VIII. *Experiments on the Restoration of Paralysed Muscles by Means of Nerve Anastomosis.** Part III.—*Anastomosis of the Brachial Plexus, with a Consideration of the Distribution of its Roots.*

By Robert Kennedy, *M.A., D.Sc., M.D., St. Mungo Professor of Surgery in the University of Glasgow.*

Communicated by Prof. J. G. McKendrick, *F.R.S.*

(Received February 11,—Read March 11, 1915.)

(Plates 23, 24.)

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* The expense of this research has been defrayed by a Government Grant from the Royal Society.

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1. Introduction.

In two previous communications I have dealt with anastomosis of nerves as applied to the facial nerve (32)* and to the nerves of the fore-limb of the dog (33), and in this, which forms the third and concluding part of my research on this subject, the question is considered as applied to the brachial plexus. The reason for making a special investigation on the brachial plexus as distinguished from the nerves in the limb at a lower level, is that the nerve trunks forming the plexus differ in an important respect from nerve trunks distal to the plexus. In the latter the nerve fibres destined for particular muscles or groups of muscles run as a rule in one nerve trunk. In making an anastomosis, when one of two such nerve trunks is cut and its peripheral end attached to a neighbouring trunk, the peripheral end is attached to nerve fibres, none of which as a rule pass to the same muscle as those of the trunk to which it belongs. This can be done by anatomosing the musculo-spiral to the median and ulnar and musculo-cutaneous, so that a definite answer can be got to the question as to the possibility of thus restoring function, provided that care is taken after recovery of function,

* The numbers in brackets refer to the Bibliography, pp. 398–400.

by means of a physiological examination, to ascertain that no intercommunication has taken place during the recovery. This was done in Part II of this research.

In the case of the brachial plexus, however, it has been found by most investigators to be characteristic of the plexus that nerve fibres destined for the same muscle or group of muscles are to be found in two or three of the contiguous roots of the plexus, making it thus impossible to destroy completely the nerve supply of one muscle by section of a single root.

It is obvious, therefore, that in all cases of anastomosis applied to this plexus, the functions of the roots must be borne in mind in any judgment as to the results of attaching one root to another with a view to restoring muscles which have been paralysed by injury to the plexus, or to the cells in the spinal cord corresponding to the plexus. This part of the research must therefore be an investigation not only into the results of anastomosing one or more roots to another or to others, but also must inquire into the distribution of the nerve fibres composing the roots which are concerned in the experiments.

The previous work on this subject is scanty, and in the main consists of operative work undertaken as a remedial procedure in the human subject where paralyses have occurred due either to trauma affecting some of the roots of the plexus or to infantile paralysis where cells in the cord corresponding to some of the roots have been destroyed.

One of the earliest of these was a case published by THORBURN (17), which, although not a special anastomosis, yet was suggestive of this. The case was one in which the entire brachial plexus had been torn across seven and a half months previously. The plexus was exposed, the entire extensive scar removed, and the proximal and distal ends drawn together without being accurately apposed. When the case was seen nearly four years later it was found that in the interval sensation had been restored throughout the entire limb, and that almost all the movements of the arm were recognisable. THORBURN calls attention to the impossibility of securing accurate coaptation, so that "nuclei might on regeneration be attached to muscles other than those for which they were intended," but states that in his opinion this is a matter of little moment as regards the resulting recovery of co-ordinated movements.

The cases in which anastomosis has been deliberatively performed are those in which the lesion has affected not the entire plexus but only a part. The commonest of these conditions is the injury which usually only involves the upper roots of the plexus, and which when caused by injury at birth is called Duchenne's paralysis, and when occurring first at adult age, Erb's paralysis, after the neurologists who first described it at the respective ages. In the case of Duchenne's paralysis, I (18) published three cases in 1903 in which the upper part of the plexus was exposed, and a cicatrix found at the junction of the fifth and sixth roots. This was excised and the fifth and sixth roots united to the three nerves which normally pass from the fifth and sixth, namely, the suprascapular, the branch to the

outer cord, and the branch to the posterior cord of the plexus. The first of these operations was performed in February, 1902. Further cases (20) were published by me in the following year, and subsequently numerous cases of the same kind were published by others. The results of these cases were satisfactory, in some cases a perfect restitution of function taking place. This method is the ideal one of treating all cases of rupture of the roots of the brachial plexus, but there may be certain cases in which the scar on the nerve trunks is so extensive that after excision it would not be possible to make a junction between the proximal and distal ends, and there are cases where the roots of the plexus have been torn out from the intervertebral foramina, and in these cases the operation of anastomosis might offer a method of treatment. Also there are cases in which the function of muscles supplied through the brachial plexus is lost not through damage to the plexus itself, but through a lesion involving the cells in the cord which are in connection with the fibres in the plexus (infantile paralysis). In such cases it is obvious that anastomosis would offer the only method of dealing with the case by operation on the nerves, although alternative methods apart from operation on the nerves might also be suitable. It is necessary to enquire into the evidence of success of the procedure of anastomosis. A number of cases of anastomosis for such conditions have now been published.

The first to publish operations of this nature were HARRIS and LOW (19). They published three cases. The first was that of a woman who had paralysis of the muscles supplied through the upper part of the plexus due to neuritis of 16 months' duration. They cut the fifth root and grafted it into the seventh root into a transverse cut, which severed the sheath and some of the nerve bundles. The section made in the seventh root did not add to the paralysis originally present.

In the second case, a man, aged 40, who had injured his plexus three years previously, there was wasting of the deltoid, biceps, and of the pectoralis major and latissimus dorsi, the serratus magnus also being affected. When the fifth root was traced up a bulbous swelling was reached $1\frac{1}{2}$ inches above the junction with the sixth root. They cut the fifth below this swelling, and attached it into a transverse cut in the sixth trunk. Before the operation, in addition to the muscular paralysis, there was "very slight anæsthesia on the outside of the arm from the shoulder to the elbow, and quite marked anæsthesia to touch and pain in the thumb and radial side of the index finger." "The day after the operation the numbness and anæsthesia of the left thumb and index finger had improved, and by the end of the week sensation in this area was absolutely normal to the most delicate tests, though the slight anæsthesia on the outside of the arm persisted." Motor power remained *in statu quo ante*, but "a month later definite contractions could be seen in the deltoid on reversing a current of 10 milliampères, though prolonged galvanic treatment some months before operation had no effect." TUBBY and JONES (26) report that in answer to a communication to HARRIS and LOW regarding the above two cases, under date November 2, 1906, they state "Neither of the cases with the Erb's

paralysis recovered any power in the deltoid and biceps, though one recovered sensation in the hand over the sixth cervical segment."

In the third case by HARRIS and LOW, a girl of two years of age affected about five months previously with infantile paralysis, there was complete paralysis and wasting of the deltoid, supraspinatus, and infraspinatus, while only slightly affected were the biceps, brachialis anticus, and supinator longus. The treatment consisted in splitting the fifth root into two longitudinal halves, and taking the half which was supposed to contain the fibres destined to supply the deltoid, and anastomosing it into the sixth. Before attaching it to the sixth it was stimulated and gave weak contractions of the deltoid. This case was shown at the Clinical Society of London in October, 1904 (22), and was reported with the following details: It was operated on five months after the onset of the paralysis, and there was no change for six months after the operation. "Slight power of abduction of the shoulder was then first noticed. Progress, at first slight, has during the last three months increased in rapidity, and she is now able to hold the arm out at right angles from the shoulder, and to raise the arm over the head." Faradic contraction was also found in the deltoid. HARRIS (29) subsequently reported the case as a very good recovery due to the operation.

