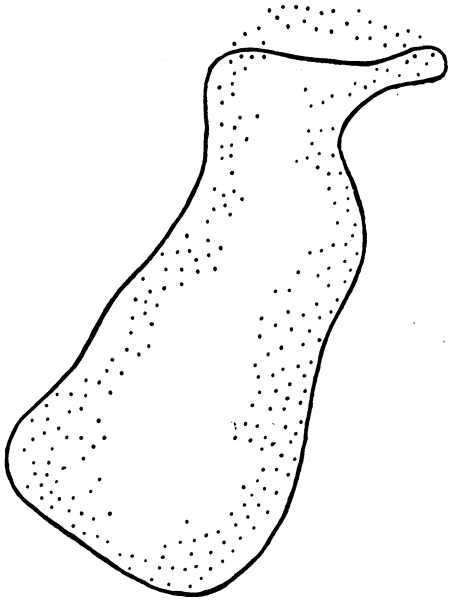


Fig. 18. Middle cutaneous. Right thigh. Outer branch. Sensibility to pain.
Tracing of results of examination with hair algometer at pressure of 2240 mgs. 3½ months after nerve section. Reduced by ¼.
The spots marked gave a distinct sensation of pricking-pain.
Enough spots only were tested to give a margin to the area analgesic to this stimulus. The stimulus used was about or a little above the normal pain threshold of the part.
There was no hyperalgesia or abnormal quality in the pain felt.

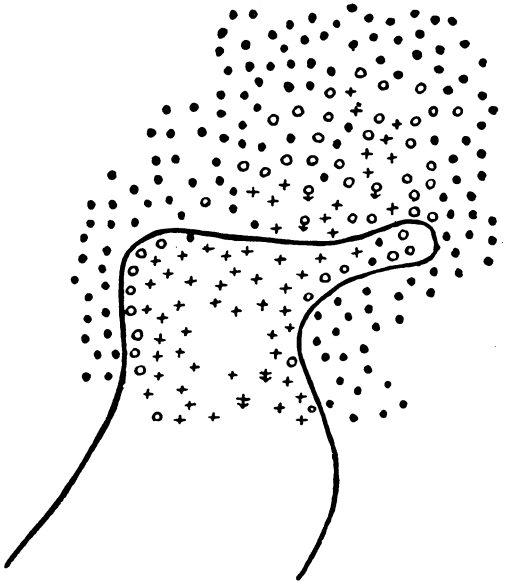


Fig. 19.

Fig. 19. Middle cutaneous. Right thigh. Outer branch. Sensibility to touch.

Earliest stage of recovery. Tracing of results of examination with von Frey hairs 4½ months after section of nerve. Natural size.

The spots marked • were touch spots which reacted to a hair of 280 mgs. pressure.

" ○ " " " 800 "

" + " " " 3480 "

The addition of the sign ↓ means that a peripherally referred sensation is felt as well as a local sensation. Only that part of the area is represented which shows changes of recovery.

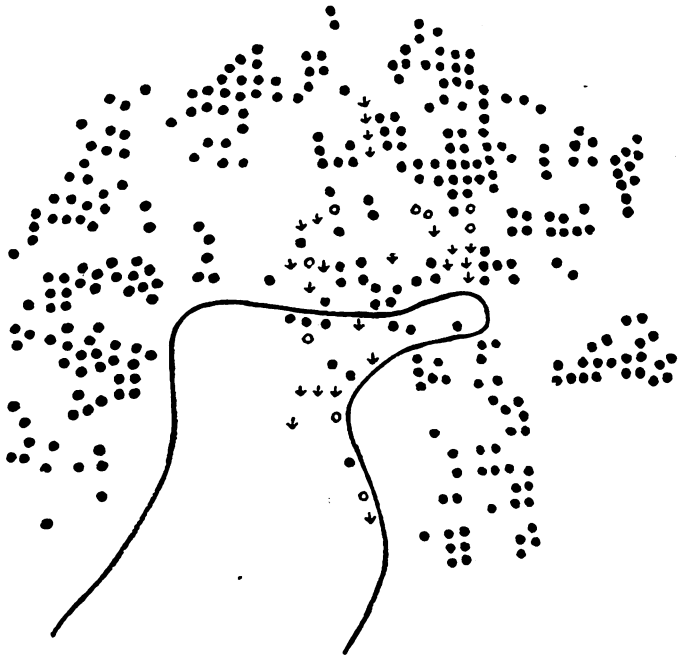


Fig. 20. Middle cutaneous. Right thigh. Outer branch. Sensibility to cold.

Earliest stage of recovery. Tracing of results of examination with temperature of 0° C. 4½ months after section of nerve. Natural size.

The spots marked • yielded a local sensation of cold.

The spots marked ↓ yielded a sensation of cold peripherally referred.

The spots marked ○ yielded both a local and a peripherally referred sensation of cold.

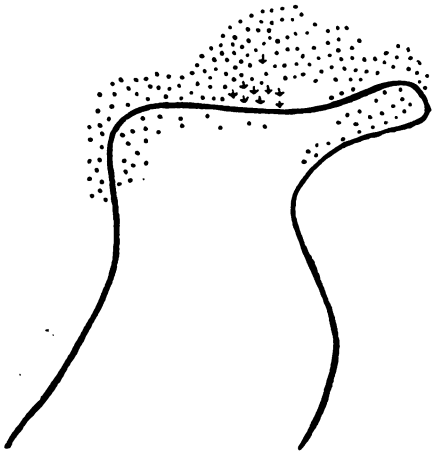


Fig. 21. Middle cutaneous. Right thigh. Outer branch. Sensibility to pain.
Earliest stage of recovery. Tracing of results of examination with hair algometer at pressure of 2240 mgs. 4½ months after section of nerve. Natural size.
The spots marked • yielded a local sensation of pricking-pain.
The spots marked ϕ yielded a sensation of pain peripherally referred.

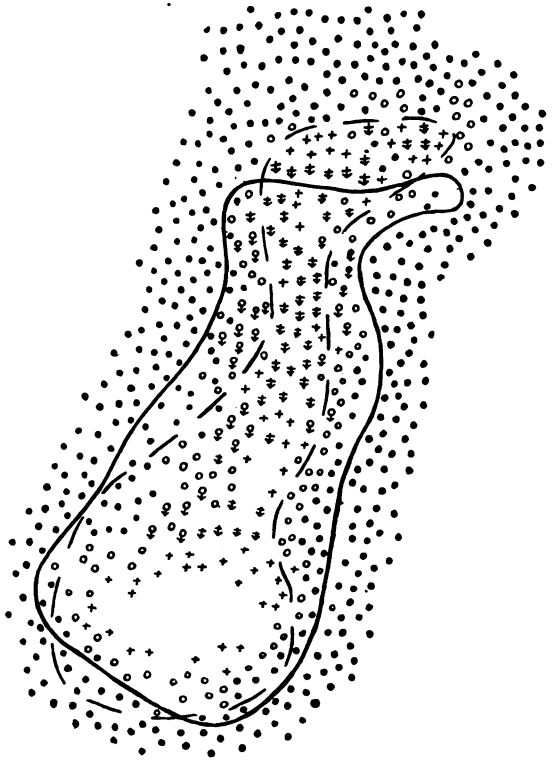


Fig. 22.

Fig. 22. Middle cutaneous. Right thigh. Outer branch. Sensibility to touch.
Later stage of recovery. Tracing of results of examination with von Frey hairs 6 months after section of nerve. Reduced by ¼.
The spots marked • were touch spots which reacted to a hair of 280 mgs. pressure.
,, ○ ,, ,, ,, 800 ,,
,, + ,, ,, ,, 3480 ,,
The addition of the sign ↓ means that a peripherally referred sensation is felt as well as a local sensation.
The broken line indicates the area within which the pilo-motor reflex was still absent.

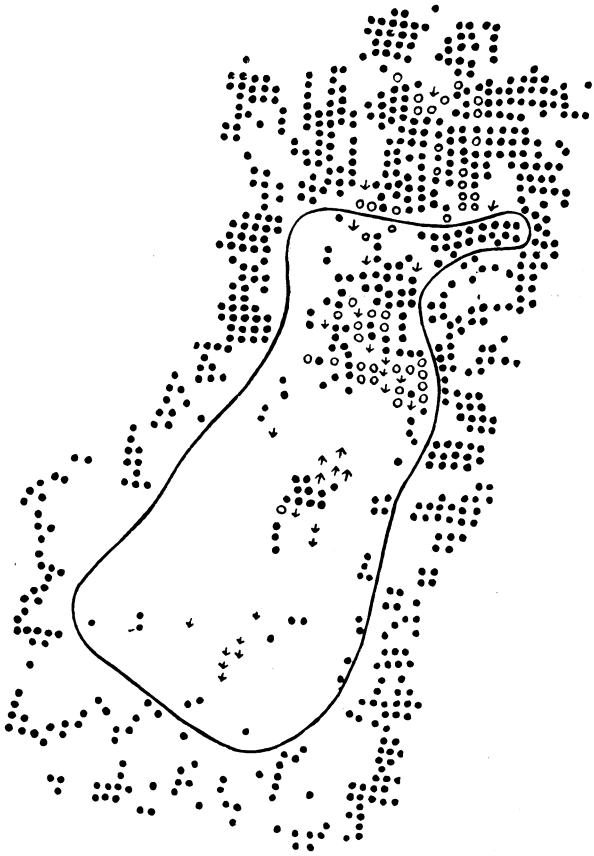


Fig. 23. Middle cutaneous. Right thigh. Outer branch. Sensibility to cold.
Later stage of recovery. Tracing of results of examination with a temperature of 0° C. 6 months after section of nerve. Reduced by ¼.
The spots marked • yielded a local sensation of cold.
The spots marked ↓ yielded a sensation of cold peripherally referred.
The spots marked ↑ yielded a sensation of cold referred proximally to point of nerve section.
The spots marked ○ yielded a local and a peripherally referred sensation.

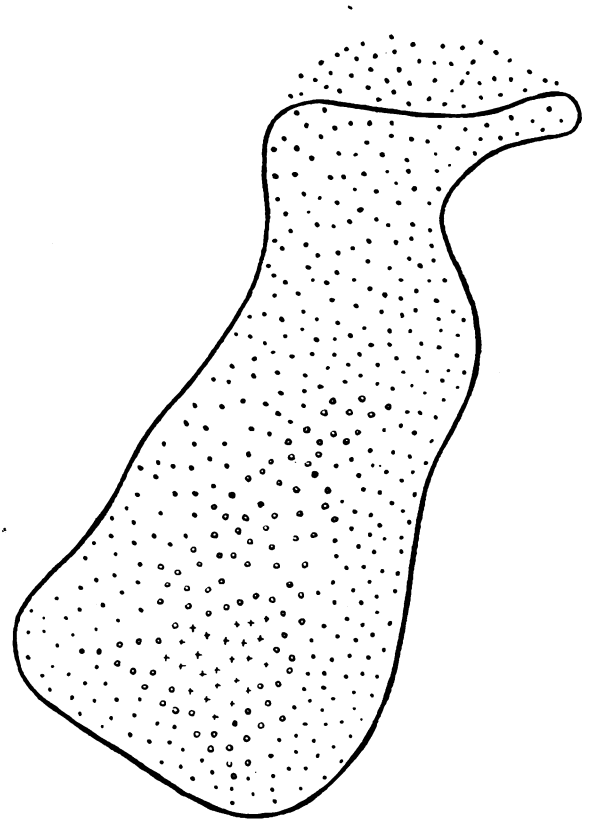


Fig. 24. Middle cutaneous. Right thigh. Outer branch. Sensibility to pain.

Later stage of recovery. Tracing of results of examination with hair algometer 6 months after section of nerve. Natural size.

The spots marked • yielded a sensation of pricking-pain with algometer at pressure of 2240 mgs.

The spots marked ○ yielded a sensation of pricking-pain with algometer at pressure of 3480 mgs.

The spots marked + yielded a sensation of pricking-pain with algometer at pressure of 5220 mgs.

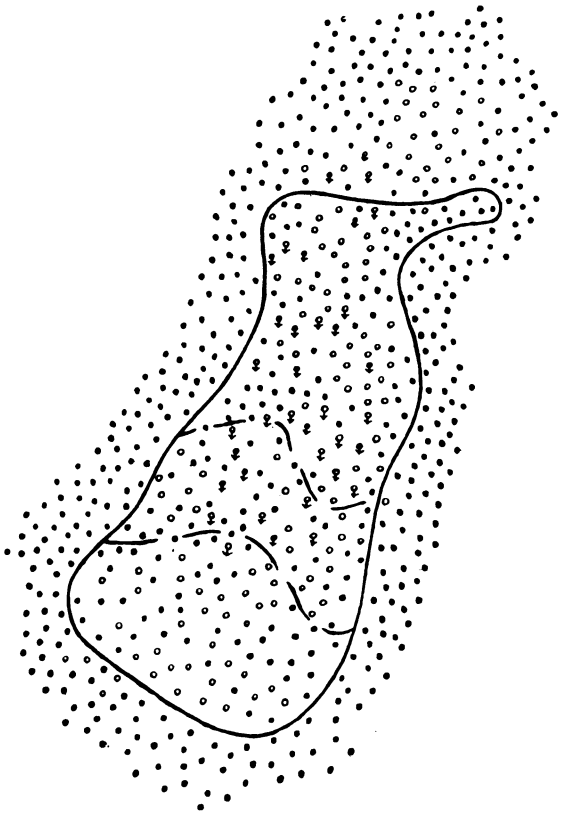


Fig. 25. Middle cutaneous. Right thigh. Outer branch. Sensibility to touch.

Advanced stage of recovery. Tracing of results of examination with von Frey hairs 8 months after section of nerve. Reduced by $\frac{1}{4}$. Markings as in Fig. 22.

The broken lines indicate the distance to which recovery of pilo-motor function had advanced down the area.

The upper line marks complete recovery.

The lower line marks incomplete recovery.

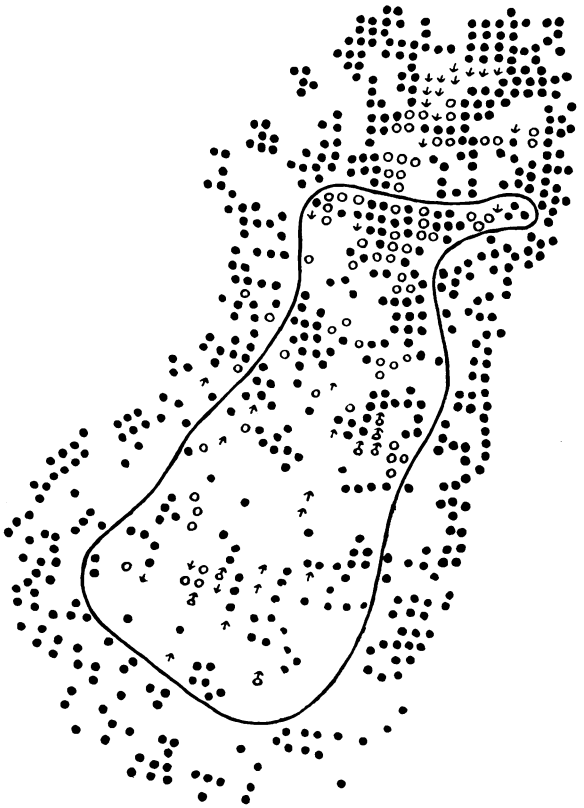


Fig. 26. Middle cutaneous. Right thigh. Outer branch. Sensibility to cold. *Advanced stage of recovery.* Tracings of results of examination with temperature of 0° C. 8 months after section of nerve. Reduced by $\frac{1}{4}$. Markings as in Fig. 23.