HARRIS and LOW have concluded from their investigations that the fifth root is not only the chief but is practically the only nerve affected in the type of paralysis known by the names of DUCHENNE and ERB. They say: "We therefore came to the conclusion that the deltoid, spinati, and biceps received their whole motor supply from the fifth nerve or from the fourth and fifth, and that the sixth nerve sent no motor fibres to these muscles" (21, p. 2). This was also the conclusion which HARRIS (21) came to from his dissection of the brachial plexus, although he found that in monkeys the muscle groups (deltoid, biceps, infraspinatus, supinator longus and brevis, and extensor carpi radialis longior) also contracted on stimulation of the sixth root, but he considers that in man the plexus is prefixed to the extent of a whole root, so that in man no result will be got in these muscles by stimulation of the sixth root. The principle of the operation which he had performed in his third case he explains (19, p. 1037) as due to the separation in the fifth root of that bundle of fibres which is intended for the particular muscles which he finds it to supply.

Following these operations cases were published by different authors. In 1905 some cases were published by LANGNECKER, HELMHOLZ, and CUSHING (24), in one of which, where all the cords of the plexus had been ruptured, CUSHING carried out the following procedure: "The nerve trunks were completely dissected out, and several complex anastomoses were made. The spinal accessory was anastomosed into the upper cord of the plexus. The operation was successful in so far as the patient has already regained use of the upper arm and still continues to improve." This operation was performed in 1904 and the report made in the following year.

SHERREN (23), in 1906, published a case in which he had performed nerve anastomosis of the fifth to the sixth anterior primary division. Before doing so, he

stimulated the roots with the interrupted current. The result of the stimulation of the fifth was negative, while that of the sixth produced vigorous contractions of the pectoralis major, chiefly its clavicular portion, with feeble response from the triceps. He concludes from this that it appears probable that the sixth nerve supplies no muscle or group of muscles exclusively in a manner similar to the supply of the spinati, deltoid, the biceps, the brachialis anticus and supinators from the fifth. He thus agrees with HARRIS and LOW as to the part served by the fifth cervical nerve in the supply of muscles.

WARRINGTON and JONES (25) made a contribution to this subject in the same year. In one case, four years after the injury, the fifth and sixth roots were cut and anastomosed into the seventh, and as a result of this procedure they note that no further muscular paralysis was caused, but that an additional area of anæsthesia developed on the hand. Electrical stimulation of the roots showed nothing as a result of stimulating the fifth and sixth roots, but the seventh gave "strong extension of the elbow and wrist and lateral rotation of the humerus." This operation was done on September 14, 1904, and by August 31, 1906, no return of motion had occurred, but "protopathic sensation" had returned. In another case, in a 26 months old child affected with infantile paralysis when one year old involving the deltoid, spinati, and flexors of the arm, they performed an anastomosis in 1905. At the operation stimulation of the fifth gave no response, but of the sixth contractions of the serratus magnus and pectoralis major. The fifth root was then cut and its distal end placed into a longitudinal cut made into the sixth. By 1906 no alteration had occurred.

In a third case in which the paralysis was due to neuritis they found a cicatrix surrounding the junction of the fifth and sixth nerves. Stimulation of the fifth got no response from the deltoid, spinati, biceps, and brachialis anticus, but feeble contractions in the supinator longus and radial extensor. Stimulation of the sixth produced vigorous contractions in the triceps, pectoralis and latissimus dorsi. Following HARRIS, they divided the fifth root longitudinally into two halves of unequal size. The larger part on stimulation gave no response. This was then cut and anastomosed into the sixth nerve. This operation was done on August 16, 1905, and on August 6, 1906, they made the following note: "The biceps, brachialis, and supinator longus show distinct recovery and the reaction to faradism is present; to galvanism there is brisk contraction with K.C.C. > A.C.C. The posterior fibres of the deltoid react both to F. and G. K.C.C. > A.C.C., contractions fairly brisk. The anterior fibres do not react to faradism and give a feeble response to galvanism. A.C.C. > K.C.C., contractions sluggish. The infra- and supra-spinati are powerless, but slight external rotation of the humerus can be performed to a moderate extent by the posterior fibres of the deltoid. Appears to have slight loss of epicritic sensation over the outer preaxial border and complains of a slight burning sensation." They do not appear to give details of the state before operation except to say that the case

was one of neuritis. From these observations WARRINGTON and JONES agree with HARRIS as to the functions of the fifth cervical nerve.

Another case of the kind was published by SARGENT (27). This was a male aged 19 years, who after influenza developed weakness and wasting of the deltoid, spinati, triceps, and biceps and an area of anæsthesia and analgesia over the shoulder and outer side of the arm. Before the operation at five months from the commencement of the affection there were weakness and wasting of the deltoid and spinati and winged scapula, but the biceps and supinator longus were fairly good. The operation consisted of exposing the plexus, and splitting the fifth root after the manner of HARRIS. The upper part was cut and turned down and implanted into the sixth root. Gradual improvement was reported and at the time of publication, namely 14 months, the deltoid and spinati were much increased in bulk and were used voluntarily with much power. The deltoid and spinati reacted to faradism and there was no sensory change.

In the discussion which followed this communication, HEAD (28) pointed out that the operation was done five months after the injury and that already some improvement had occurred in the biceps and supinator longus. He stated that in a traumatic case not much improvement would be expected before a year, and thought that this case should have been left alone. He also elicited the fact that no increase in the paralysis had resulted from the incision made in the sixth root for the purpose of the anastomosis and stated that the root which had been divided had nothing to do with the return of power, and was of opinion that the course followed subsequent to the operation was that followed by an ordinary well treated traumatic case. In support of this it was remarked by WILSON that muscles which were not influenced by the operation had also improved, namely the serratus magnus and triceps.

In 1909 TUBBY (30) published some cases in which a similar procedure had been adopted. In the first case there had been laceration of the brachial plexus, and complete paralysis of the arm was the result. The operation was performed in February, 1906, or about six months after the injury, and consisted of dissecting away a scar involving the upper cords of the brachial plexus. On the fifth root a fibro-neuroma was found and was excised and the distal part of the fifth was grafted into the sixth. The other cords of the plexus were healthy and it was thought that the paralysis had been due to scar pressure. There was no improvement till March, 1908, or 25 months after the operation, when return of power in the biceps was noted, enabling the forearm to be flexed to right angles with the arm. There was also some recovery in the deltoid and faradic irritability had returned. By another year complete recovery of the biceps and brachialis anticus was reported, and the deltoid acted better, "so that he could draw his arm away from the side for about four inches." Sensation returned in the arm down to the elbow. The recovery of muscles was limited to the biceps, brachialis, and part of the deltoid. The supinator longus did not respond, nor did the muscles below the elbow.

His next case was one of infantile paralysis causing partial loss of power in the left arm. The arm hung by the side, but the elbow and wrist could be flexed. The deltoid, supra- and infra-spinati, biceps, and supinator longus were wasted and did not respond to faradism. The slight flexion present was thought to be due to the action of the muscles attached to the internal condyle. Eight months after, the anterior primary division of the fifth cervical was grafted on to that of the sixth, in such a way that both proximal and distal ends of the divided fifth were attached to the sixth about $\frac{1}{2}$ inch apart. A year later contractions had appeared in the biceps and the muscle was more bulky. Also there was improvement in the posterior part of the deltoid. There was still further improvement a year later.

In another case of infantile paralysis affecting the deltoid since the age of 10, TUBBY three years subsequently, in 1906, found the deltoid wasted and showing no faradic irritability. He exposed the plexus and stimulated the fifth root and found that this on the inner side gave contractions of the biceps and supinator longus and extensor carpi radialis longior. Stimulation on the outer side gave no effect, and he concluded that these were the fibres supplying the deltoid, and followed then the method of HARRIS, dividing the root half through its thickness and splitting it longitudinally for an inch. He then turned down the flap and attached it into a longitudinal slit in the sixth root. Twelve months after this operation the deltoid responded to faradic stimulation. The muscle increased in size and firmness and was felt to harden when voluntary effort was made. At 18 months afterwards, the boy could abduct the arm 6 inches from the side, and at two years, 8 inches.

KILVINGTON (31) also in 1909 reported a case in which the procedure was somewhat different. His patient was aged 12, and suffered from birth paralysis of the upper extremity, the two most outstanding defects being loss of power to abduct the arm at the shoulder joint and to flex the elbow. He, therefore, cut across the musculo-cutaneous nerve and joined it into a notch made in the ulnar, and he also cut the circumflex and joined its distal end to the nerve supplying the long head of the triceps. He gives no further details, except that when last seen "his power in abducting the arm with the deltoid was good and he could slightly bend the elbow, but with not sufficient power to raise any weight."

It is unnecessary to follow further the published clinical cases, as they are all more or less of the same nature as those already quoted. On making a careful study of these, several considerations suggest themselves which make further investigation desirable. In the first place the method of making the anastomosis in some of the cases calls for consideration. Thus in some a paralysis of a group of muscles regarded by many as under the control of the fifth and sixth cervical nerves has been treated by dividing the fifth nerve and inserting its distal end into the sixth, and recovery reported after this procedure. This has been done by those who believe that the sixth cervical nerve is not involved in these cases, and the recovery reported naturally is taken as a confirmation of this view. But it does not necessarily follow that an

improvement following an operative procedure is in consequence of that. There is the possibility that the recovery is a spontaneous one, and this must, therefore, be inquired into.

The cases of anastomosis which have been quoted give examples of the procedure adopted for different conditions. They have not all been cases of traumatic rupture, but some of them have been cases of neuritis and others of infantile paralysis. Now in all these conditions spontaneous recoveries are known to occur to a degree more or less complete, but in any case to as great an extent as most of the recoveries which have been reported as following these operations. This is the criticism which was put forward by HEAD in connection with one of these cases as quoted above, and, as he pointed out, much recovery would not be expected in such cases before the lapse of a year. Therefore an operative intervention during that period as was done not only in the case referred to but also in some of the others, cannot have the recovery following it attributed to the operation with certainty. This is a criticism which is all the more justified in consideration of the fact that the nerve root which was divided and anastomosed, on examination by electrical stimuli previous to division, showed in some cases conductivity already or still present. This may be held as evidence of a commencing or progressing spontaneous recovery, at the dates at which these operations were done. It is, therefore, possible that the recoveries reported have been due to this.

A third consideration is suggested in some of the cases where the operation was undertaken long after the onset of the paralysing lesion. Recovery taking place in paralysed muscles under such circumstances would be strong evidence in favour of the recovery being in consequence of the anastomosis, but in some cases this recovery has taken place so early after the intervention that one is led to doubt that the recovery is the result of the anastomosis. We know that muscles after long periods of severance from the central nervous system require long periods of restoration of that connection before they become capable of responding to normal stimuli, and in any case in which restoration occurs earlier than expected, in the circumstances, careful investigation of all the conditions must be made before such evidence can be accepted. Thus it is possible that the preliminary examination may have been insufficient, and that improvement resulting may have been due to a course of treatment, *e.g.*, massage and passive movements following the operation, which has brought about improvement by the mobilisation of the joints and in other ways.

All clinical cases are thus apt to be vitiated as evidence in support of the success of anastomosis, for the reason that a physiological examination, or a *post-mortem* examination of the seat of anastomosis, cannot be made after the recovery has occurred, so as to ascertain if the recovery is due to the anastomosis. This can alone be done by experimental investigation in animals. For the purpose of investigating the brachial plexus from the point of view of comparing the results with those found in operative anastomosis in man, it is necessary to make the experiments

in an animal in which the plexus approximates as closely as possible to that of man. Therefore these experiments must be made in monkeys. During the past few years I have made a series of such experiments, the histories of which will now be related.

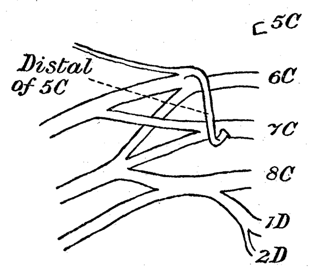
2. The Author's Experiments.

(1) *Experiments in which Attachment was made of the Severed Root or Roots of the Brachial Plexus to Another Root or Roots of the Brachial Plexus.*

a. One root cut off from its centres and attached to another root.

Experiment I.—*Section of the Anterior Primary Division of the Fifth Cervical Nerve and Attachment of the Peripheral Segment into the Trunk of the Anterior Primary Division of the Seventh Cervical Nerve.* (*Plate* 23, *figs.* 1, 2.)

On May 8, 1909, in a young male *Macacus rhesus* the fifth and sixth anterior primary divisions were exposed and followed from their point of junction inwards to the intervertebral foramina, and then the seventh and eighth cervical and combined trunk of the first and second dorsal nerves were also exposed. The seventh trunk was first half cut through on its inner side. The fifth trunk was then cut close to the vertebræ and the distal end sutured into the cut made in the seventh nerve. The central end of the fifth was then damaged by driving a bone plug into the intervertebral foramen through which it emerged. The wound was closed and sealed with collodion.



Later on the same day it was observed that the animal, which had recovered from the anæsthetic in about ten minutes, was keeping its arm close to the side, having apparently no power to abduct. It, however, clearly had excellent power of flexion at the elbow, as it held the forearm flexed at an acute angle, and at will extended the forearm and again flexed it. The wrist was held semiflexed, as is customary with monkeys sitting in respose, but at will could be seen being extended and flexed freely.

May 9, 1909 (1 day): The animal is using the affected hand for picking up food and is flexing and extending well at the elbow.

May 10 (2 days): When a piece of biscuit is held to him he takes it with the affected hand and carries it to his mouth without any difficulty, showing supination and flexion of the forearm in so doing. It is noticed, however, that the finger and the thumb grasp the biscuit with a slight defect, the movement not being so quickly performed as with the other hand, but once it is grasped it is held firmly and quickly carried to the mouth.

May 12 (4 days): Shows flexion and extension at the elbow joint with apparently as much freedom as in the case of the opposite arm. Supination is freely carried out in feeding. There is no attempt being made to abduct the arm.

May 16 (8 days): Animal *in statu quo*. He has pulled out the stitches and the wound is soundly healed.

May 18 (10 days) (Plate 23, fig. 1): In feeding to-day it is observed that there is considerable power of abduction of the arm, the arm being elevated to the extent of forming a right angle with the body. This movement takes place in a forward and outward direction. The flexion power in the elbow enables an acute angle to be formed between the arm and forearm, being quite a normal range. There is, however, some evidence of lack of power in the arm, as he will hang on to the bars of his cage with the hand of his sound arm and by his two feet and will then take the biscuit offered him with the affected hand, but he cannot be induced to hold on with the latter and take the biscuit with the unaffected hand.

May 27 (19 days): The arm within the last few days has recovered a practically normal range of abduction and can be elevated almost vertically upwards, and as he can be induced to take food by reaching up for it with the affected arm, he was photographed in this attitude to-day (Plate 23, fig. 2).

June 23 (46 days): No defect in movements of right arm can now be discovered.

January 26, 1910: The animal died to-day. It had up to the last maintained the condition of the arm reported in the last note.