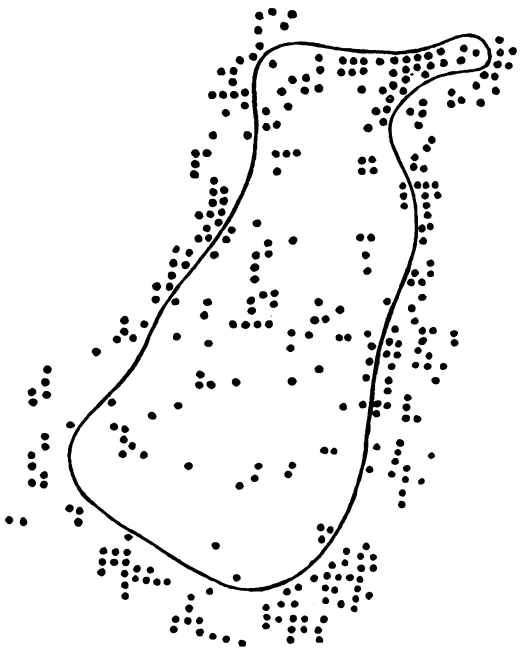


Fig. 27.

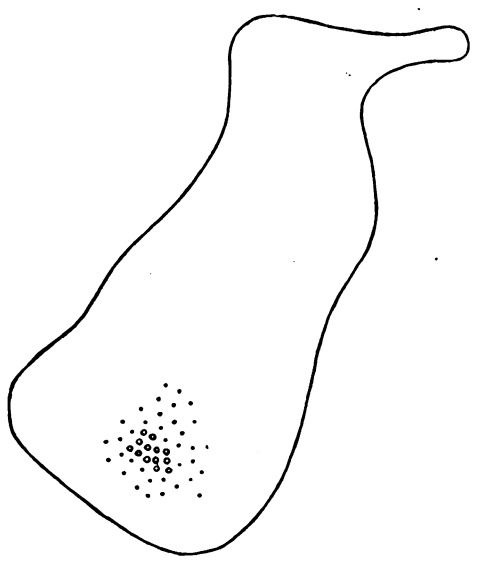


Fig. 28.

Fig. 27. Middle cutaneous. Right thigh. Outer branch. Sensibility to heat.
Advanced stage of recovery. Tracing of results of examination with temperature of 50° C. (122° F.) 8 months after section of nerve. Reduced by ¼.
The spots marked are those which yielded the sensation "hot."

Fig. 28. Middle cutaneous. Right thigh. Outer branch. Sensibility to pain.
Advanced stage of recovery. Tracing of results of examination with hair algometer. Reduced by ¼.
The whole area has recovered sensibility to stimulation with algometer at pressure of 2240 mgs., with the exception of the spots marked ○ which react to algometer at pressure of 3480 mgs.

PART IV. GENERAL CONSIDERATIONS.

On the relation of these observations to the conclusions of other investigators.

We have so far limited ourselves to a statement of the facts we have collected during our investigation and have avoided all general considerations, except in one or two places where a rigid exclusion of such would have interfered with the intelligibility of the exposition. We must now however concern ourselves more directly with the general aspects of the subject, and shall begin with some reference to the conclusions of other workers. As our work would not have been undertaken but for the demonstration by Head of the value of investigations carried out on subjects with scientific training, it is natural that we should wish to discuss first the bearing of our observations upon the views of this observer concerning the afferent peripheral nerves. As is well known he was led, as the result of work in conjunction with Rivers[7] and Sherren[8] upon an area of anæsthesia experimentally produced in himself, and of observations on a very large number of patients who were suffering from nerve injury, to enunciate an hypothesis of cutaneous sensory function which differed in a striking way from previously accepted views. The discussion of this work naturally divides itself into two more or less distinct parts, namely that concerned with the verifiability of the facts recorded and that concerned with the satisfactoriness of the generalisations based on them. Briefly summarised the facts recorded are as follows. Section of a cutaneous nerve produces an area of altered sensibility, the whole of which is anæsthetic to cotton-wool. The boundary of this area, that is to say the line outside which there is normal sensibility to cotton-wool and inside which there is no sensibility to cotton-wool, marks a transition of the abruptest kind. Within this area the defect of sensibility is not equally distributed, for there is a more or less central region which is insensitive not only to tactile stimuli, but to painful and thermal stimuli also. Between the limit of this area and the outline of tactile anæsthesia is an intermediate zone which while insensitive to tactile stimuli and to Weber's test, is sensitive to thermal stimuli differing widely in temperature from that of the skin, and is hypersensitive to painful stimuli. This hypersensitiveness to pain is accompanied by a peculiar qualitative alteration in painful sensations; these become diffuse, radiating, peculiarly unpleasant and produce in the subject an almost irresistible tendency to the making of some motor response.

The boundary between this intermediate zone and the central area of total anæsthesia is indefinite. When regeneration occurs, two stages are noticeable and separated in time by a considerable interval. The first consists in the acquisition by the area formerly anæsthetic, of the sensory characters of the intermediate zone. The central region and now therefore the whole affected area is sensitive to pain and to extremes of temperature, but is still insensitive to tactile stimuli and to Weber's compass test. The second change, which occurs much later and much more slowly, is the reappearance of tactile sensibility, of sensibility to Weber's test and to temperatures near that of the skin. The sensory capacities of the skin then return to it during regeneration in two groups. The return of the first group is peculiar in that it causes not merely the reappearance of sensibility to pain but also the appearance of hyperalgesia. The effect of the return of the second group of sensory capacities, not only restores all the remaining functions of the skin, but causes also the disappearance of the hyperalgesia which follows the return of the first group.

These observations were regarded by Head and his collaborators as showing that the sensory functions of the skin are separable into two groups each of which is subserved by a distinct kind of nerve fibre. One group includes functions which are regarded as being the more primitive and less delicate: these are sensitiveness to pain and to thermal stimuli of extreme degree, and are referred to as "protopathic." The second group, which is regarded as comprising sensory mechanisms of a more elaborate and delicate kind, is concerned with sensibility to touch, to temperatures near that of the skin and with the capacity to feel as distinct two simultaneous contacts. This group is called "epicritic." Thus the area of altered sensibility following section of a nerve has in the central part, which is totally anæsthetic, lost both its protopathic and its epicritic supply, whereas the intermediate zone has lost its epicritic supply only, and when regeneration occurs the central area recovers protopathic sensibility first, thereby acquiring the form of sensibility which has been possessed by the intermediate zone throughout. Thus it is obvious that the hypothesis asserts as a cardinal fact, that the form of sensibility possessed by the intermediate zone from the moment when the nerve is cut, is identical in all essential particulars with that present in the central and formerly totally anæsthetic region at the end of the early stages of regeneration.

We may now enter upon the discussion of the extent to which our observations confirm those of Head. We shall deal first with the

subject of tactile sensibility. At the beginning of his paper, Head shows that it is of cardinal importance to recognise that not only the skin but the deeper structures also are sensitive to contacts, so that in testing the sensibility of the skin it is essential to know whether the impression to which the subject is responding is coming from the superficial or deeper parts[9]. All the work we have done tends to confirm the importance of this view and to show that the investigation of the problems of sensation in the abnormal is not possible without the recognition of it. To make sure that he is obtaining responses to impressions of purely cutaneous origin, Head uses one of what we have called the minimal pressure methods, that is to say he makes use of a stimulus which is supposed to be too light to stimulate the subcutaneous structures, it being assumed that touches which are only just heavy enough to be constantly felt must be limited in their effects to the skin. We are able to confirm most thoroughly his statement that such a method, for example that of cotton-wool or the camel's hair brush, gives an extremely definite outline which is very easily obtained and remarkably constant. It does moreover on the whole correspond fairly closely with the outline of the area which the subject distinguishes as distinctly numb. It is not possible however to accept the results of this method as giving by any means a complete account of the state of sensibility to light contacts in skin deprived of the whole or part of its nerve supply. The outline given must of course be an arbitrary one even if the stimulus could be regarded as absolutely constant, a state of affairs which is of course far from being the case. The boundary given is that at which the skin ceases to respond to a pressure approximately constant. The method gives us no certain evidence that the skin outside is of normal tactile capacity and no evidence whatever that the skin inside is incapable of response. It is assumed that if we use a heavier stimulus the responses may be coming from the subcutaneous tissues, but we have no right to assert that they are not coming from the skin. Holding as he does the view that touch and pressure form a single continuous series of sensations produced by stimuli, which are in series of increasing strengths, so that the differences both subjectively and objectively are merely those of degree[10], it is natural that Head should regard the information given by the cotton-wool method as adequate or at any rate incapable of much expansion; for it is clear that according to this view it is impossible to be certain when a subject responds to a stimulus applied in the intermediate zone that the impression has not come from the sub-

cutaneous tissues. As we have already shown however there is good reason for believing that touch and pressure are sensations introspectively quite distinct, so that a trained observer can always distinguish them with ease and is therefore independent of the strength of the stimulus in determining whether the origin of the sensation is to be ascribed to the skin or not. The distinction between touch and pressure or between what we have called moving contact and static contact has recently been dealt with in some work carried out in the physiological laboratory of Cornell University by Elsie Murray[11]. The work was all done on the normal skin and therefore under circumstances requiring exceptionally delicate introspective analysis; her conclusions however are in agreement with our results from work on hypoæsthetic areas. The recognition of the fact that touch is a sensation *sui generis* opens up the intermediate zone to investigation. Before referring to the results of such examination a few words are necessary to define precisely the nature of this zone. According to the statement of Head, the area inside the cotton-wool line is sensitive to painful stimuli in its outer parts and analgesic only in its central parts, so that outlining the affected area according to sensibility to pin-pricks gives a very different result from outlining the area according to sensibility to cotton-wool. This observation we have been able to confirm in the area of each of the seven nerves we have cut. It is necessary however to make some comment upon the way in which this intermediate zone is outlined. The importance of an approximately constant stimulus in distinguishing sensations derived from the skin and the deeper structures was very rightly insisted upon by Head in the matter of touch. It is however obvious that in spite of the well-known relative insensibility to pain of the subcutaneous tissues, the same principle applies to the investigation of pain. Now very little experience is necessary to show that the use of the needle in the ordinary way as a source of painful stimuli, involves a very considerable variability in the strength of the stimulation. Hence a comparison of the limit of analgesia obtained in this way, i.e., with a variable stimulus, with the limit of tactile anæsthesia obtained with cotton-wool, i.e., with a constant stimulus, has certain unsatisfactory features the recognition of which very considerably diminishes the significance of the intermediate zone. Again when this zone is examined for sensibility to touch with the higher von Frey hairs, it being of course clearly understood by the subject that he is to respond only to sensations having the characteristics of true touch, it is found that there is a gradually increasing tactile

hypoæsthesia present, and that this passes into total tactile anæsthesia at a line corresponding fairly closely with the limit of the other total losses. We have found this persistence of sensibility to touch in the form of a hypoæsthesia extending well within the cotton-wool line in all our observations; that is to say in the case of the area of one nerve on the face, three nerves in the upper limb and three nerves in the lower limb. We are therefore compelled to conclude that the intermediate zone as regards sensibility to touch is merely a region of transition between the first considerable reduction in sensitiveness represented by the cotton-wool line and the region of total loss which, as we have already said, falls somewhere in the same neighbourhood as the other total losses.

If the views we have expressed as to the meaning of the cotton-wool or brush line are correct we should expect to find that an adequately minute method of examination would reveal defects of tactile sensibility outside that line. The existence of such minor grades of hypoæsthesia we have already described in Part II. When it is fully recognised that tactile sensibility is distributed in spots, as of course has been abundantly proved to be the case, it becomes extremely probable that there must be slight degrees of hypoæsthesia which cannot be detected by cotton-wool. The conditions necessary to give a sharp outline to cotton-wool are that the touch spots must be numerous and closely set and that the reduction in their sensitiveness shall be concentrated. In a part which is normally not very sensitive to touch, that is to say where the touch spots are scattered, the hypoæsthesia will be much spread out, and over a considerable area cotton-wool will be recognised in what appears to be a very capricious way, perhaps only half the contacts being responded to. Here it will be almost impossible to obtain a cotton-wool outline at all. Such regions when examined with von Frey hairs show a very gradual transition from normal sensibility to anæsthesia. The two places in which we have found this very noticeable are on the outer side of the thigh near the knee and the back of the forearm near the elbow. In such places it is obvious even to examination with cotton-wool, that one is dealing with a gradual transition rather than with a concentrated change, but as a matter of fact everywhere outside the cotton-wool line careful examination with the von Frey hairs shows a territory variable in width in which a diminution of tactile sensibility can be detected. We are thus driven to the conclusion that section of a cutaneous nerve produces an area of total loss of tactile sensibility smaller than Head describes as that of epicritic loss and surrounded by a broad band of hypoæsthesia larger than the epicritic loss.

The limit of anæsthesia to cotton-wool being obtained with a stimulus which is considerably above the normal threshold for touch, falls somewhere in the outer part of this surrounding hypoæsthesia but not at its margin. Moreover, when the finer qualitative methods of testing are used, it is found that the cotton-wool outline so far from being the utmost limit of change, is surrounded by a large zone of qualitative modification; and that this area, while scarcely hypoæsthetic to the ordinary quantitative examination, has an outline very constant and always capable of detection by the stroking method. Such a qualitative change will of course be impossible to detect by examining the area with cotton-wool.

To summarise the comparison of our observations with those of Head in regard to touch, we may say that the results obtained *with the methods he used* are entirely in accordance with his, but that with other methods a certain number of facts have been observed, to which he did not call attention.

It will be noticed that we have said nothing about regeneration of tactile sensibility; we propose later on to deal with the subject of regeneration as a whole.

The statement of Head that in the intermediate zone there is anæsthesia to temperatures between 20° and 40° C. and sensibility to temperatures outside this range, we can in a general way confirm. We have found however that it needs certain modifications. In the first place there is no very precise correspondence between the line of insensibility to cotton-wool and this altered form of thermal sensibility. Sometimes the thermal change stretches beyond the cotton-wool line, at other times it withdraws within it. Moreover the insensibility to intermediate temperatures seems subject to considerable variations and as a rule seems to be less in the more external parts of the area than it is in the inner. With regard to the sensibility to extreme temperatures possessed by the intermediate zone, the statement of Head that this region responds to these temperatures, leaves it open to doubt as to whether the sensations experienced are of normal intensity or not. This is a point of considerable importance, because if there are two independent sets of nerves subserving the temperature sense, it is clear that the isolated paralysis of those concerned with intermediate temperatures should not be accompanied by any diminution of the activity of those concerned with extreme temperatures. Now we have found that while sensibility to extreme temperatures does undoubtedly persist, it persists in a distinctly modified form; stimuli which should cause a sensation of cold being felt as cool and stimuli which should cause

a sensation of heat being felt as warm, and this goes with insensibility to intermediate temperatures, so that in a region where the subject cannot recognise temperatures of 20° to 40° C., temperatures of 0° and 50° C. will be felt as cool and warm respectively, or where ice is felt as cool intermediate temperatures will not be recognised. It seems therefore that sensibility to intermediate temperatures cannot be lost without some accompanying modification of sensibility to extreme temperatures, and thus the complete independence of the two systems, which would appear to be demanded by the hypothesis of Head, does not exist. As we have already pointed out in the Introduction, theoretical considerations indicate that a thermo-hypoæsthesia should appear as an extension of the normal insensibility to temperatures near that of the skin, and a diminution in the intensity of sensations derived from temperatures outside the intermediate range. Now this is precisely the state of affairs found in the intermediate zone and it would seem to us that the facts are more satisfactorily generalised in the statement that there is a thermo-hypoæsthesia than in the supposition that one of two hypothetical forms of sensibility to temperatures has disappeared leaving the other not, as should be the case, unmodified, but distinctly enfeebled.

We should like to call attention to the fact that the view expressed here does not in any way conflict with the actual observations reported in Head's work, for he says there merely that the intermediate zone is sensitive to extremes of temperature, but he does not say that this sensibility is of normal acuteness.

It is in connection with sensibility to pain that the observations of Head contrasted most strikingly with previously accepted views. He found that the intermediate zone was the seat of hyperalgesia and that during regeneration the first change was the appearance of hyperalgesia in the region previously analgesic, this hyperalgesia of regeneration differing only from that following immediately upon the nerve section in being more intense. In our own observations we have been able in certain respects to confirm these results, but only with modifications which, though at first sight comparatively insignificant, seem to us to be very important from the point of view of interpretation. In the first place such hyperalgesia as is present before the onset of regeneration we have found not to be present continuously from the operation onwards, there being two distinct intervals during which the central area of cutaneous analgesia can be shown to be surrounded by a hypoalgesia rather than a hyperalgesia. These periods include the first

ten or twelve days after the operation and the time from the eighth or ninth week after the operation until the beginning of regeneration. It is clear that if these results are to be accepted, such hyperalgesia as occurs cannot be regarded as directly due to the nerve section, that is to say, cannot be regarded as due to the absence from the skin of some form of sensibility. For if it were due to such a mechanism the hyperalgesia must appear at once upon the cutting of the nerve. The fact that it does not do so is confirmed by the observation that when a cutaneous nerve is paralysed by a local anæsthetic no hyperalgesia is found. Such an observation was published by Langley who after cocainisation of the cutaneous branch of the musculo-cutaneous of the leg found no increased sensitiveness to pain [12]. Before we were aware of this experiment we had made a similar observation upon the internal saphenous nerve of one of us. The nerve in this case was paralysed by use of the eucaine-adrenalin mixture but the result was identical as regards sensitiveness to pain with that of Langley. Whatever then may be the explanation of the hyperalgesia which does undoubtedly follow the section of a sensory nerve, it would seem that we are at any rate no longer compelled to ascribe it to a mechanism so inassimilable with the rest of our knowledge of sensation as that suggested by Head, according to whose view increase in sensitiveness to one stimulus is produced by a loss of sensitiveness to a totally different one.

It seems probable from the description of Head that the hyperalgesia he found in the intermediate zone was not always uniformly distributed all over the surface, but tended at times to occur in distinct small areas; moreover, he states definitely that the boundary between the hyperalgesia and the analgesia is a very indefinite one, so that in the central part of its distribution at any rate the hyperalgesia he found must have had a patchy distribution. Our observations have shown us that this patchiness of distribution is a constant and characteristic feature of such hyperalgesia as is found before the occurrence of regeneration. It will be necessary for us to return to the discussion of these phenomena later on, but it seems advisable in the interests of clearness to leave them for the present as we have mentioned all the points which are relevant at this stage.

To summarise the comparison of our observations on the results of nerve section with those of Head, we may say that there is a very considerable resemblance between the two, and that most of such differences as there are, have been obtained by the use of further elaborations of the methods he employed. Nevertheless, it must be

confessed that such differences as we have found have led us to doubt more and more the capacity of his hypothesis to generalise the facts in a satisfactory way. There is however one small and comparatively insignificant field of investigation in which our results are in more direct conflict, namely the effects of nerve section upon sensibility to Weber's compass test. In his original article Head states quite definitely that loss of epicritic sensibility removes the capacity to distinguish two simultaneous contacts; that is to say that within the intermediate zone the compass points cannot be distinguished however widely separated. This statement he repeats a year later without modification in his work upon the grouping of afferent impulses within the spinal cord, and he seems to regard this loss as being that of a specific capacity and not merely as the result of a reduction in ordinary tactile sensibility. Seeing that in the areas where this loss is said to have occurred there is admittedly a reduction in tactile sensibility, which as Head himself says must have an effect upon the results of Weber's[13] test, we do not see how this distinction can have been established. It would seem therefore more simple to regard defects in the discrimination of two points following section of a cutaneous nerve as being merely a measure of defects in tactile sensibility, and indeed it was used as such by Head and Sherren. This view of course would accord very well with the known importance of deep sensibility in this test, as is shown for example by Spearman's observation of the remarkable enfeeblement of the discrimination of points that is produced by muscular fatigue, and would accord with the result of Weber's test as carried out by ourselves, for we have found in the parts corresponding with the so-called intermediate zone, instead of an abolition of the power to discriminate two points, a diminution in it which has always been strictly proportional to the amount of tactile hypoæsthesia. Of course in the central region where the contact could not be felt at all there was no power of discrimination, but everywhere else some such power was present.

So far we have made no reference to the relation of our observations on the phenomena of regeneration to those of Head. Now as we have already pointed out, the validity of Head's hypothesis depends on the establishment of a substantial identity between the state of affairs in the intermediate zone and that in the formerly analgesic part of an area during the early stage of recovery. It will therefore be more convenient to point out what bearing our results have upon this identity before dealing with the general facts of regeneration. It is evident that it

was recognised by Head himself that sensibility in the intermediate zone was not completely identical with that in the recovering area. In discussing the phenomena of recovery after section of nerves supplying the hand he makes the following statement.

"But although sensation from the whole affected parts of the hand closely resembles in quality that of the intermediate zone present immediately after the nerve has been divided, yet in the intensity and the rapidity of reaction the sensitiveness of the recovering parts is considerably greater. We have no satisfactory measure of the intensity of pain, and can judge only by the statement and behaviour of the patient. By such standards it is certain that a prick now produces a more unpleasant sensation over the same parts than shortly after the accident before recovery could have begun. Moreover cold and heat are felt with greater promptitude over the recovering area of the hand than over the intermediate zone between the touch and prick borders. Thus although the quality of the sensation that can be evoked from those parts of the hand where sensibility to prick has returned closely resembles that of the intermediate zone, the intensity, and therefore the extent, of the innervation has considerably increased[14]."

This difference in the intensity of sensation is not however the only difference between the recovering area and the intermediate zone which he observed. Shortly before the passage quoted above, the following is to be found.

"In the earlier period of recovery whilst the analgesia is retreating from the hand all sensation of true heat is not infrequently absent. The recovering parts are sensitive to cold and to the unpleasant 'burning' or 'stinging' aspect of a hot stimulus but not to heat itself. Sensations of cold play therefore a greater part in the effect produced by this area of the skin upon consciousness and this part of the hand always 'feels colder' than normal. Ultimately however, temperatures of 50° C. or above can be appreciated without hesitation as heat."

It is obvious from a careful reading of the paper that another peculiarity of the recovering area had been noticed. In describing recovery of thermal sensibility Head and Sherren in the part of their paper already quoted, make this statement.

"A test tube containing water at any temperature below 20° C. is appreciated as cold and it matters little whether it contains ice or water at 18° C., both are said to be 'ice-cold.'" No special prominence is given by the authors to the facts contained in the last two quotations and it seems clear that they do not attach any special importance to

them. Nevertheless there can be little doubt that the last quotation contains a reference to the phenomenon of intensified cold which we have described as being a constant and characteristic feature of a recovering area. Similarly in regard to the quotation concerning the absence of true heat from recovering areas, it would seem that no special importance is ascribed to this phenomenon which is referred to as occurring "not infrequently" and as "ultimately" passing off. We have already described the absence of true heat as being very constant and long persistent during recovery and we shall later attempt to show that it may probably be regarded, paradoxical as this may seem, as a phenomenon in essence identical with that of intensified cold. Now there is no hint in any of Head's descriptions that these peculiarities with regard to cold and heat were found in the intermediate zone, and it would seem probable that as they attracted his attention, to some extent at any rate, in recovering areas they would not have escaped him had they been present immediately after the nerve section. According to him, such differences as are present between the intermediate zone and an early recovering area are due to a greater extent of innervation in the latter case. It is difficult to see how this could account for an object at a temperature of 18° C. being felt as ice-cold, that is as colder than it is felt on normal skin, and the difficulty would be greater in explaining thus those cases, which Head himself says are not infrequent, where no true heat can be felt, although intensified cold is present.

Our observations have shown us that in the region corresponding with the intermediate zone extreme temperatures, although responded to and discriminated, always yield sensations below the maximum intensity and that in early recovering areas the same temperatures produce in the case of cold a greatly intensified sensation, and in the case of heat no sensation of true heat at all. We cannot but regard therefore the two kinds of area as possessing forms of thermal sensibility fundamentally different.

In all his descriptions one is given to understand by Head that the intermediate zone is exactly limited by the cotton-wool line; that is to say that outside this line sensibility to temperature and to pain is normal while inside there are hyperalgesia and insensibility to intermediate temperatures. It would appear that he regards this exact correspondence as essential to the validity of his hypothesis, as clearly it must be if the various factors of the protopathic forms of sensibility are at all closely interdependent. *A priori* it would seem extremely improbable that if the loss of sensibility to cotton-wool and

the change of sensibility to pain coincide with one another so precisely, the phenomenon should have been noticed by no earlier observer. In our own work we have found that the correspondence is by no means close and that the distribution of the sensory changes in relation to the cotton-wool line is so variable that it is not possible to regard them as being confined to or occupying the whole of the zone intermediate between the cotton-wool line and the limit of anæsthesia. We have so far used the term intermediate zone for convenience in discussion, but it must be clearly understood that it has been used merely as a term of identification and not as implying that those forms of sensibility which are usually found there are limited to it or extend throughout it. For example, the thermo-hypoæsthesia which produces insensibility to intermediate temperatures and reduction in the intensity of the sensations derived from the extreme temperatures, usually occupies an area distinctly larger than that insensitive to cotton-wool; it is not however necessarily concentric with the cotton-wool line and in most cases as a matter of fact passes within it somewhere or other. This applies both to the hypoæsthesia to heat and to that to cold. The same is true of the alterations of sensibility to pain. As we have already shown two modifications in this form of sensibility occur before the onset of regeneration, namely, the appearance of a zone of hypoalgesia surrounding the analgesia, and the temporary appearance of a peculiar patchy hyperalgesia. The hypoalgesia is present before the hyperalgesia appears and persists after the latter has ceased to be detectable. The distribution of it corresponds in a general way with that of the thermo-hypoæsthesia already described. It is more difficult to outline precisely than the thermo-hypoæsthesia, but there can be no doubt that it does not correspond exactly with the cotton-wool line and may extend outside it. The hyperalgesia, which, as we have already said, is only temporary, has an extremely irregular distribution; it may extend from far outside the cotton-wool line, through the intermediate zone and crop up as it were in small islets in the midst of the central analgesia. It is essentially patchy and irregular, and of all the varieties of altered sensibility shows the least inclination to be limited to the region intermediate between the cotton-wool line and the analgesia. Thus it will be seen that we have nowhere found in our observations that close coincidence amongst the various forms of sensory loss which seems to have been found by Head and would appear to be essential for the maintenance of his hypothesis.

So far we have dealt with two important corollaries which should

follow from Head's hypothesis, namely, the identity of the intermediate zone and the recovering area, and secondly the question of the coincidence of the distribution of loss of sensibility to touch and to intermediate temperatures. A third equally important subject for discussion is that of the various possible dissociations of sensibility which may follow peripheral nerve lesions. The ordinary form of dissociation described by Head is that which he explains as being due to the loss of epicritic sensibility being larger than the loss of protopathic sensibility, thus producing an intermediate zone insensitive to touch and to intermediate temperatures but sensitive to pain. It is obvious that according to the hypothesis only one other form of dissociation can occur, and this, to use Head's terms, would be described as due to the protopathic loss being larger than the epicritic, thus producing an intermediate zone sensitive to touch and to intermediate temperatures, but insensitive to pain and extreme temperatures. This form of dissociation is described by Head as occurring exceptionally after division of a cutaneous nerve, and then in small parts only of the total area of altered sensibility. Before we discuss the instances of this which he gives, we may mention the forms of dissociation which are found in various parts of the body in the normal, and those we have ourselves observed after division of sensory nerves. The principal work of this kind was done by von Frey[15]. According to him there are three elementary forms of sensibility, touch, temperature and pain. In certain parts of the body one of these occurs alone; in certain parts two only occur and the general surface of course has the three. The only form of sensibility which is found singly is sensibility to pain. This occurs in the central parts of the cornea and in the dentine and pulp of the teeth; that is to say in these regions the only sensations which can be elicited are sensations of pain. Such an occurrence would seem to conflict with Head's hypothesis. For if the cornea is insensitive to touch and therefore destitute of epicritic sensibility, the only form of sensibility it can possess must be protopathic, and if it is possessed of protopathic sensibility, in addition to being sensitive to pain, it must be sensitive to extreme temperatures. Of the possible combinations of two elementary forms of sensibility, von Frey describes two; namely, pain and temperature, and touch and temperature. The first couple is found at the margin of the cornea and on the conjunctiva and also on the glans penis. This type is consistent with the parts possessing isolated protopathic sensibility but not wholly so, since von Frey thinks that the conjunctiva is probably sensitive to cold but not to heat. The

second type in which two forms of sensibility can occur together is the combination of touch and temperature and is found in places within the mouth. If the mucous membrane of the mouth were possessed of epicritic sensibility alone, it could not possess the sensibility to extreme temperatures which it undoubtedly has. It will be seen then, that on the whole the observations of von Frey cannot very well be assimilated with the views of Head. Nevertheless, those who have carefully read the various papers of von Frey can scarcely fail to be struck by the excellence of the work embodied therein and will feel that his conclusions are worthy of very respectful treatment.