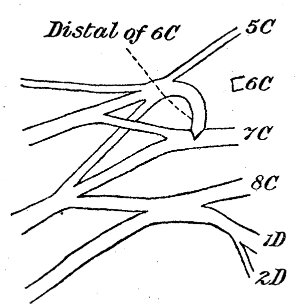
Post-mortem Examination.

The central segment of the fifth trunk is seen close to the intervertebral foramen and presents a bulbous swelling. No strands resembling a prolongation of the nerve can be found. A thin translucent band dissected out from the surroundings in contact with it was examined in a teased preparation, but no nerve fibres were found. Between the junction of the fifth and sixth roots and the seventh root there is a globular swelling consisting of dense tissue having the consistence of a neuroma, which represents the turned down peripheral segment of the fifth root. The left plexus dissected out shows a normal arrangement. The deltoid and biceps muscles of the two arms were dissected out and carefully examined and those of the right arm did not show any difference in bulk as compared with those of the left arm.

Experiment II.—*Section of the Anterior Primary Division of the Sixth Cervical Nerve and Attachment of the Peripheral Segment into the Trunk of the Anterior Primary Division of the Seventh Cervical Nerve.* (*Plates* 23, 24, *figs.* 3, 4, 5).

On May 16, 1909, in a young male *Macacus rhesus* the brachial plexus was exposed as in the previous experiment, and the trunk of the anterior primary division of the seventh cervical cut half through on its outer side above the point of its breaking into divisions. A fine catgut thread was made to transfix the seventh above and below the point of hemisection and was then carried through the distal segment of the sixth cervical previously cut close to the point of its emergence from the intervertebral

foramen. The central segment of the sixth was then lacerated by the foramen having a plug of bone driven into it, and the catgut suture on being tied brought the peripheral end of the sixth into the gap made in the seventh. The wound was closed and sealed.



The monkey recovered from the anæsthetic in a few minutes, and it was then seen that the arm was held in a position of extension at the elbow, and no attempt appeared to be made to flex it.

May 17, 1909 (1 day): No abduction of the arm has been noticed, and no such movement can be induced. The arm hangs down by the side but is used for resting on, and the hand is being made use of. The elbow is held extended, but there appears to be some power of voluntary flexion, when it is induced by the offer of food, as an effort is then made to move the arm. Supination has not been observed.

May 21 (5 days): Slight flexion of elbow can be performed, but not nearly to a right angle. No abduction of arm has been seen. May 28 (12 days): Wound healed.

June 2 (17 days): The animal was photographed showing the position in which the limb has been held since the operation (Plate 23, fig. 3).

June 21 (36 days): To-day for the first time it was noticed that the animal was able to make use of his right arm. An improved degree of flexion has been developed at the elbow, and the hand is raised to receive a bit of biscuit, but he immediately takes the biscuit out of the hand and carries it to the mouth with the sound hand. In taking the biscuit with the right hand he shows considerable power of grasping, and shows also loss of supination.

June 23 (38 days): The arm appears to be able to be flexed to form an angle of 120° between arm and forearm. This is shown during his efforts to escape while a noose is being thrown over his head. There is no indication of power to abduct, but the grasp of the hand is good.

June 25 (40 days): There has been considerable progress, as the animal can now almost carry a morsel of food into his mouth with the affected hand, and also shows some power of abduction of the arm when he is attempting to reach up for food offered him. Supination is not evident. While fighting to escape a noose being put over his head he raises the hand as high as the level of his nose when he is in the erect posture, but evidently the incomplete power of flexion of the elbow and supination of the forearm prevents him carrying food to the mouth. The amount of flexion at the elbow now present allows the forearm to form a right angle with the arm. The animal was photographed to show flexion of the forearm (Plate 23, fig. 3).

June 30 (45 days): To-day the animal can abduct the arm, raising the arm well above the head while stretching up to reach a morsel of food held above his head.

Flexion of the elbow enables an acute angle to be formed between forearm and arm. Now the animal succeeds in carrying food to his mouth with the right hand, but there is clearly an effort required, as he occasionally helps the right hand up by giving it a lift with the left hand. Supination is developing, and it is apparently the defect in this movement which is now the only bar to a free and full use of the arm. There appears to be still a defect in the action of the extensors of the forearm, as there is a tendency to have a slight flexion at the wrist, but this is only very slight and does not prevent voluntary extension of the wrist, and even over extension and full extension of the fingers and thumb.

July 1 (46 days): Photograph taken (Plate 24, fig. 5).

July 2 (47 days): Further improvement of the movements has taken place in the past two days, as the morsels of food can now be carried to the mouth with ease, and the power of supination is much improved. The only defect still noticeable is the weakness in the extensor muscles in the forearm, but since the last note this has improved.

July 6 (51 days): All the movements appear now to be restored to the normal practically, *i.e.* all the movements which the animal can be induced to make in feeding and in defence when it is attempted to put a noose over his head. Thus abduction and elevation of the arm, flexion of the forearm, and movements of the hand and wrist and supination of the forearm are all apparently normal.

Physiological Examination.

July 10 (55 days): To-day at 10 A.M. the brachial plexus was exposed. It was very carefully approached and exposed, so that any communications between the central end of the sixth cervical and the peripheral end of the same might not be damaged by knife or blunt instrument until the stimulations were carried out. The plexus was thus to begin with exposed as close to the vertebræ as possible without doing more than exposing the anterior borders of the intervertebral foramina. Distal to this the fifth nerve could be seen, and the seventh and combined trunk of the eighth cervical and first and second dorsal, and passing from the fifth to the seventh could be seen a somewhat cicatricial connection, representing the peripheral segment of the sixth. The following stimulations were then made, using the current from a secondary coil of a strength just enough to produce a disagreeable sensation on the tongue.

1st. *The Fifth Nerve.*—On stimulating this trunk the deltoid was felt to contract without resulting in abduction of the arm. No contraction of the biceps could be felt, also no other muscle could be felt contracting. There was on stimulation a distinct movement of the limb, and that was external rotation of the humerus.

2nd. *Central Segment of the Sixth Nerve.*—Stimulation at the intervertebral foramen through which the sixth nerve emerges gave no movements of the arm,

and no contractions of any muscular fibres in the arm could be felt, seen, or otherwise ascertained.

3rd. *The Seventh Nerve.*—Stimulation of this nerve gave extension at the elbow joint, and the triceps and biceps were both felt to contract. The deltoid was also felt to contract, but this was not sufficiently strong to cause abduction of the arm. There were also contractions of the muscles of the forearm, both of the flexors and of the extensors, but the flexors appeared to contract more powerfully, and the movement produced was one of flexion of the fingers and wrist.

4th. *The Eighth Cervical and First and Second Dorsal.*—Stimulation of these combined roots produced movements of the hand, namely, strong flexion of the fingers, and the flexor muscles were found powerfully to contract. The biceps and the triceps were also felt to contract.

5th. *The Distal Segment of the Sixth Nerve.*—This segment of nerve was embedded in the scar tissue stretching between the fifth and the seventh trunks, and stimulation on the surface of this mass caused contractions of the deltoid, biceps, and triceps, but no contractions of any muscles in the forearm.

This piece of nerve was then cut across in a line running approximately parallel between the fifth and seventh nerves, and the distal stump was held up and stimulated, and this produced contractions of the deltoid and triceps without producing actual movements of the limb. No attempt was made to reunite the divided peripheral segment of the sixth, and the wound was closed with sutures and sealed with collodion. The examination had lasted one hour and a quarter.

At 3 P.M. it was found that the limb was hanging at the side and was not being used. On making the animal fight there was some evidence of some power of flexing at the elbow, although it was only slight. The animal had not completely recovered from the anæsthetic.

July 11 (1 day after the examination): To-day the animal holds out the affected hand to receive food, and shows that he has recovered power of flexion at the elbow to nearly a right angle. He takes the food with the hand with some difficulty, moving the fingers stiffly. He cannot apparently do more, and makes no attempt to raise the morsel of food to his mouth, but passes it into his sound hand to be raised to his mouth. No shoulder movements are seen.

July 12 (2 days): More freedom in movement of elbow and hand.

July 13 (3 days): The elbow can be bent quite to a right angle.

July 14 (4 days): Flexion at the elbow can form an acute angle. The stitches have been pulled out, but the wound remains edge to edge.

July 15 (5th day): The monkey can now put a piece of biscuit in his mouth with the right hand. There is now slight abduction of the arm.

July 16 (6 days): The wound appears to be soundly healed.

July 27 (17 days after the examination): The position now is as follows: The elbow can be flexed to an acute angle, the forearm can be supinated, the grasp is a

little awkward, the arm can be abducted nearly to right angles, and a morsel of biscuit can be carried to the mouth with the affected hand.

August 5 (26th day): Further improvement is shown.

September 25 (77 days after the examination): For some time past the recovery has been complete, the arm being used normally in every way as far as could be ascertained, *i.e.* used in feeding, fighting, and in climbing. Supination appeared to be perfect.

January 16, 1910 (190 days after the examination): Animal collapsed and died.

Post-mortem Examination.

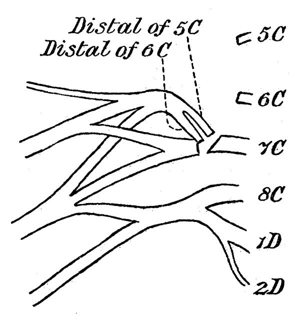
The left brachial plexus presented the ordinary type. The junction of the fifth and sixth cervical nerves was situated about $\frac{1}{4}$ inch from the exit from the intervertebral foramina. The junction of the eighth cervical and first and second dorsal was $\frac{3}{8}$ inch from the vertebræ. On the right side the fifth cervical was found intact, and in the next intervertebral foramen was found the stump of the sixth nerve, presenting a bulbous swelling, and attached to the junction between fifth and sixth nerves by no firm connective tissue, but surrounded by tissue easily dissected off. The turned-down trunk of the sixth nerve was found attached to the seventh and the second section practised at the physiological examination had healed.

The musculature of the right arm showed evidence of the reduction of nerve supply in the lesser bulk of the muscles when contrasted with those of the left arm. Especially the biceps, coraco-brachialis, supinators longus and brevis, brachialis anticus, and deltoid showed wasting, and were paler in colour than the corresponding muscles on the opposite side.

(*b*) Two contiguous roots cut off from their centres and attached to another root.

Experiment III.—*Section of the Anterior Primary Divisions of the Fifth and Sixth and Seventh Cervical Nerves and Suture of the Peripheral Segments of the Three Nerves to the Central Segment of the Seventh Nerve.*

On September 12, 1910, at 10 A.M., in a young male *Macacus rhesus*, the posterior triangle of the neck on the right side was opened up so as to expose the brachial plexus. The junction of the fifth and sixth cervical nerves was found in close apposition to the vertebræ. It was hooked outwards and the two nerves put on the stretch. They were then sectioned close to the vertebræ, and the central segments lacerated by the introduction of a silver plug into each intervertebral foramen. Next, the seventh nerve was divided completely across except the perineurium of one side, at a point proximal to the giving off of the branch to the posterior cord of the plexus.



Stimulation of the distal segments of the fifth and sixth produced contractions of

the deltoid, and of the biceps in each case. The distal segments of the three divided nerves were sutured to the proximal segment of the seventh with horsehair. The wound was then closed and sealed.

At 2 P.M. the monkey was moving about and eating, and it was seen that the arm was held close to the body, and no attempt at abduction could be induced. The elbow was held extended, and no attempt at flexion was noticed. The forearm was pronated, and no supination could be induced. The hand was shut and the wrist flexed, and there were occasional flexion movements of the fingers, and extension of the two distal phalanges of the fingers, but no attempt to extend the fingers at the metacarpo-phalangeal joints.

October 10 (28 days): There is still the loss of abduction of the arm, of flexion of the forearm, of supination of the forearm, and there is only a slight degree of extension of the wrist, but there is marked weakness of the extensors in the forearm, as shown by the inability to extend the fingers. The thumb is particularly affected.

December 12 (91 days): The movements of the hand are not so defective as they were, there being distinct improvement in the power to extend.

December 21 (100 days): Still further improvement in extension of the hand and wrist, and improvement in flexion at the elbow.

January 16, 1911 (126 days): The monkey now makes almost normal use of the hand, and is able to abduct the arm to a considerable degree, enabling him to reach up in climbing, and to reach up to take food offered him. The flexion of the forearm is apparently normal. The extensors of the wrist and fingers are so well recovered that it is difficult to detect anything wrong. It is noticed that he takes food preferably with the left hand, but he then immediately uses the right hand also and carries the food with it independently to the mouth, apparently as freely as with the left hand.

Physiological Examination.

January 20, 1911 (130 days): An incision was made in the neck and over the right shoulder and down to the olecranon, so as to lay bare the posterior triangle of the neck, the deltoid, biceps, and triceps muscles. The brachial plexus was then exposed, and the thickened mass formed by the fifth and sixth joined to the seventh was evidenced by the presence of the horsehair suture at the seat of suture. From this mass it was easy to trace inwards the seventh nerve to its point of emergence from the vertebral column. Below that point two nerve trunks were defined, the eighth cervical and the trunk of the first and second dorsal. Above the seventh there was no nerve visible in the region which normally is crossed by the two upper trunks of the plexus. The following stimulations were carried out.

1st. *The Central Segments of the Fifth and Sixth.*—In the neighbourhood of the intervertebral foramina through which these trunks are transmitted, stimulations gave no contractions in the arm.

2nd. *The Mass Representing the Distal Segments of the Fifth and Sixth and possibly Part of the Distal Segment of the Seventh.*—Stimulation here produced different contractions and different movements according to the point stimulated. Thus at the external part the stimulus produced distinct and strong contraction of the deltoid and some abduction of the arm. More internally a point was found which gave powerful contractions of the biceps and strong flexion of the forearm. Still more internal, a point gave contractions of the triceps and strong extension at the elbow. These different contractions were the result of applying a minimal current to different points on the surface on the same circumference of the mass representing the combined peripheral segments.

3rd. *The Central Segment of the Seventh Nerve.*—Stimulation here gave contractions of the deltoid, and some abduction of the arm, contractions of the biceps and strong flexion of the forearm, contraction of the triceps and extension at the elbow, and extension of the fingers and thumb. These results, as is evident, were not evoked at one and the same time but were the result of applying the electrode to different points on the surface of the trunk.

4th. *The Eighth Cervical and First and Second Dorsal.*—The eighth cervical joined the other trunk lower down than usual. When the faradic current was applied there were no contractions found in the deltoid or in the biceps, but the triceps contracted and the elbow was extended. There was also extension of the hand and adduction at the wrist produced. On examination the upper of the two trunks was seen to be the larger. Stimulation of the lower trunk gave flexion of the fingers and wrist strongly, and stimulation of the upper gave strong extension of the hand and fingers, extension of the forearm and contraction of the triceps. There were no biceps or deltoid contractions. Stimulation in the region of the spinal accessory gave only contractions of the trapezius and elevation of the shoulder. Stimulations with the galvanic current in the various nerves gave the same results. There was good irritability to the faradic current applied directly to the deltoid, the biceps and the triceps. The wound was closed and sealed.