We have found that dissociations of sensibility are not uncommon in the marginal regions of affected areas, but as a rule they represent merely varying grades of hypoæsthesia, and do not lend themselves to exact observations upon the possibilities of dissociation. We had, however, one opportunity of observing a dissociation which was very little confused by the presence of hypoæsthesia. The anæsthesia produced by division of the anterior and posterior branches of the internal cutaneous nerves of the forearm formed a V-shaped figure, the areas of the two branches meeting below and running side by side for about three inches. Along this line of union were three small patches of skin which still retained a certain form of sensibility. This they received as we ultimately found from what we call the middle branch of the internal cutaneous, a small nerve coming off from the posterior branch high up and supplying the hollow of the V with all forms of sensibility. These islets were insensitive to pain and temperature but sensitive to touch. Sensibility to touch was of almost normal intensity, insensitiveness to pain and temperature complete, so that if the investigation had been confined to the use of painful and thermal stimuli the islets would have been indistinguishable from the surrounding completely anæsthetic parts. Thus these areas resemble fairly closely the area found by Head on his own forearm and described by him as possessing epicritic sensibility but not protopathic, the chief differences being that in our area sensibility to touch was good and the loss to temperature complete, whereas in Head's, tactile sensibility was poor and sensibility to intermediate temperatures was present. "The area was small," he says, "and its epicritic sensibility was of a low order, but in spite of these disadvantages it became obvious after repeated testing that the area was capable of appreciating temperatures between 36° C. and 45° C. It was however entirely insensitive to temperatures of 50° C. and above. To ice and to all forms of cold this part was equally insensitive. It would therefore seem

that by a fortunate chance in nerve distribution we had divided those fibres which subserve protopathic sensibility, leaving untouched at any rate some of those which conducted the impulses of epicritic sensibility. Such an observation can only be explained by assuming that the two forms of sensibility depend upon two separate systems in the peripheral nerves. Experiments with so delicate a sensory change can only be carried out satisfactorily by frequent repetition, by selection of occasions when the patient is from the sensory point of view in excellent condition and under the rigid check of a large number of controls [16]." This description, it may be remarked, does not correspond precisely with what we should expect of an area possessed of epicritic sensibility alone, for the range of intermediate temperatures which can be appreciated over such an area is given by Head as extending down to 22° C., and therefore including temperatures which applied to normal skin would elicit sensations of cool. To these of course the area should have been sensitive, but we are told it was insensitive to all forms of cold[1]. Furthermore the temperatures to which it is described as being sensitive are just those which applied to normal skin give sensations of warmth. Now we have already called attention to the fact that what appear to be sensations of warmth are frequently experienced when a thermo-anæsthetic region is being stimulated with objects of any temperature. Such hallucinatory warmth is as likely to be produced by a cylinder of 0° C. as by one at 50° C. or by one at a temperature felt as indifferent over normal skin. We are not told that temperatures outside the range from 36° C. to 45° C. were unaccompanied by any sensation of warmth, information which would be essential to prove that the sensations elicited by temperatures of 36° C. to 45° C. were not hallucinatory, nor are we told that temperatures within the range which was supposed to be appreciated could be discriminated. Without such observations, the probability seems very great that the area was merely one of an ordinary form of thermo-anæsthesia. This suggestion would seem to be confirmed by the apparent difficulty there was in the demonstration of the change. In our experience hallucinatory warmth is a very capricious phenomenon, and if it is to be

[1] It has already been pointed out by von Frey that this area did not show a true anæsthesia to intermediate temperatures but that the condition of the thermal sensibility in it could be described consistently with the description of Head as one of anæsthesia to cold. The absence of the sensation "hot" and the presence of the sensation "warm" are explained by von Frey, following the hypothesis of Alrutz, as a consequence of the anæsthesia to cold. We shall refer again to this hypothesis below. (Cf. Part IV, Section 4.)

regarded as the explanation of this peculiar dissociation it would at any rate very well account for the supposed sensibility to temperatures between 36° C. and 45° C. being difficult to demonstrate and dependent on the excellence of the subject's condition from the sensory point of view. Another hint that the explanation of this case, which we tentatively suggest is perhaps correct, is to be found in the same paragraph as that we have just quoted. A case is referred to there in which after operative interference with the nerves at the base of the brain, a patient developed analgesia "unaccompanied by an equivalent loss of sensibility to light touch"..."here there could be no doubt that the patient could appreciate warmth but not heat and he many times stated that a temperature of 55° C. was neither hot nor cold but that 43° C. was undoubtedly warm[17]." Here we have the same inconsistency with the hypothesis, namely the absence of sensibility to temperatures which should have produced sensations of coolness, and from the way in which the facts are stated it may perhaps be inferred that the patient did not invariably call temperatures of 43° C. warm.

Before we leave the subject of dissociated sensibility, a few words may be added upon the sensibility of certain internal parts. The parietal peritoneum appears to afford an example of a part possessing sensibility to pain only and thus resembling the cornea and the pulp of the teeth. Ramström's recent careful observations upon patients during abdominal operations done under local anæsthesia seem to show quite clearly that the parietal peritoneum is entirely insensitive to touch and pressure and to temperature stimuli; thus failing to be classifiable under either of the categories of Head's hypothesis. It is interesting to note that this part of the peritoneum appears to afford a still further specialisation, in that pain is not elicited by any stimulus except traction[18].

We may now enter upon the comparison of our observations upon the phenomena of recovery. The outstanding difference between Head's conclusions and ours is that we do not find the discrepancy he did between the return of sensibility to pain and the return of that to touch. This at first sight appears to be a grave conflict in observation, but there are one or two considerations which suggest that the inconsistency between the two series is due to a certain extent to the difference in the methods employed. It is certain that for a long time after the characteristic sensation of true touch can be elicited from the recovering area, tactile sensibility is present only in a very hypoæsthetic form, in spots very sparsely scattered and that the sensations which are experienced are for

the most part accompanied by forms of localisation which give them a striking strangeness. Again, the whole subject of sensibility to pain is rendered difficult by the fact that we have no absolute means of determining whether a given sensation of pain is due to an impulse coming from the skin or from the deeper structures. So that observations upon areas which are supposed to be insensitive or hypersensitive to pain or recovering sensitiveness to it are of comparatively little value unless the observations are made with the use of a constant stimulus. The difficulty here is precisely the same as that which was so clearly pointed out by Head in regard to defects of tactile sensibility and it can be overcome in the same way, namely, by choosing a stimulus which there is reason to believe cannot act upon the deeper nerve endings, and is constant in intensity.

The three phenomena which we regard as being especially characteristic of a regenerating area, namely intensified cold, the delay in the return of heat and the reference peripheral and otherwise of cold, pain and touch, seem all to have been noticed by Head, but he does not appear to have regarded them as constant or of any great importance, though they give to sensations derived from a recovering area a series of qualities totally unlike anything experienced before the onset of regeneration. Nor does he seem to have distinguished clearly between the stinging diffuseness which all painful sensations originating in a regenerating area possess, and the precisely localised distant sensation which is given by peripheral or proximal reference. We may add that the constancy of these phenomena became plain to us only after we had abandoned the attempt to outline the changes that were occurring and had adopted the method of recording precisely the situation of each spot stimulated and the qualities of the resulting sensations.

On the peripheral mechanisms of sensation.

As our experience has increased we have become more and more impressed with the validity of the doctrine that all forms of sensibility possessed by the skin are distributed in minute isolated spots; that the spots sensitive to heat and to cold are irregularly arranged in more or less compact groups; that touch is intimately associated with the hair bulbs and that pain spots are more uniformly and more closely set than the others. These views of course agree with the conclusions of the classical researches of Goldscheider[19] and von Frey.

The problems concerning the essential nature of the impulses which

originate the various forms of sensation were not primarily set before us when we began this investigation. Incidentally however our observations have led in this direction and have suggested certain hints which, though not going far, may perhaps be of some interest to those more directly concerned with the subject.

With regard to sensations originated by contact we have no doubt that touch and pressure form two independent series originated peripherally by physical and physiological mechanisms quite distinct, and leading to sensations which are introspectively quite easily distinguishable. Touch is essentially associated with movement, pressure with continued compression. The essence then in the origination of the former is change and the sensation therefore shows a close temporal dependence on the stimulus. Pressure, or, as we call it, static contact in contradistinction to moving contact, is essentially of considerable extent in time and therefore much less closely correspondent with the duration of the stimulus. Consequently we shall expect to find in the physical mechanism of touch, means whereby movement is very directly transformed into a nervous impulse. The simplest mechanism by which this is effected is undoubtedly that wherein the whole surface is made very mobile through the thinness of the epidermis as in the lips, or the softness of it as in the tongue. That this is the source of the extremely delicate tactile sensibility of the lip is shown by the marked effect produced by allowing the surface to dry. A moist lip is sensitive to the very finest von Frey hairs; if it be allowed to dry, even only so far as to give the slightest glaze to the surface, a marked raising of the touch threshold at once occurs. It is obvious however that the mechanism which is quite satisfactory in the lip is unsuited to the general surface of the body on account of the liability to injury it brings with it, and the impossibility of keeping the surface sufficiently moist. The problem is solved for the skin by the utilisation of the hair bulbs as end-organs for touch. The sensitiveness of the part to touch now depends no longer necessarily upon the extent to which the surface is movable, but upon the extent to which the hair bulb is movable. The hair is important in two respects. Its principal function undoubtedly is to conduct below the surface of the skin the movement which must reach the hair bulb before a touch impulse can be generated. Secondly, it seems to be of value in keeping the hair follicle rigid, thus allowing contacts anywhere over the latter to cause movements of the hair bulb away from the surface. This second function of the hair is suggested by von Frey's observation that

the tactile sensibility of a hair bulb is diminished when the hair is pulled out. The importance of the first mechanism is shown by the fact that comparatively hairy parts like the thigh are more sensitive to touch than parts like the front of the forearm, where the skin looks so much more delicate and sensitive, and the hairs are so much finer. It would seem that up to a certain point increase in the thickness of the hair is an advantage to tactile sensibility, but beyond this the advantage is lost through the relative immobility of the larger bulb. If a part not thickly covered with hair is carefully examined, occasional hairs will be found that are notably thicker than their fellows. The touch spots of these hairs are usually below the average sensitiveness. Again in a hairy part like the front of the thigh, double and even triple hairs occasionally occur, apparently growing either from the same bulb or from bulbs in such close contact as to be, as far as movement is concerned, one. These multiple bulbs are always relatively insensitive. The third mechanism, whereby tactile acuity is attained, is that present on the palms of the hands and the soles of the feet. Here the skin is not hairy, and the epidermis is not thin, but is traversed by a series of concentric furrows apparently for the purpose of rendering it flexible without impairing its resistiveness to injury. That the sensitiveness of the skin of the hand depends on the flexibility of the epidermis is shown by the marked effect of thickening of the latter in diminishing sensory acuity.

One of the most important reasons why the essential nature of the physical processes which originate afferent impressions call for elucidation is that without such knowledge we are completely unable to conceive what is the mechanism underlying a hypoæsthesia, and this need should always be kept in view in considering any hypothesis which purports to explain the nature of cutaneous sensibility. This requirement seems to be to some extent met in the views we have put forward concerning the mechanism of touch. It may be supposed that the sensitiveness of the hair bulb is dependent on the number of nerve fibrils going to it and possibly also on their reaching it in different directions, so that the maximal neural disturbance shall be produced by movement of the hair. Suppose now the number of fibrils conveying impulses away from a given hair situated in a region where the supply of two nerves overlaps, be considerably reduced by division of one of the nerve trunks, it is clear that the normal amount of neural disturbance can only be produced by a greater movement of the hair than is usually necessary; that is to say the hair bulb must be more firmly pressed on for a touch impulse to be originated, or in

terms of sensibility the threshold of the touch spot is raised. It would seem that it is only the swing of the bulb away from the surface which is efficient, consequently when a von Frey hair has been used which produces the maximum swing, the strength of stimulation to the touch spot is not increased by using a heavier pressure. This view corresponds with the results we have obtained on hypoæsthetic areas. Testing from the periphery towards the centre we have found that if a hair which exercises a pressure of about 3000 milligrammes does not elicit sensations of touch, in general no further increase in the strength of the stimulus will do so.

The fundamental problems of thermal sensibility seem always to have been particularly difficult and confusing, so that it is not surprising that much which has been written about them has added to, rather than elucidated, the complication. Moreover, in the mere description of facts it is so easy with the best of intentions to be ambiguous, that it is not always possible even to apply the facts already recorded. Of the two principal troubles in description we have met with, one has been to know whether when the observer has said the subject could appreciate hot or cold stimuli as the case might be, the sensation experienced was what would have been felt on normal skin, or merely some member or other of the hot or cold series respectively. Some of this difficulty is due to the fact that we have no word to describe the general qualitative tone of a thermal sensation, apart from the name of some actual thermal sensation. It would be much more satisfactory in descriptive work if the terms positive and negative were used for the two thermal series of stimuli and sensations according to their relation to the temperature of the skin for the stimuli and to indifference for the sensations, so that the terms heat and cold might be altogether avoided in this connection. When we are told that a subject could appreciate heat the intention of the author is left undetermined: we do not know whether he means to tell us that the maximum sensation of the positive series was experienced, or merely that sensations were experienced which possessed the general tone of the positive series. The statement that the subject could appreciate positive temperature does not give us the idea that the author may wish to convey anything more than that temperatures above that of the skin were appreciable. We feel justified in labouring this point because as we have already repeatedly said the response to a thermal stimulus is not complete unless it contains the statement not only of the series to which the sensation belongs but also of the

place in the series which the sensation occupies. A second ambiguity frequently found is due to the failure to specify what is meant by a subject appreciating a given temperature. For such a statement to be of any value we must know how often the subject was tested with this temperature and in what proportion of cases he responded correctly, and even then unless the number of tests is great and the proportion of correct answers very high his statement will be of little value unless it is corroborated by discrimination tests. Furthermore it must be recognised that even discrimination tests, if the stimuli are of widely different temperatures, may be unsatisfactory, for it is obvious that two temperatures may be successfully discriminated when one only of them gives rise to a thermal sensation.