January 26 (6 days after the examination): There has been little disturbance from the examination except that the paralysis of the deltoid and biceps has reappeared, but the hand is not much affected by the manipulation of the nerves.

February 19 (30 days after): The abduction movement is still in abeyance.

February 27 (38 days after): He can feed himself with the hand. There are only trivial abduction movements of the arm. Shoulder is stiff but elbow is all right.

April 24 (94 days): The animal was killed. He had recovered the use of the hand and elbow, but the shoulder was stiff and the movements somewhat limited.

Post-mortem Examination.

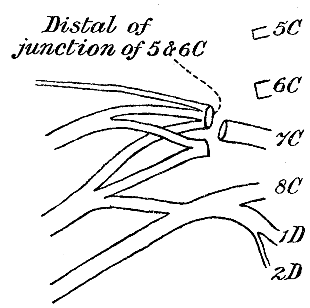
The left brachial plexus was of the usual type. The right plexus showed a mass attached to the seventh trunk containing the horsehair suture. The eighth cervical

and first and second dorsal were normal. The fifth and sixth central ends were not visible.

The muscles of the arm generally presented less bulk than those of the opposite side. Thus the circumferential measurement of the exposed muscles was 6 cm. at the level of the posterior axillary fold, and this compared with 7·5 on the left side. The deltoid also was less bulky. The forearm also was less in bulk than the left forearm. The right at the upper part had a circumference of 6 cm. and this compared with 7 cm. in the case of the left. The atrophy appeared not to be limited to any special group but to be general.

Experiment IV.—*Section of the Anterior Primary Divisions of the Fifth and Sixth and Seventh Cervical Nerves and Suture of the Peripheral Segments of the Three Nerves to the Central Segment of the Seventh Nerve.*

On August 6, 1914, in a large male *Macacus rhesus* the right brachial plexus was exposed and a transsection was made through the junction of the anterior primary divisions of the fifth and sixth cervical nerves at the point at which it subdivides into its branches. The anterior primary division of the seventh nerve was also cut through at a corresponding level. The proximal parts of the fifth and sixth nerves were then again divided as high up as possible and removed. Fully three-quarters of an inch of nerve was removed in each case. The proximal end of the seventh and the distal of the seventh and the branches of the fifth and sixth were all sutured together with a horsehair, which was passed through the respective nerves before the sections were made. Before the nerves were cut they were stimulated with a weak faradic current and gave the following responses:—



Stimulation of the fifth gave contractions of the deltoid and of the biceps, and abduction of the arm and flexion at the elbow joint, and rotation outwards of the arm. The same results were got on stimulating the sixth nerve. On stimulating the seventh nerve at different points on its circumference extension of the elbow was got, and contractions of the triceps felt, and extension of the fingers.

The wound was sutured and sealed with collodion.

August 7 (1 day): The right arm is found hanging flaccid by the side, and there is no power apparently to abduct. The forearm is hanging in a position of slight flexion, but there is apparently no power of making flexion movements. The forearm is kept pronated. It is not possible to get a proper examination of the hand, but the extensors of the fingers appear to be somewhat affected, although not completely paralysed.

August 26 (20 days): Hand is used for grasping. Forearm cannot be flexed at all or supinated. No abduction of the arm can be made. The wound has healed *per primam.*

October 5 (60 days): No change.

October 24 (79 days): It appears as if an improvement has taken place in the flexion of the elbow, as the animal is occasionally seen flexing it, although not so far as a right angle, but ordinarily he lets it hang in the same position as it was immediately after the operation, *i.e.* at maximum extension a position of slight flexion. This is the first day that this has been noticed although the animal has been seen several times since the last note.

October 29 (84 days): The animal now for the first time since the operation takes a biscuit with the affected hand, and flexes the elbow in attempts to carry it to the mouth, but he cannot do so as it cannot be flexed quite to a right angle. He therefore passes the biscuit into the other hand and takes it to the mouth.

November 8 (94 days): Improvement is evident to-day, as the animal can now flex the forearm sufficiently to carry a piece of biscuit to the mouth with the affected hand. Abduction of the arm is still apparently impossible, although evident attempts to do so are seen.

November 28 (114 days): There is further improvement, as there is ability to abduct the arm voluntarily to an extent greater than a right angle, and the use of the hand for raising food to the mouth is quite free.

December 2 (118 days): There is free use of the right arm. The monkey when offered food holds out the affected arm, showing supination, and takes it with the hand and carries the morsel to his mouth in a normal manner, showing also normal range of flexion at the elbow. He uses for this purpose the affected hand rather than the normal hand, because he has been trained to do so by withdrawing the food when he attempts to take it with the normal hand. He grasps the bars of his cage with the affected hand as with his normal hand in order to climb, and in doing so shows his capacity to supinate at least a half of the normal range. When the morsel of food is held up he raises his arm at the shoulder joint to reach it and can do so to a point above the level of his head, and abducts the arm at the shoulder joint more than a right angle in doing so.

Physiological Examination.

December 3 (119 days): Same condition as yesterday.

The right brachial plexus was exposed by the usual incision and a mass was found representing the junction of the nerves. In order to disturb it as little as possible stimulations were made over it with a minimal faradic current before it was further isolated. The result at various points was contraction of the deltoid, biceps, triceps, and slight movements resulting from contractions of these muscles. Further dissection was then made and it was seen that the seventh nerve entered the lower part. Above this was a strand of tissue entering the mass, but higher than that nothing resembling a nerve could be seen in the position of the fifth. Before elevating this trunk and this strand stimulation was made with the faradic current. On the proximal aspect of the mass

the electrode was placed where the fifth nerve ought to have been, but there was no response in the muscles of the arm. Also the strand of tissue which lay in such a position that it might have been the sixth was stimulated repeatedly but no contractions took place in the muscles of the arm.

When the seventh trunk was stimulated vigorous contractions resulted in the arm muscles. These contractions were in the deltoid, biceps, and triceps, and movements of extension of the hand, strong extension of the forearm and flexion of the forearm. This was gradually ascertained by stimulation at different points on the nerve trunk as it was gradually being raised.

Also the results of stimulating the mass at the junction were again noted. This gave contraction of the deltoid and slight abduction of the arm, contractions of the biceps less strong, and feeble flexion of the forearm. At other points on the mass the result was strong contraction of the triceps and strong extension at the elbow joint. At another point extension of the hand resulted. Thus different results were got by minimal stimulation applied at different points of the mass.

The strand of tissue proximal to the mass which lay in the position of the sixth was next carefully stimulated again, and even strong currents failed to cause contraction in muscles. It was removed and the wound was closed and sealed. Examination was then made of the condition of the deltoid and biceps by direct stimulation with the faradic current, using a sharp electrode and thrusting it into the muscle substance. By this method good contractions were obtained in these muscles.

December 4 (1 day after physiological examination): The animal will not come forward for examination but is seen making extension and flexion at the wrist and flexion and extension at the elbow, but does not make abduction of the arm.

December 8 (5 days after): The animal now comes forward and the arm can be voluntarily flexed as well as before the examination, *i.e.*, to an acute angle, and he takes food with the hand but he does not use the hand to carry it to the mouth. No abduction of the arm was seen.

December 9 (6 days after physiological examination): No abduction of the arm seen, but all other movements as before the examination.

December 11 (8 days): Slight abduction of the arm now seen.

December 13 (10 days): Further improvement in the abduction of the arm.

December 15 (12 days): Still further improvement in the abduction of the arm.

December 18 (15 days): Still more abduction. Wound healed by first intention.

December 28 (25 days): Movements of the hand and elbow remain as good as before the examination, but there is less ability to abduct the arm than there was before the physiological examination. The monkey always takes the food offered to him with the affected hand, but helps it up to his mouth with both hands.