Our observations have not furnished us with material which throws much light on the more intricate parts of thermal sensibility but have brought before us certain aspects of the problem which do not always receive all the attention they deserve. In the first place there can be no doubt that one of the most significant features of thermal sensations is what we may call their relativity. They do not register temperatures as such or even give us direct information concerning the relation of a stimulus temperature to that of the skin, but measure for us the rate at which heat is being lost or gained. Biologically considered it is obviously unimportant what a temperature is in relation to the melting point of ice or the boiling point of water, if it is not widely different from that of the skin, and comparatively unimportant what the temperature of an object is if the latter does not possess such a conductivity and specific heat as to cause rapid gain or loss of heat. Thus it is clear that the first factor in the physical basis of sensation is the loss or gain of heat by the skin and not mere temperature. The positive and negative series of thermal sensations both begin in a sensation which is scarcely distinguishable from indifference, they then pass through a range in which they become more and more unlike one another until the maximum sensations of heat and cold are reached. Supposing now the stimulus temperature is made still more different from that of the skin the sensations change in an interesting way: the element of heat or cold becomes less distinct and is accompanied by a sensation which everyone who experiences it agrees to call burning. If the thermal difference is still further increased, the sensation becomes purely burning and loses all true temperature quality. Further intensification of the stimulus produces pure pain of a pricking character and quite indistinguishable from that produced by a needle. We

have thus the interesting fact that the two series begin by being indistinguishable where they are subminimal and end by being indistinguishable where they are supramaximal. There is this difference, however, between the subminimal and the supramaximal sensations that the supramaximal is recognised by everyone as due to a thermal stimulus although acknowledged to contain no true thermal element. The 'burning' sensation of extreme cold is well known although not so commonly experienced as that of extreme heat. The fact that very rapid heat change produces the same sensation whether the stimulus belongs to the positive or negative series suggests that the basis of the thermal impulse is of physical rather than chemical origin, at any rate for extreme temperatures. This view is supported by the fact that the effective stimulus is heat change rather than temperature—a fact within general experience and recognised by common knowledge.

Our observations have not yielded results capable of modifying or enlarging such views as are at present current concerning the peripheral mechanism of pain sensations, so that it is unnecessary for us to enter here upon that subject.

On the constitution and distribution of the cutaneous nerves.

Each cutaneous nerve we have divided has proved to contain fibres concerned with at least seven different functions, four transmitting afferent impulses, namely those of touch, cold, heat, pain; and three transmitting efferent impulses, namely vaso-motor, pilo-motor, sudo-motor. The extent to which the estimation of pressure is a function of the sensory mechanisms of the skin seems to us still to be an open question, so that we have not included it amongst the list of the functions certainly cutaneous. In a general way there seems to be no doubt that the estimation of pressure is in the main carried out by structures deeper than those which subserve touch and probably largely subcutaneous. There is, however, much evidence that pressure sensations can be originated in the skin. The two chief facts favouring this view are first, that distinct pressure sensations are not infrequently experienced during the investigation of a hypoæsthetic area with von Frey hairs which are certainly too weak to stimulate subcutaneous nerve endings; secondly, if the area of change following the section of a large cutaneous nerve be investigated with von Frey hairs from the periphery towards the centre, a zone is reached, usually with a hair of about 3000 milligrammes, within which no sensations of touch are felt. If a heavier

hair is used and the examination is continued centripetally, pressure sensations only are experienced through another zone, inside which again a still heavier hair excites no sensation whatever (Fig. 29). This last observation raises the question of the distribution in depth of cutaneous nerves. It seems generally to be assumed that such nerves are more or less limited to the skin and immediately adjacent parts, but that their distribution in depth varies considerably.is shown by the fact that the larger the area of the nerve the more profound is the anæsthesia at the centre of it; and in some cases, such as the internal saphenous, the subject may be absolutely unconscious of any stimulation whatever applied over the centre of the area. Here again, as with pain, there seems to be no natural boundary between the skin and subcutaneous parts. While it is possible to investigate the problem on hypoæsthetic areas with stimuli too light to reach beyond the skin, it is unfortunate that the sensations of pressure produced by such stimuli are so vague and baffling as to be of very little value.

Section of the nerve trunk produces an area of loss of function implicating all the seven kinds of nerve mechanism. For six of these it can be made out definitely that there is a central area where the loss is complete and a surrounding zone where the loss is incomplete. The changes produced on vaso-motor function though undoubtedly paralytic in nature are shown by such unobtrusive signs that it is not possible to say whether this distribution in complete and partial losses occurs in this case, as it certainly does with the other motor activities of the nerve. The various areas of loss although they do not coincide for the various functions do, in a rough way, correspond. We may take it, therefore, that each kind of fibre in the nerve is distributed independently of the others but approximately conforming to a general type, so that each will supply the central area completely and the surrounding zone incompletely, and the outlines obtained for the various losses partial and complete will correspond fairly closely in size, but less closely in shape. The fact that areas of complete and incomplete loss of pilo-motor and sudo-motor function are found, forms a valuable and perfectly objective piece of evidence confirming the view that the other functions are distributed in the same way. All these losses can be mapped out and measured with considerable precision and there can be no doubt that the arrangement of them is directly dependent on the mode of distribution of the nerve. There is, however, another change the significance of which is much more obscure. As we have already said in the descriptive part of this paper, every area of sensory loss is

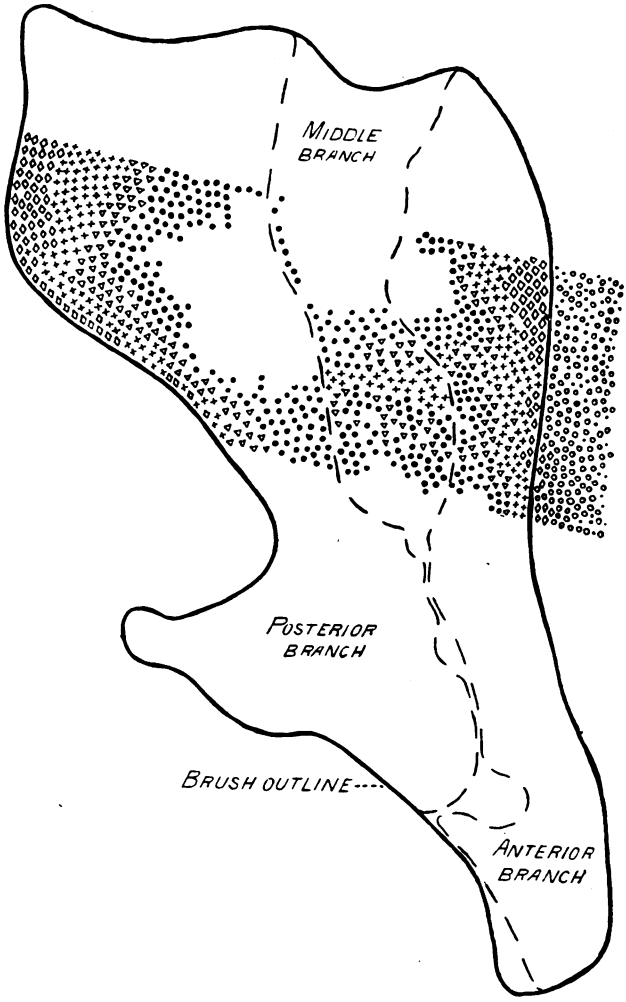


Fig. 29. Internal cutaneous. Left forearm. Anterior, posterior and middle branches.

Sensibility to touch. Tracing to show gradual increase of hypoæsthesia towards the middle of the area. Reduced by $\frac{1}{3}$.

The spots marked • were touch spots which reacted to a hair of 280 mgs. pressure.

,,	○	,,	,,	,,	800	,,
,,	◇	,,	,,	,,	1780	,,
,,	+	,,	,,	,,	3480	,,
,,	▽	,,	,,	,,	4750	,,
,,	●	,,	,,	,,	6275	,,

The continuous line encloses the area anæsthetic to the camel's hair brush after section of all three branches of the nerve.

The broken line indicates the areas of the different branches.

The whole area was investigated in detail, part only of the record is reproduced here.

surrounded by a wide zone which we have called the zone of minimal hypoæsthesia where there is a change which, though very easily recognisable qualitatively, is very difficult to measure. The outline as marked by stroking touch is usually easy to find, but whether this is the case or not it is always strikingly constant. The meaning of this change is extremely obscure. We have made many observations which seem to show that it is a slight tactile hypoæsthesia but we are not prepared to say that this evidence is conclusive, or to deny that the name 'zone of minimal hypoæsthesia' embodies a certain element of hypothesis. The outstanding and unquestionable fact is that the region is the seat of a qualitative change. The existence of it seems to indicate that apart from the overlapping of nerve distribution which leads to the appearance of the ordinary zone of hypoæsthesia surrounding the anæsthesia, there is another kind of overlapping much more extensive and much more complete.

The most interesting problem presented by the results of nerve section before the occurrence of regeneration, is concerned with the appearance of hyperalgesia. The main facts about this are fairly straightforward. It first appears from ten to twelve days after the operation and disappears in six or seven weeks, as a rule therefore well before recovery of sensation has begun. At first it is somewhat diffuse, for the most part lying between the outlines of hypoæsthesia and anæsthesia, but it may in places extend outside the former and inside the latter, and shows a striking tendency not to correspond with the outline of any sensory or motor loss. The hyperalgesia is always most acute in the neighbourhood of the more obvious veins and as it clears up it becomes more and more limited to these regions. The more we have seen of this condition the more impressed we are by the fact that its distribution is totally unlike that of any other effect of nerve section. Nevertheless it is undoubtedly dependent upon the latter. It occurs in the region affected by this and never extends above the point of division of the nerve. In some cases we have thought that the most tender veins were a little thickened, but we are not by any means sure of this. The whole aspect of the phenomenon suggests strongly that it is a secondary process due to the presence of some irritating substance produced as the result of the division and degeneration of the nerve. As is well known to anyone who has operated much under local anæsthesia the vessels are extremely sensitive and very often they are the only structures in an imperfectly infiltrated area injury to which causes pain. Again the subcutaneous veins are known to be frequently

accompanied for considerable distances by nerve twigs, so that supposing they were subject to irritation they might very well be tender in the neighbourhood of or even within an area the superficial sensibility of which had been lost. It is a familiar clinical fact that very slight grades of phlebitis produce not so much pain as hyperalgesia of the veins. Such a vein responds to the lightest touch with an outburst of pain which tends to fade and return repeatedly for several minutes. If then an irritating substance were produced in the skin during the degeneration of the nerve, one of its effects might very well be the production of hyperalgesia obviously connected with the veins. There is abundant evidence that toxic substances are produced during the degeneration of nerve fibres: such substances must tend to be localised in the affected region by the vaso-motor paralysis we have shown to follow a nerve section, and there is enough discrepancy between the distribution of the hyperalgesia and the distribution of the sensory and motor losses to suggest that the former is produced by a substance originating in the degenerating nerve and escaping only slowly from the affected region. Again, if the hyperalgesia is produced in the way we are suggesting here, it would follow as a corollary that when a nerve was divided in such a way that degeneration could not occur, hyperalgesia would not develop. That is to say, section of a nerve anywhere distal to the spinal ganglion might lead to hyperalgesia but section of a posterior root would not. Now we have it on the authority of Head that division of posterior roots does not produce the hyperalgesia which follows division of a peripheral nerve or, as he puts it, after a section of posterior roots the protopathic loss is equal to or is greater than the epicritic loss.

This hypothesis is of course advanced in a tentative way only and we feel that a considerable amount of experimental work must be done before it can be established. With this caution we may perhaps venture to point out one or two directions in which some such view would seem to throw light on certain very obscure problems of which the most important is that of the so-called trophic lesions. These mysterious conditions seem fairly readily to fall into two classes; first the more or less obviously traumatic, such as those associated with pressure, with analgesia, with circulatory disturbances, and secondly the apparently spontaneous, such as herpetic eruptions, and the formation of bullæ and of acute ulcers. This second class it is in which the very lesions themselves seem strongly to suggest that they are due to the presence locally within the skin of some irritant substance. It is

interesting to notice that according to Head the liability to these lesions is confined to the earlier period following the nerve section and that when regeneration is well started, at a time, that is to say, when all evidences of local irritation have disappeared, this liability ceases.

On the sensory peculiarities of recovering areas.

The most interesting fact presented by an area during recovery of sensibility is the remarkable qualitative peculiarity of the sensations derived from it. During the first few months the state of affairs is a moderately stable one presenting sharply defined characteristics. Of the four primary sensations those of pain and of cold are intensified that of heat is reduced and that of touch is practically normal. This statement of course refers only to the sensations experienced by the subject and in describing the actual state of sensibility in the part it will be necessary to add that there seems to be true hypersensitiveness to pain, this sensation being produced by a weaker stimulus than on normal parts and being abnormally unpleasant; that to cold sensibility is also altered in the direction of a hypersensitiveness, so that not only does a sensation of icy coldness replace the sensation of normal coldness but the same sensation of intense cold is elicited by temperatures which on normal skin would have been felt as cool; that while touch when felt is felt as of normal intensity, it is elicited only by stimuli considerably above the normal threshold, and finally that the maximal sensation of the positive thermal series is not producible by any stimulus.

Of these various modifications that of thermal sensibility seems the most anomalous and the significance of it is undoubtedly very obscure. There are some facts, however, which seem to us to throw light on it. In the first place, as is well known, stimulation of a normal area with extremes of cold or heat more than adequate to produce a normal maximal sensation, produces in both cases a sensation of a stinging burning character in which it can be recognised that there is a certain thermal element, although it cannot be recognised whether this thermal element belongs to the positive or negative series. It is clear therefore that this burning sensation is compound, consisting of a thermal element which is comparatively insignificant and an element common to the results of stimulation with any temperature sufficiently removed from that of the skin. This latter element is obviously pain and direct introspective study of the burning sensation readily resolves it into a

large pain factor and a small and vague thermal one. Now if the series of sensations warm, hot, burning be carefully studied introspectively, it will be found that the transition from hot to burning is extremely gradual and often difficult to distinguish, whereas that from warm to hot is quite abrupt and easy to recognise. This suggests that the sensation hot is more directly allied with burning than it is with warm. If this were the case it would mean that hot is a compound sensation containing in addition to the thermal element a pain factor. The sensation of heat is so distinctly pleasant that it seems paradoxical to imagine that it has any character of pain in it, but we find that it possesses a certain quality such as might be called brightness or sting, which suggests a resemblance in nature to the distinctly unpleasant burning. The same can be said of cold. When this sensation is well developed it also has an element of sting in it which cuts it off very distinctly from what we may call the much smoother sensation of cool. A study of the normal then would seem to show that for each series of temperatures there are two groups of sensations, one of a purely thermal quality, warm or cool as the case may be, and characteristically smooth or soft; the other a mixed quality, hot or cold, which is compounded of a large thermal element and a small pain element and thus comes to possess its characteristic brightness or sting. Numerous grades of both qualities are distinguishable but the transition is abrupt between the two groups. The range of temperatures capable of producing the sensation of cold is very much greater than the range capable of producing sensations of heat. The former is at least 40 degrees centigrade and the latter 10 or 15. It is obvious therefore that intensification of a cold stimulus adds to the compound sensation less pain for equal thermometric increments than does intensification of a heat stimulus.

According to such a view the changes found in a recovering area would be explained by the hypersensitiveness to pain which is known to exist there. The intensification of cold is possible because increase of the stimulus adds very little to the pain factor and the series being a long one, even with the hypersensitiveness to pain a considerable range of cold sensations is possible before the burning sensation is reached. That the pain factor is present in excess is shown by the fact that the burning sensation can be elicited with temperatures above 0° C. if a large area be stimulated, and by the fact that temperatures which normally should produce coolness now produce only sensations containing a distinct sting of cold. In the positive series the result is different

because the thermometric range capable of causing sensations of heat is so much shorter; here the sensation of true heat is replaced by burning or even by pure pain. It is very striking how close is the correspondence between the subsidence of hypersensitiveness to pain and the reappearance of sensibility to heat in its normal form. The close association between sensibility to pain and to temperature demanded by this hypothesis is confirmed by many facts of observation of which we may mention the great frequency with which these two forms of sensibility are lost together. As we have already said we have several times observed the existence of areas which were analgesic and thermo-anæsthetic but sensitive to touch; we have not observed any definite and sharply marked areas where there was a dissociation of sensibility to pain and sensibility to temperature.

The accompanying scheme embodies the view we have expressed as to the nature of thermal sensibility and illustrates the relationship to pain of the various sensations in a way which may help to make the exposition less obscure.

The top line contains the names of the various sensations which may be experienced. The bottom line gives the result of careful introspective analysis of these sensations. In the middle part are given the constituents of these, an attempt being made to

Description of unanalysed sensation	Pain	Sting	Icy	Cold	Cool	Indifferent cool	Indifferent	Indifferent Warm	Warm	Hot	Sting	Pain
Constituents of analysed sensation (accessible by introspection)	Pain	Cool			Cool	Minor degrees of Cool	(Intermediate anæsthesia)	Minor degrees of Warm			Warm	Pain
	Pain	Pain	Cool							Warm	Pain	Pain
	Pain	Pain	Pain	Cool	Cool					Pain	Pain	Pain
	Pain	Pain	Pain	Pain	Pain				Warm	Pain	Pain	Pain
Description of analysed sensation	Pure Pain	Mixed pain and thermal			Pure thermal		(Intermediate anæsthesia)	Pure thermal		Mixed pain and thermal		Pure Pain

show in a very rough way the proportions in which the different factors are present. We do not of course mean to imply that, for example, the sensation of icy coldness contains twice as much pain as that of coldness or two-thirds the pain of the sting of extreme cold. What we desire to show rather is that the change from "cold" to "icy" or from "icy" to "sting" is due in each case to the addition of a pain factor. We have attempted also to bring out the fact that the "cold" series is longer than the "hot" series.

The view that the sensation "hot" is compound is by no means new. According to Alrutz[20] in agreement with whom is von Frey, the sensation depends on the simultaneous excitation of thermal spots of the two kinds, namely those sensitive to warmth and those sensitive to cold. This view was suggested by a phenomenon originally observed by von Frey and called by him "paradoxical cold." The cold spots were found by him to be excitable by many stimuli other than cold; among such stimuli are temperatures of 45° C. and upwards, that is temperatures which when applied to the skin in the ordinary way arouse the sensation "hot." Now when cold and warmth spots are stimulated in conjunction as they are by the application of hot objects, the cold spots must be regarded as yielding their characteristic form of response no less than the warmth spots. It is this contribution of the cold spots which gives to the resulting sensation its characteristic quality of "hot." So far there was considerable *prima facie* evidence in favour of the hypothesis ultimately enunciated by Alrutz, who at the same time brought forward two further weighty arguments. These were, first the observation that on parts of the skin which are insensitive to cold, heat stimuli however strong produce no sensation "hot" but sensations of warmth and of pain only; and secondly the further observation that on parts of the skin acutely sensitive to cold but feebly sensitive to warmth the sensation "hot" can be produced but no sensation of intense warmth.

This attractive and ingenious hypothesis, though supported by very strong evidence derived from examination of the normal, does not seem to us to be capable of assimilating all the facts derivable from examination of hypoæsthetic and recovering areas. A complete discussion of the question is not possible for us here and is not altogether within the scope of this paper. A few comments may however be made. First we would say, we have not found "paradoxical cold" to be so constant and definite a phenomenon as Alrutz seems to find it; secondly, the hypothesis of Alrutz furnishes no explanation of the close resemblance and ultimate complete identity of the supernormal sensations of the

positive and negative series, that is to say of the "sting" and "burning" sensations which result from stimulation with extreme degrees of heat or cold; thirdly it does not explain the fact that the sensation "cold" differs from the sensation "cool" by just the same abrupt addition of brightness or sting as the sensation "hot" differs from the sensation "warm"; finally that during recovery a condition occurs in which there are present acute sensibility to cold and sensibility to warmth, that is to say a condition in which exist all the factors necessary, according to Alrutz, for the production of the sensation "hot" and yet this sensation cannot be produced.

If these views are to be accepted, the highly anomalous condition of sensibility found during regeneration would be shown to be in fact much less discordant with the rest of our knowledge than it appears at first sight to be. The unusual features will be accounted for by the presence of hypersensitiveness to pain. What this hypersensitiveness is due to is a problem upon which our observations have thrown no light. We have already given a good deal of evidence for supposing that the hypothesis advanced by Head cannot be sustained. We will point out again that while sensibility to pain becomes very well marked before sensibility to touch has regained its normal acuity, yet the latter form of sensibility is always the first to be recognisable in a recovering area. The hyperalgesia persists in a marked form for many months and then begins to decline. This diminution is gradual and is accompanied by the reappearance step by step of normal sensibility to heat.

As we have said we have no explanation to offer of the hyperalgesia of recovery, but the facts that we possess concerning it seem to be consistent with the view that it depends on some condition of the recovering nerve or nerve ending which is only very slowly restored to the normal.

The second great problem offered by the facts of regeneration is that of referred sensation. Most of the facts are very definite and easily observed. Reference of sensations is the earliest phenomenon and almost the last evidence of abnormality in a recovering area. As far as we have observed the direction of the reference is always longitudinal in the limbs. It can always be obtained not only from recovering areas but also from the nerve trunk outside the area as far up as the point of section, but never from the nerve trunk above the point of section. In this connection it should be noted that there is a marked difference between sensitiveness to stimulation of the nerve above the point of section and of the nerve below; not only is the latter much more

sensitive but it seems to possess specific sensibility, for when it is stimulated appropriately, peripherally referred sensations of touch, pain and of cold can be produced. In the limbs peripheral reference is always a much more striking phenomenon and more extensively developed than is proximal reference. The region to which sensations are referred is always near but not necessarily at the peripheral apex of the anæsthesia, and if the nerve has been faradised before section the point of reference can be exactly foretold before regeneration has begun. Proximal reference is much less extensively developed. It is felt most commonly at the point of nerve section but sometimes in the neighbourhood of the proximal margin of the formerly anæsthetic area. The referred sensation, peripheral or proximal, has all the qualitative peculiarities which we have described as being characteristic of recovering areas, and is accompanied by the same desire on the part of the subject to rub or scratch the part in which the sensation is felt, in this case not the part stimulated. Such are the facts of reference as it occurs in the limbs.

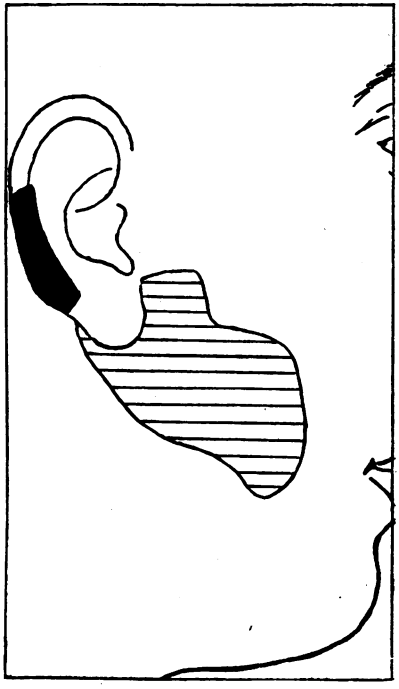


Fig. 30.

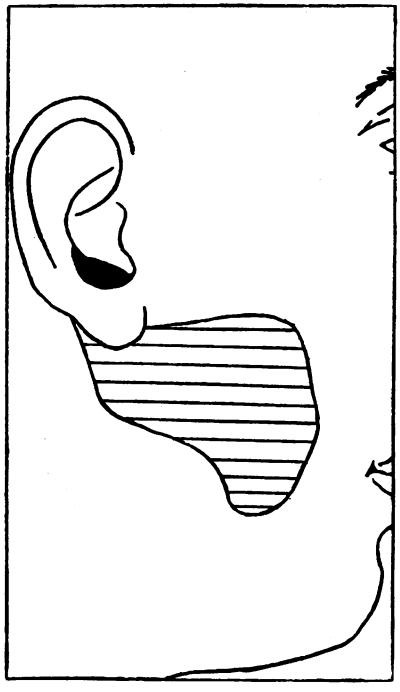


Fig. 31.

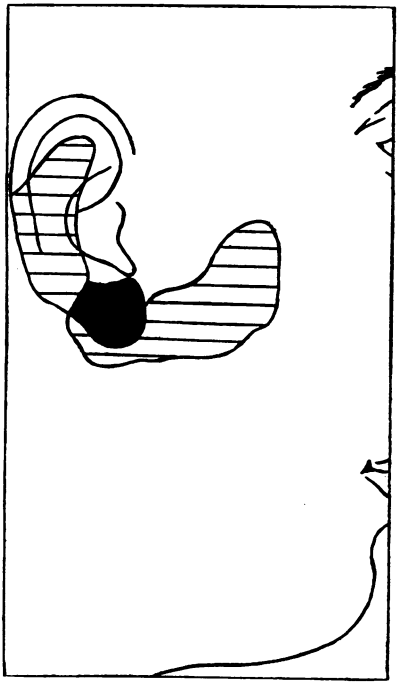


Fig. 32.

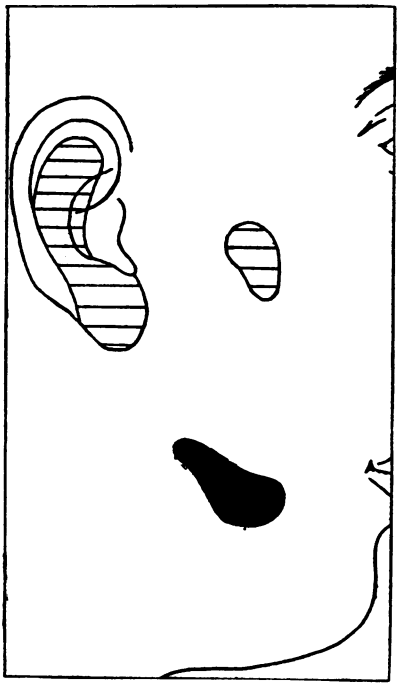


Fig. 33.

Figs. 30, 31, 32, 33. Analysis of diametric reference in area of great auricular nerve, 9 months after section.

At this period recovery of sensory *acuity* was practically complete. A very slight hypoæsthesia was detectable with stimulus intensities below the normal threshold. Qualitative abnormality was still present but much less marked than it had been.

Hyperalgesia of recovery had disappeared.

The sensation "hot" was obtainable. The sensation "cold" no longer showed intensification.

The original maximal outline of change could still be marked out by stroking touch.

The reference phenomenon was still strongly marked.

It was found that reference occurred only to four relatively small, precisely localisable spots and that reference to each spot was produced only by stimulation of a certain area. All the areas had definite outlines though there was a certain amount of overlapping. The stimulus used was a stroking touch.

In each of the figures one of the four spots of reference is shown and the corresponding area from which the sensation was referred.

The shaded area denotes the area from which the sensation was referred.

The solid area denotes the spot in which the referred sensation was felt.

It will be noticed that the solid area is always considerably smaller than the shaded.

It is interesting to note that 10 months later still (19 months after section of the nerve) all four varieties of reference were distinctly recognisable, and, as regards topography, unaltered. The intensity of the referred sensation was however less.

In the one case we have observed of a nerve not in the limbs—the great auricular—another kind of reference, which we have called diametric, occurs (Figs. 30, 31, 32, 33). No fully developed instance of this was found in either of the six limb nerve areas but we have sometimes noticed a vague suggestion of it. It has always been much less distinct than proximal reference, and incomparably less so than peripheral.

The explanation of these remarkable phenomena presents considerable difficulties. There does not seem to be anything in Head's hypothesis of two distinct systems of nerve fibres which throws any light on the subject. According to him sensations originating in the protopathic system are characteristically diffuse and badly localised, and the disappearance of these characters is due to the reappearance of epicritic sensibility. Now touch sensations are referred just as frequently as any other and with these according to him the protopathic system has nothing to do. Moreover, sensations which are referred are not diffuse and are not badly localised in the sense of being vaguely localised, they are in fact extremely definite and are placed by the subject with great precision on a spot which may be as much as a foot away from that stimulated.

In a discussion of the views of Head, von Frey[21] suggests that the sensory peculiarities of the recovering areas may be ascribed to changes in the central parts of the nervous mechanism consequent upon the section of the nerve. He refers to the changes in the spinal ganglia which Koester has shown to follow section of sensory nerves and regards these changes as evidence that there probably are corresponding modifications of function in the central nervous system. We fully agree that this suggestion indicates a direction of enquiry which is only too likely to be ignored in researches upon the peripheral nerves. The suggestion makes it of great interest to investigate in certain special ways the condition of sensibility in diseases such as herpes zoster and tabes in which there are known to be changes in the spinal ganglia. The sensory peculiarities which are to be looked for can be very precisely formulated, so that the presence or absence of them could be very readily determined. Altogether apart from the results of such enquiries, there are however certain facts which seem to us not to be very readily assimilable by von Frey's hypothesis; of these perhaps the most important is the observation that the recovering nerve shows a peculiar sensitiveness from the point of section downwards, whereas from the point of section upwards it shows no trace of

such sensitiveness. This seems to us strong evidence that the changes of sensibility present are of peripheral origin.

As far as we are aware the only other hypothesis which has been advanced in explanation of the phenomenon of reference is that of Langley. According to this, the reference of sensation is explained by the supposition "that in regeneration some of the sensory nerve fibres make abnormal connections just as we know may occur with motor fibres in regeneration. The relative amount of local and of referred sensation would then depend on the number of nerve fibres supplying a given spot which had made normal and of those which had made abnormal connections[12]." This hypothesis has the great advantage of simplicity and in the case of a very small area, such as that which was observed by Langley, would account for all the facts which could be observed. Observations however on larger areas such as we have used, yield facts which present certain difficulties. Of these the most serious seem to us to be the overwhelming predominance of peripheral reference, and the fact that from the whole of the large area which yields this form every referred sensation is felt in one small definitely localised spot. These objections obviously do not apply in the case of diametric reference as seen for example in the area of the great auricular nerve (see Figs. 30, 31, 32, 33).