Final Physiological Examination.

December 29 (26 days after the first examination and 145 days after the initial operation): The first trunk to be exposed was immediately stimulated. It gave extension of the forearm and supination. It was found ultimately to be the seventh. The deltoid was next exposed by removing the integuments, and by direct faradic stimulation its contractions were good in every part. The biceps was next exposed and it gave good contractions on direct faradic stimulation. The plexus was then fully exposed by detaching the clavicle from the sternum and throwing it outwards, and the integuments were removed from the limb as far down as the wrist. Stimulation was then made with the faradic current.

The seventh cervical in the main gave contractions of the triceps and extension, but other contractions as at the previous examination were got by stimulating at different points of the circumference. A mass was seen at the distal end of the seventh representing the junction between the fifth, sixth, and seventh, and stimulation here gave strong contraction of the deltoid and at one point flexion of the fingers and at another extension of the arm. The suprascapular nerve issuing from the mass gave well marked external rotation of the humerus. Stimulation of the eighth cervical gave strong extension of the elbow, strong pronation, strong flexion of the fingers and hand and internal rotation of the arm.

The left plexus was then similarly exposed and faradic stimulation of the two corresponding parts on the two sides one after the other gave the following results:—

First and second dorsal—

Left.—Contraction of latissimus dorsi, contractions of the flexors of the fingers and flexion of the fingers; contraction of the pronators and pronation; slight contraction of the triceps. *Right.*—The same.

Eighth cervical—

Left.—Strong contractions of the triceps, and strong extension of the elbow; strong contraction of the pronators and strong pronation; contraction of the flexors in the forearm and flexion of the fingers; internal rotation of the arm. *Right.*—The same.

Seventh cervical—

Left.—Internal rotation of the arm and pronation of the forearm; contraction of the flexors of the hand and flexion of the hand; strong contraction of the triceps and extension at the elbow.

Right.—External rotation of the humerus; contraction of the triceps and extension at the elbow; contractions of the flexors in the forearm and flexion of the hand.

Sixth cervical—

Left.—Shoulder pushed forward; contraction of deltoid and abduction of arm; contraction of biceps and strong flexion of the forearm; contraction of the coraco-

brachialis; supination; contraction of extensor muscles in forearm and extension at the wrist.

Fifth cervical—

Left.—Rotation outwards of the arm; contraction of the deltoid and abduction of the arm; contraction of the biceps and flexion at the elbow.

Stimulation of the circumflex on the affected side caused strong contractions of the deltoid and abduction of the arm. Stimulation of the outer head of the median gave strong contractions of the biceps and flexion at the elbow.

The animal was then killed.

Post-mortem Examination.

December 30, 1914: The muscles of the right arm have all a healthy appearance, none showing the pale colour of muscles which have been deprived of their nerve supply.

They appear generally to be less bulky than those of the opposite side, but the biceps and deltoid and supinator longus appear to have suffered most.

The circumference of the middle of the arm was 10·5 cm. as compared with 11·3 cm. in the case of the sound side. In the forearm at the junction of the upper and middle thirds the circumference measured 9·5 cm. on the affected side as compared with 11 cm. on the sound side.

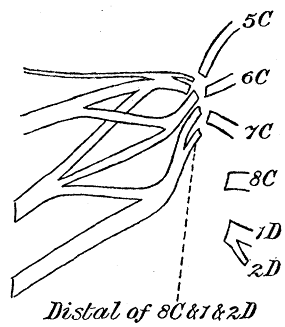
(*c*) Three contiguous roots cut off from their centres and attached to three roots.

Experiment V.—*Section of the Anterior Primary Divisions of the Fifth, Sixth, Seventh, and Eighth Cervical, and First and Second Dorsal Nerves, and Suture of all the Peripheral Segments to the Central Segments of the Fifth, Sixth, and Seventh Nerves.*

On November 6, 1910, in a large female *Macacus rhesus* the right brachial plexus was exposed. The fifth and sixth cervical nerves were stimulated with the faradic current, and the result in both cases was contraction of the deltoid and of muscles on the front of the arm, producing respectively strong movements of abduction of the arm and flexion at the elbow joint. Stimulation of the eighth cervical gave strong extension of the wrist, but when the same trunk was stimulated at another point of its circumference feeble flexion of the wrist was the result. Stimulation of the first and second dorsal produced strong flexion of the wrist.

The anterior primary divisions of the eighth cervical and of the first and second dorsal were then divided as high as possible so as to keep the central ends of these nerves as far away as possible from the seat of suture. The distal ends were then transfixed with a horsehair. Next, the two ends of the horsehair were carried

through the seventh, sixth, and fifth nerves at a distance from each other of about $\frac{1}{4}$ inch. The fifth, sixth, and seventh nerves were then divided each between the two points of transfixion, and the suture being then tied brought the three central ends into contact with the five peripheral ends. The skin was then sutured and sealed with collodion.



After recovery from the anæsthesia there was found to be complete paralysis of all movements of the arm. The limb hung flaccid by the side and the fingers were semiflexed. No movements took place except a slight antero-posterior swinging movement at the shoulder. This state was the same on the evening of the same day.

November 15 (9 days): Nothing noteworthy has occurred until to-day, when it was noticed that the monkey has sustained a burn of the fifth degree over the outer aspect of the wrist and hand, covering an area of the size of a sixpence. This must have been due to the animal while out of her cage having been allowed to place her hand, which was devoid of sensation, in contact with the stove.

December 12 (36 days): Following the burn the animal chewed her fingers and thumb so badly that to-day the hand had to be amputated. No pain was shown while this was being done.

January 14, 1911 (69 days): There appears to be some sensation in the arm, and for the past 14 days the stump has been healing better.

February 19 (105 days): Sensation as shown by needle pricks has distinctly returned in the arm.

March 8 (122 days): No return of motion can be found, but sensation is good.

Physiological Examination.

March 19 (133 days): The plexus was exposed, and the trunks of the fifth, sixth, and seventh were found leading into a mass formed where the junction had been made. The muscles of the limb were exposed, namely, the deltoid, triceps, biceps, scapular muscles, and forearm muscles. They were of healthy appearance, and all gave normal responses on direct stimulation with the faradic current.

Distal to the mass forming the junction a large trunk was seen which on stimulation with the faradic current gave contractions in the deltoid, triceps, and scapular muscles. This trunk was the combined fifth and sixth, and further stimulations of it at other points of its circumference gave contractions in the biceps and brachialis anticus. The supra-scapular was found, and on faradic stimulation it gave contractions of the scapular muscles, and adduction and external rotation of the arm took place.

Faradic stimulations were then carried out on the trunks proximal to the mass at the junction. The fifth gave slight contractions of deltoid, coraco-brachialis, and strong contractions of the scapular muscles, which caused movements at the shoulder

joint. The sixth gave contractions of the scapular muscles, of the triceps, and of the deltoid. The seventh and eighth cervical and first and second dorsal could not be properly defined from each other, but a mass occupying the position of these trunks was stimulated at many points, and contractions of most of the muscles of the limb resulted. Distinct contractions were noted in the biceps, coraco-brachialis, and triceps in consequence of this stimulation. The animal was then killed.

Post-mortem Examination.

The plexus of the left side conformed to the usual type. That of the right side showed that reunion of the eighth cervical and first and second dorsal had taken place, as their central ends could be traced into the common mass. The muscles of the limb had a normal appearance, but were less bulky than those of the opposite limb.