In considering the problem of reference it seems to us that there are certain facts not obviously related to the subject which may throw some light upon it in an indirect way. When a normal nerve trunk is stimulated with the faradic current the subject experiences a sensation which he localises at the spot in which, if the nerve is cut and allowed to regenerate, peripherally referred sensations will be felt. This suggests that there is some analogy between the action of a stimulus which produces peripheral reference and stimulation of a nerve trunk. Again, before and during regeneration the whole of the nerve trunk below the point of section is known to present certain remarkable anatomical changes and the nerve when it is in an accessible situation shows a thickening obvious to the naked eye through the skin. We have observed this thickening quite distinctly in four different nerves. Moreover all parts of the nerve trunk which are below the section and can be stimulated show a remarkable increase in sensitiveness and a direct sensibility to the three kinds of stimulus which produce referred sensation. These facts suggest that reference is in some way connected with the stimulus acting through some abnormal mechanism upon the nerve fibre. Some confirmation of this view is provided by the fact that peripheral reference is always most intense in the neighbourhood of the

nerve and is distributed, even at the time of its maximal development, in a scattered way quite consistent with its being due to stimulation of twigs of the nerve. Some weight perhaps is due to the observation that the referred sensation is much more bulky than the local sensation if there is one. This seems to hint that the referred sensation is not simply an ordinary sensation felt in the wrong place, as might be expected if it were solely due to a fibre having made an abnormal connection, but that some mechanism has come into action whereby the effect of the stimulus has been magnified. The evidence therefore seems to be tending in the direction of the view that both the qualitative peculiarities of sensation during recovery and the phenomena of reference, the two great characteristics of sensibility in a recovering area, are related to some special feature in the circumstances of the regenerating nerve fibres which renders these latter abnormally accessible to stimuli.

We may add that we do not regard these speculations as in any way incompatible with the acceptance of the hypothesis of Langley. We are inclined to regard them as complementary to it, for a not inconsiderable experience in the investigation of the phenomena under discussion seems to us to show that without some amplification this hypothesis does not completely deal with all the facts.

SUMMARY.

1. The material for this paper was obtained by the division in one or other of us of seven cutaneous nerves.

2. In each case the area of skin supplied by the nerve showed in consequence of the operation defects in seven distinct functions: four sensory, namely sensibility to touch, cold, heat, pain; and three motor, namely vaso-motor, pilo-motor, sudo-motor.

3. In each case the sensory changes showed a central area of profound loss; an area of moderate extent surrounding this of partial loss; and a large area in which a qualitative change could be detected.

4. The loss of motor function showed a central area of profound loss and a surrounding area of partial loss.

5. The seven areas corresponded on the whole fairly closely but no two of them coincided absolutely.

6. During a certain period following the nerve section, from about the second to the sixth week, hyperalgesia may appear. The characters of it point to its being a complication due to the presence of an

irritative change rather than to its being due to any kind of sensory loss.

7. Sensibility to touch is subserved by a nervous mechanism distinct from that of sensibility to pressure; the former occurs in the skin only, the latter chiefly in structures deep to the skin. It is probable, however, that the skin possesses some sensibility to pressure. A touch sensation is introspectively quite distinct from a pressure sensation. The touch stimulus is intimately associated with movement.

8. Thermal sensibility is not directly concerned with the temperature of the stimulating object. The essential quality of the thermal stimulus, that is, the thing measured by the thermal sensation, is the rapidity of thermal change. There are two pure thermal sensations, cool and warm. Cold and hot are probably compounds due to the addition of a pain factor to the pure thermal element.

9. The skin is normally anæsthetic to temperatures not widely different from its own. A thermo-hypoæsthesia will appear as an increase of the intermediate anæsthesia and a diminution in the intensity of such thermal sensations as are experienced.

10. After section of a nerve recovery of function occurs only as a result of regeneration. This applies to all the sensory functions and to the motor with the possible exception of the vaso-motor function.

11. Recovery of all the functions which are dependent on regeneration begins about the same time.

12. The rate at which the various returning functions spread over the area is about equal, but the rate at which they progress towards normal acuity is not so.

13. Sensations derived from a recovering area show a remarkable qualitative peculiarity. Cold, pain and the pain element of heat are intensified, but touch is little changed, though more difficult to elicit.

14. A large number of sensations elicited from a recovering area are referred to distant parts of the area or to the point of the nerve section. The referred sensation may be felt alone or combined with a local sensation.

15. During regeneration stimulation of the nerve trunk below the section produces peripherally referred sensations of cold, pain or touch according to the stimulus, even when the nerve is stimulated outside the formerly anæsthetic area.

16. Peripheral reference is the earliest phenomenon of recovery and the last sign of abnormality.

APPENDIX I.

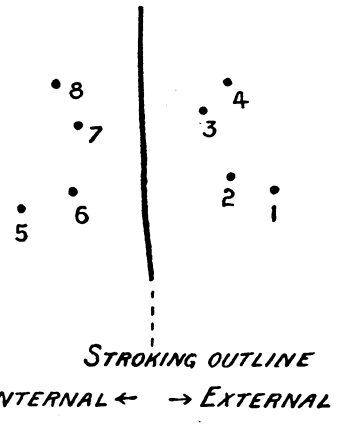
Quantitative examination of areas of minimal hypoæsthesia.

We have selected the following tables to show the results of actual examinations on a number of touch spots chosen at random inside and outside the line dividing minimal hypoæsthesia from normal skin. As will be seen, there is a slight tendency for the results to be worse inside the line than outside. Many other similar observations have yielded corresponding results, the slightness of the change quantitatively being always in striking contrast with its constancy and definiteness qualitatively.

TABLE I.

Results of the examination of 8 *hair-bulbs;* 4 *internal and* 4 *external to the stroking outline on the anterior aspect of the area of one internal saphenous nerve.*

Pressure of von Frey hairs in milligrammes ...		10	22	40	70	140
Bulbs external to stroking outline	1.	0	1	1	1	1
	2.	0	0?	1?	1?	1?
	3.	0	1?	1?	1	1
	4.	0	1	1	1	1
Bulbs internal to stroking outline	5.	0	0	1?	1	1
	6.	0	0	0?	1?	1
	7.	0	0	1?	1?	1
	8.	0	0	1?	1?	1



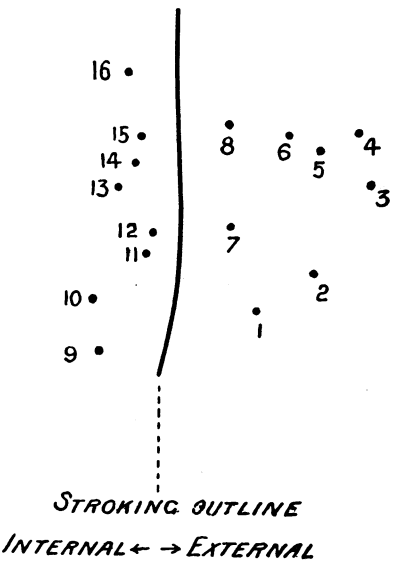
With von Frey hair of 10 milligrammes pressure the hair of bulb 5 gave a distinct sensation. The response of the other hairs was very doubtful.

With von Frey hair of 22 milligrammes pressure the hairs of bulbs 1 to 5 inclusive gave a distinct sensation. The response from the other hairs was again doubtful.

TABLE II.

Results of the examination of 16 *hair-bulbs;* 8 *internal and* 8 *external to the stroking outline on the anterior aspect of one middle cutaneous nerve of the thigh.*

Pressure of von Frey hairs in milligrammes ...		10	22	40	70
Bulbs external to stroking outline	1.	0	0?	1	1
	2.	0	0?	1?	1
	3.	0	1	1	1
	4.	0?	1	1	1
	5.	0	1?	1	1
	6.	0	1?	1	1
	7.	0	1?	1	1
	8.	0?	1	1	1
Bulbs internal to stroking outline	9.	0?	0?	1	1
	10.	0	1?	1	1
	11.	0	1	1	1
	12.	0	1?	1	1
	13.	0	0?	1	1
	14.	0	1?	0	1
	15.	0	1?	1?	1
	16.	0	0	1	1



With von Frey hair of 10 milligrammes pressure the hairs themselves of the bulbs reacted both inside and outside the stroking outline, but not constantly.

With von Frey hair of 22 milligrammes pressure the hairs of bulbs 1 to 8 inclusive gave a definite sensation. Those of 10, 11, 13 and 16 a vague tickle.

With von Frey hair of 40 milligrammes pressure the hairs of bulbs 1 to 13 gave a distinct sensation, the other three giving only a vague tickle.

With von Frey hair of 70 milligrammes pressure the whole of the skin reacted independently of the bulbs.

APPENDIX II.

TABLE I.

Three weeks subsequent to division of the posterior branch of the internal cutaneous nerve of the forearm the area of loss of sensation to the brush was tested with ice-cold cylinders. The sensation of 21 of the spots touched was described as warm. Six further observations were made on these spots with the result shown below. As will be seen only one of them gave the sensation warm in each case observation.

Aug. 23

Spot	Observation 1	Observation 2	Observation 3	Observation 4	Observation 5	Observation 6
1.	Indifferent	Indifferent Warm	Indifferent	Indifferent	Distinctly Warm	Indifferent
2.	Indifferent	Indifferent Warm	Indifferent	Indifferent	Warm	Indifferent
3.	Indifferent	Indifferent	Indifferent	Indifferent	Warm	Indifferent
4.	Distinctly Warm	Indifferent	Distinctly Warm	Indifferent	Indifferent	Indifferent Warm
5.	Warm	Indifferent	Warm	Indifferent	Indifferent	Indifferent Warm
6.	Indifferent	Indifferent Warm	Indifferent	Indifferent Warm	Warm	Warm
7.	Indifferent	Indifferent Warm	Indifferent Warm	Indifferent Warm	Warm	Warm
8.	Warm	Indifferent Warm	Indifferent	Indifferent	Warm	Warm
9.	Warm	Distinctly Warm	Indifferent	Warm	Indifferent	Indifferent
10.	Distinctly Warm	Warm	Indifferent	Indifferent	Indifferent Warm	Warm
11.	Distinctly Warm	Indifferent Warm	Indifferent	Indifferent	Warm	Distinctly Warm
12.	Distinctly Warm	Distinctly Warm	Warm	Warm	Distinctly Warm	Warm
13.	Warm	Indifferent	Indifferent	Distinctly Warm	Warm	Indifferent
14.	Distinctly Warm	Warm	Indifferent	Warm	Distinctly Warm	Indifferent Warm
15.	Distinctly Warm	Warm	Indifferent	Distinctly Warm	Distinctly Warm	Indifferent Warm
16.	Distinctly Warm	Warm	Indifferent	Distinctly Warm	Warm	Indifferent Warm
17.	Indifferent	Warm	Indifferent	Warm	Warm	Warm
18.	Indifferent	Warm	Indifferent	Indifferent Warm	Warm	Warm
19.	Distinctly Warm	Indifferent	Warm	Warm	Warm	Indifferent
20.	Distinctly Warm	Indifferent	Warm	Indifferent	Warm	Indifferent
21.	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent

Tables II and III. The posterior branch of the internal cutaneous nerve of the forearm was divided on August 6th, 1907. The area of affected sensibility was tested with ice-cold cylinders on August 23rd. Certain spots were marked in permanently. These were tested on August 25th and September 24th and 25th with ice-cold cylinders both as regards their reaction to temperature and their power of discriminating between two temperatures. The answers are recorded below.

The difference between the spots which gave "warm" to 0° C. and those which gave "cool" or "cold" is very well shown.

TABLE II.

			Temperature :— 0° C.	10° C.	22° C.	32° C.	40° C.	50° C.
Spot No. 1	Aug. 25	Observation 1	—	—	—	—	—	—
	,,	Observation 2	—	—	—	—	—	—
	Sept. 24	Observation 3	Indifferent	Indifferent	Warm	Warm	—	—
	Sept. 25	Observation 4	Indifferent	Indifferent	Warm	Warm	—	—
Spot No. 2	Aug. 25	Observation 1	Indifferent	—	—	Warm	Warm	Warm
	,,	Observation 2	Indifferent	—	—	Warm	Warm	Warm
	Sept. 24	Observation 3	—	—	—	—	—	—
	Sept. 25	Observation 4	—	—	—	—	—	—
Spot No. 3	Aug. 25	Observation 1	Warm	—	—	Warm	Warm	Warm
	,,	Observation 2	Indifferent Cool	—	—	Indifferent Cool	Indifferent	Indifferent
	Sept. 24	Observation 3	Warm	Warm	Indifferent	Warm	—	—
	Sept. 25	Observation 4	Warm	Warm	Warm	Warm	—	—
Spot No. 4	Aug. 25	Observation 1	Warm	—	—	Warm	Warm	Warm
	,,	Observation 2	Warm	—	—	Warm	Warm	Warm
	Sept. 24	Observation 3	Warm	Warm	Warm	Warm	—	—
	Sept. 25	Observation 4	Warm	Warm	Warm	Warm	—	—
Spot No. 5	Aug. 25	Observation 1	Indifferent Warm	—	—	Indifferent Warm	Warm	Warm
	,,	Observation 2	Indifferent Warm	—	—	Warm	Warm	Warm
	Sept. 24	Observation 3	Warm	Warm	Warm	Warm	—	—
	Sept. 25	Observation 4	Warm	Warm	Warm	Warm	—	—

TABLE II. (*Continued.*)

			Temperature:— 0° C.	10° C.	22° C.	32° C.	40° C.	50° C.
Spot	Aug. 25	Observation 1	Indifferent Cool	—	—	Indifferent Warm	Indifferent Warm	Indifferent Warm
No. 6	,,	Observation 2	Warm	—	—	Indifferent Warm	Warm	Warm
	Sept. 24	Observation 3	Warm	Warm	Warm	Warm	—	—
	Sept. 25	Observation 4	Warm	Warm	Warm	Warm	—	—
Spot	Aug. 25	Observation 1	Warm	—	—	Warm	Warm	Warm
No. 7	,,	Observation 2	Indifferent	—	—	Indifferent	Indifferent	Indifferent
	Sept. 24	Observation 3	Warm	Warm	Warm	Warm	—	—
	Sept. 25	Observation 4	Warm	Warm	Warm	Warm	—	—
Spot	Aug. 25	Observation 1	Cold	—	—	Warm	Warm	Warm
No. 8	,,	Observation 2	Cold	—	—	Warm	Warm	Warm
	Sept. 24	Observation 3	Cold	Cool	Warm	Warm	—	—
	Sept. 25	Observation 4	Cool	Cool	Warm	Warm	—	—
Spot	Aug. 25	Observation 1	Intense Cold	—	—	Warm	Warm	Warm
No. 9	,,	Observation 2	Intense Cold	—	—	Warm	Warm	Warm
	Sept. 24	Observation 3	Intense Cold	Intense Cold	Intense Cold	Warm	—	—
	Sept. 25	Observation 4	Intense Cold	Intense Cold	Cold	Indifferent	—	—
Spot	Aug. 25	Observation 1	Intense Cold	—	—	Warm	Warm	Warm
No. 10	,,	Observation 2	Intense Cold	—	—	Warm	Warm	Warm
	Sept. 24	Observation 3	Intense Cold	Intense Cold	Cold	Warm	—	—
	Sept. 25	Observation 4	Intense Cold	Intense Cold	Cool	Warm	—	—

TABLE III.

Discrimination between temperatures:—			0° C. & 10° C.			0° C. & 22° C.			0° C. & 32° C.			0° C. & 50° C.			10° C. & 22° C.			10° C. & 32° C.			22° C. & 32° C.			32° C. & 40° C.			32° C. & 50° C.		
			Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong
Spot No. 1	Aug. 25	Observation 1																										
	,,	Observation 2																										
	Sept. 24	Observation 3	0	0	6	0	0	6	2	0	4				4	0	2	3	0	3	0	0	6					
	Sept. 25	Observation 4	2	1	3	1	1	4	5	1	0				3	3	0	3	1	2	2	0	4					
Spot No. 2	Aug. 25	Observation 1							3		3	3		3										2		4	4		2
	,,	Observation 2							3		3	4		2										3		3	3		3
	Sept. 24	Observation 3																											
	Sept. 25	Observation 4																											
Spot No. 3	Aug. 25	Observation 1							2		4	3		3										2		4	4		2
	,,	Observation 2							3		3	0		6										2		4	1		5
	Sept. 24	Observation 3	0	0	6	0	0	2							2	2	2				1	3	2						
	Sept. 25	Observation 4	3	0	3	3	0	3	1	1	4				0	0	6	3	0	3	1	1	4						
Spot No. 4	Aug. 25	Observation 1							2		4	4		2										3		3	4		2
	,,	Observation 2							2		4	4		2										3		3	2		4
	Sept. 24	Observation 3				0	0	3							3	2	1												
	Sept. 25	Observation 4	3	0	3	3	2	1	4	2	0				2	0	4	0	0	6									
Spot No. 5	Aug. 25	Observation 1							1		5	2		4										2		4	3		3
	,,	Observation 2							1		5	2		4										2		4	2		4
	Sept. 24	Observation 3				0	0	3							1	1	4												
	Sept. 25	Observation 4	0	3	3	3	2	1	4	1	1										3	0	3						
Spot No. 6	Aug. 25	Observation 1							3		3	1		5										1		5	4		2
	,,	Observation 2							2		4	1		5										1		5	2		4
	Sept. 24	Observation 3																1	1	4	0	6	0						
	Sept. 25	Observation 4	1	1	4	2	2	2	3	2	1				0	0	6				0	1	5						
Spot No. 7	Aug. 25	Observation 1							1		5	0		6										0		6	0		6
	,,	Observation 2							1		5	2		4										0		6	1		5
	Sept. 24	Observation 3				0	0	3	0	0	6							1	2	3									
	Sept. 25	Observation 4	2	0	4	3	0	3	2	2	2				1	0	5	5	0	1	3	3	0						
Spot No. 8	Aug. 25	Observation 1							6		0	6		0										3		3	3		3
	,,	Observation 2							3		3	6		0										4		2	4		2
	Sept. 24	Observation 3	5	0	1	1	0	5	3	0	3				3	1	2	2	0	4	4	0	2						
	Sept. 25	Observation 4	2	2	2	5	1	0	6	0	0				5	0	1	6	0	0	6	0	0						
Spot No. 9	Aug. 25	Observation 1							6		0	6		0										2		4	4		2
	,,	Observation 2							3		3	5		1										4		2	3		3
	Sept. 24	Observation 3	4	0	2	3	0	3	6	0	0				4	0	2	5	0	1	6	0	0						
	Sept. 25	Observation 4	1	1	4	4	1	1	6	0	0				3	0	3	6	0	0	6	0	0						
Spot No. 10	Aug. 25	Observation 1							6		0	4		2										0		6	5		1
	,,	Observation 2							6		0	6		0										3		3	4		2
	Sept. 24	Observation 3	6	0	1	1	0	5	6	0	0				6	0	0	6	0	0	6	0	0						
	Sept. 25	Observation 4	4	0	2	3	2	1	6	0	0				6	0	0	6	0	0	5	0	1						

Tables IV and V. These show the result of similar observations on spots within the area of altered sensibility three weeks after section of the anterior branch of the internal cutaneous nerve of the forearm. Observations 1 and 2 were made on consecutive days.

It will be seen once more that spots which gave "warm" to 0° C. almost invariably proved to be incapable of discriminating temperatures anywhere in the thermometric scale.

TABLE IV.

	Observation	Temperature:— 0° C.	10° C.	22° C.	32° C.	40° C.	50° C.
Spot No. 1	1	Intense Cold	Intense Cold	Cold	Warm	Warm	Warm
	2	Intense Cold	Intense Cold	Cool	Warm	Warm	Warm
Spot No. 2	1	Intense Cold	Intense Cold	Cold	Warm	Warm	Warm
	2	Intense Cold	Intense Cold	Cold	Warm	Warm	Warm
Spot No. 3	1	Cold	Cold	Warm	Warm	Warm	Warm
	2	Cold	Cold	Indifferent	Warm	Warm	Warm
Spot No. 4	1	Cold	Cold	Cool	Warm	Warm	Warm
	2	Cold	Cold	Cold	Warm	Warm	Warm
Spot No. 5	1	Cool	Cool	Warm	Warm	Warm	Warm
	2	Cool	Cool	Cool	Warm	Warm	Warm
Spot No. 6	1	Cool	Cool	Warm	Warm	Warm	Warm
	2	Cool	Cool	Indifferent	Warm	Warm	Warm
Spot No. 7	1	Indifferent Cool	Indifferent Cool	Warm	Warm	Warm	Warm
	2	Indifferent Cool	Indifferent	Indifferent	Warm	Warm	Warm
Spot No. 8	1	Indifferent Cool	Indifferent Cool	Warm	Warm	Warm	Warm
	2	Indifferent	Indifferent Cool	Warm	Warm	Warm	Warm
Spot No. 9	1	Indifferent	Indifferent	Warm	Warm	Warm	Warm
	2	Indifferent	Indifferent	Indifferent	Warm	Warm	Warm
Spot No. 10	1	Indifferent	Indifferent	Indifferent	Warm	Warm	Warm
	2	Indifferent	Indifferent	Indifferent	Warm	Warm	Warm
Spot No. 11	1	Indifferent	Warm	Warm	Warm	Warm	Warm
	2	Indifferent	Warm	Warm	Warm	Warm	Warm
Spot No. 12	1	Warm	Warm	Warm	Warm	Warm	Warm
	2	Warm	Warm	Warm	Warm	Warm	Warm
Spot No. 13	1	Warm	Warm	Warm	Warm	Warm	Warm
	2	Warm	Warm	Warm	Warm	Warm	Warm

TABLE V.

Discrimination between temperatures:—		0° C. & 10° C.			0° C. & 22° C.			0° C. & 32° C.			0° C. & 50° C.			10° C. & 22° C.			10° C. & 32° C.			22° C. & 32° C.			32° C. & 40° C.			22° C. & 50° C.			32° C. & 50° C.		
	Observation	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong	Right	No answer	Wrong
Spot No. 1	1	2	2	2	4	1	1	5	1	0	6	0	0	1	1	4	5	1	0	6	0	0	6	0	0	6	0	0	6	0	0
	2	2	2	2	6	0	0	6	0	0	6	0	0	4	2	0	6	0	0	6	0	0	5	1	0	5	1	0			
Spot No. 2	1	3	3	0	3	3	0	4	2	0	5	1	0	5	1	0	5	1	0	6	0	0	6	0	0	6	0	0	6	0	0
	2	3	2	1	2	4	0	5	1	0	6	0	0	4	2	0	3	3	0	6	0	0	6	0	0	5	1	0			
Spot No. 3	1	1	3	2	5	0	1	5	0	1	4	1	1	1	4	1	5	1	0	6	0	0	6	0	0	3	0	3	6	0	0
	2	0	3	3	3	3	0	6	0	0	4	1	1	6	0	0	4	2	0	6	0	0	3	1	2	6	0	0			
Spot No. 4	1	4	2	0	4	1	1	5	1	0	6	0	0	4	0	2	5	1	0	6	0	0	6	0	0	6	0	0	6	0	0
	2	4	2	0	5	1	0	5	1	0	6	0	0	4	2	0	6	0	0	6	0	0	6	0	0	6	0	0			
Spot No. 5	1	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	5	1	0	4	2	0	6	0	0	6	0	0
	2	5	1	0	4	2	0	6	0	0	6	0	0	4	2	0	6	0	0	4	2	0	6	0	0	6	0	0			
Spot No. 6	1	1	3	2	1	4	1	3	2	1	3	3	0	1	3	2	3	1	2	2	0	4	2	4	0	4	2	0	1	1	4
	2	1	4	1	0	3	3	1	0	5	4	2	0	2	4	0	3	3	0	2	3	1	1	3	2	6	0	0			
Spot No. 7	1	1	1	4	2	3	1	2	1	3	2	3	1	0	5	1	3	3	0	3	1	2	1	1	4	2	2	2	2	3	0
	2	0	1	5	1	2	2	2	2	2	0	2	4	2	4	0	0	6	0	3	2	1	1	2	3	5	1	0			
Spot No. 8	1	2	1	3	2	0	4	4	2	0				1	2	3	1	0	5	3	2	1	0	4	2						
	2	0	2	4	2	2	2	2	4	0				1	3	2	3	3	0	2	2	2	3	1	2						
Spot No. 9	1	0	2	4	5	1	0	3	3	0	0	2	4	0	4	2	0	4	2	2	1	3	2	2	2	1	0	5	1	1	4
	2	2	1	3	3	0	3	2	2	2	2	3	1	1	3	2	3	2	1	2	3	1	3	1	2	6	0	0			
Spot No. 10	1	0	3	3	4	1	1	0	3	3	1	0	5	4	2	0	0	1	5	2	2	2	2	1	3	1	0	5	0	0	6
	2	1	0	5	1	1	4	2	2	2	3	1	2	4	2	0	2	2	2	3	1	2	2	1	3	5	1	0			
Spot No. 11	1	0	2	4	0	0	6	2	0	4	5	1	0	3	0	3	2	1	3	1	3	2	4	2	0	6	0	0	6	0	0
	2	1	0	5	1	1	4	2	2	2	6	0	0	2	2	2	2	1	3	1	2	3	5	1	0	6	0	0			
Spot No. 12	1	2	3	1	2	1	3	2	2	2	2	2	2	2	0	1	2	1	3	0	0	6	2	4	0	0	0	6	0	0	6
	2	1	1	4	1	3	2	2	1	3	0	0	6	3	0	3	1	3	2	1	2	3	2	2	2	2	3	1			
Spot No. 13	1	1	1	4	2	0	4	0	1	5	0	2	4	2	1	3	2	2	2	0	1	5	4	1	1	1	0	5	0	0	6
	2	0	4	2	1	3	2	2	1	3	3	1	2	3	3	0	3	3	0	3	1	2	2	1	3	2	4	0			

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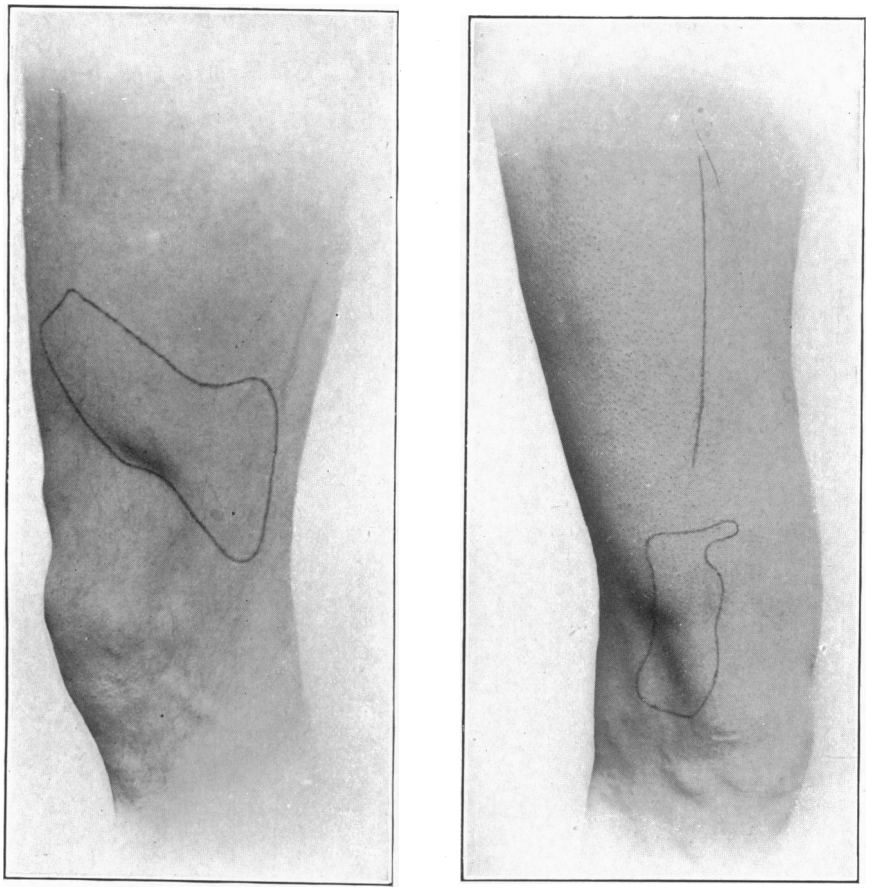

Fig. 3. Antero-external aspect of left thigh to show area of anæsthesia to the camel's hair brush produced by section of the outer branch of the middle cutaneous nerve. The scar of the wound through which the nerve was divided can be seen above.

Fig. 14. Antero-external aspect of right thigh.

Showing area of anæsthesia to camel's hair brush produced by section of outer branch of middle cutaneous nerve.

The short oblique line at the top of the photograph marks the scar of the wound through which the nerve was divided.

The vertical line running downwards from the scar shows the course of the nerve as defined with the faradic current before the operation.

The smallness of the area of anæsthesia and the distance of it from the point of nerve section were in this case very striking.