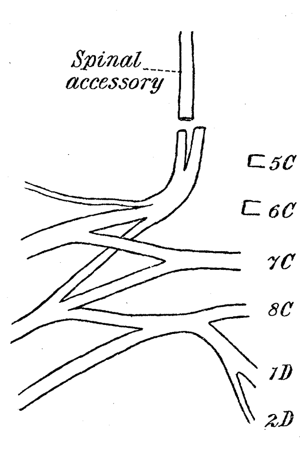
(2) *Experiments in which Attachment was made of the Severed Roots to a Nerve not belonging to the Brachial Plexus.*

(*a*) Two contiguous roots cut off from their centres and attached to the central segment of the nerve not belonging to the plexus.

Experiment VI.—*Section of the Anterior Primary Divisions of the Fifth and Sixth Cervical Nerves and Suture of the Peripheral Segments of these to the Central Segment of the Divided Spinal Accessory.*

On August 27, 1910, in a young male *Macacus rhesus* the posterior triangle of the neck of the right side was laid open, and the spinal accessory nerve found just under the edge of the trapezius. It was stimulated with the faradic current in order to make sure that it was the right nerve, and vigorous contraction of the trapezius was the result.

The fifth and sixth cervical nerves were then found, and the junction of these two was seen to be very close to the vertebræ. The fifth and sixth were cut as close to the vertebræ as possible. A silver wire was then inserted into the two intervertebral foramina, and the two central ends lacerated. The fifth and sixth peripheral segments were then stimulated with the faradic current, and contractions of the deltoid and biceps were evoked in both cases. A horsehair suture was next passed through the two peripheral segments and these adapted to the spinal accessory, which was transfixed with the same suture at a suitable point. The spinal accessory was then cut below the point at which it was transfixed, and when the



suture was tied the two distal segments of the plexus nerves were displaced upwards

away from the position of their central ends and attached to the spinal accessory. The wound was closed and sealed.

After recovery from anæsthesia, examination showed that the arm hung apparently flaccid by the side. There appeared to be no power of abduction of the arm or of flexion at the elbow, or of supination of the forearm, but the hand was seen to be making movements. The arm was held as much extended as is possible in the monkey.

August 29 (2 days): Examination to-day shows that the paralysis is not so extensive as appeared to be the case on the day of operation. The only completely paralysed movement is abduction of the arm. The forearm can be flexed with some difficulty. There is no apparent defect about the movements of the hand, and even some supination of the forearm is being practised. The animal can carry to his mouth with the right hand a morsel of food.

September 18 (22 days): For some time past the only evidence of paralysis is the want of abduction of the arm. This is still absolute. Otherwise the arm is used in feeding, etc., in a quite normal way.

November 6 (71 days): There is still no abduction of the arm and no other apparent defect.

December 12 (107 days): There is now distinct abduction of the arm present, exhibited when the animal is held by the hind legs and when he is attempting to climb the bars of his cage.

December 21 (116 days): The movements of the arm are now all very markedly restored, abduction of the arm being considerably improved. The arm is thinner than the sound arm.

January 16, 1911 (142 days): The animal has now recovered so much abduction of the arm that he can reach up to receive food till the arm is raised through a range greater than a right angle. Otherwise the movements are all apparently normal.

Physiological Examination.

January 18 (144 days). To-day the following examination was made:—

A. *Stimulation of the Spinal Accessory—*

The spinal accessory was exposed in the upper part of the neck in front of the sterno-mastoid and just below the digastric muscle. It was held up and stimulated with a weak faradic current. This produced one outstanding movement, namely, elevation of shoulder. It also produced contractions of sterno-mastoid, and of deltoid.

The incision was then extended downwards so as to lay open the posterior triangle of the neck, and into the arm so as to expose the deltoid muscle, and the nerve was again stimulated at the same point, when the deltoid was seen to undergo contraction.

B. *Stimulation of the Brachial Plexus*—

The plexus having been laid bare, it was seen that the junction with the spinal accessory was marked by the encapsuled horsehair suture. No trace of central segments of the fifth and sixth cervical nerves could be seen, although the intervertebral foramina through which they normally issue were exposed. Below these points the seventh nerve was seen, and further down the combined trunk on the eighth cervical and first and second dorsal. These nerves were stimulated with the faradic in the following way. Before making the observation the incision was extended further down the arm to the elbow so as to expose the biceps and triceps.

1st. *Side of the Vertebræ above the Level of the Seventh Nerve, where the Fifth and Sixth Nerves formerly issued.*—Stimulations at these points gave no contractions of the arm. The only contractions evoked were those of the muscles in the neck which were being directly irritated by the current.

2nd. *The Combined Fifth and Sixth Cervical Distal Segments, where they were turned up to meet the Spinal Accessory.*—Stimulation of this part of the nerves resulted in strong contraction of the deltoid and abduction of the arm, and slight contraction of the biceps and slight flexion at the elbow joint.

3rd. *The Seventh Cervical.*—Stimulation gave strong contraction of the biceps and strong flexion of the forearm.

4th. *The Combined Eighth Cervical and First and Second Dorsal.*—These yielded on stimulation flexion and extension of the wrist and fingers according to the point on the surface of the trunk on which the electrode was laid.

The exposed deltoid was directly stimulated by the faradic current and showed that the entire muscle had recovered its faradic irritability.

The triceps and biceps gave very strong contractions on direct faradic stimulation.

The wound was closed and sealed.

January 26 (8 days after the examination): The wound has healed by first intention. There is no abduction of the arm, and only slight flexion of the arm, but the movements of the hand do not appear to have been affected by the examination.

February 19 (32 days): The hand is used in feeding quite well and abduction of the arm is distinctly present. This has been the condition for some days past. The animal can reach up its arm the height of its head to reach a piece of food, and the arm can be flexed to right angles. There is some stiffness of the joints.

February 27 (40 days after the examination): The movements appear all to be perfect except abduction of the arm, which is not up to the normal standard.

March 18 (59 days): The animal died to-day.

Post-mortem Examination.

The left brachial plexus showed the ordinary arrangement.

The right showed the absence of the fifth and sixth roots.

The spinal accessory was traced down and broke off in the mass formed at the junction through which it was being traced.

This mass joined it to the peripheral segments of the fifth and sixth cervical. The muscles of the arm and forearm were generally less bulky than those of the left corresponding muscles. This was rather more noticeable in the case of the deltoid.

Experiment VII.—*Section of the Anterior Primary Divisions of the Fifth and Sixth Cervical Nerves and Suture of the Peripheral Segments of these to the Central Segment of the Divided Spinal Accessory.*

On August 28, 1910, in a young male *Macacus rhesus*, the same procedure was carried out on the right side as in the previous experiment. In the case of this animal also, the junction between fifth and sixth lay very close to the vertebræ.

Stimulation of the fifth and sixth junction, previous to suturing, produced contractions chiefly in the deltoid, and also in the biceps and in some muscles of the forearm. The spinal accessory was also tested with the faradic current before dealing with it. The suture was of horsehair. The two central ends in the intervertebral foramina were lacerated before closing the wound.

After recovery from anæsthesia it was seen that the arm was in the same position as in the case of the previous experiment, *i.e.*, the arm hung by the side without attempts at abduction being made. The forearm was held in the extended position and was not observed being flexed. The forearm was pronated and the wrist and hand were moved quite normally.

August 29 (1 day): The arm is now seen to be not so extensively paralysed as appeared immediately after the operation. It is kept hanging at the side without abduction movements being made, but there is power to flex at the elbow to a reduced extent, and extension seems quite strong. The flexing is apparently done with some effort. There appears to be some power of supination. The movements of the hand are unaffected, and, when a morsel of food is put into the right hand, it can be carried to the mouth by that hand. The only completely paralysed movement is abduction of the arm.

September 18 (21 days): For some time past the only apparent defect in the arm is the movement of abduction at the shoulder joint, which is never observed to be performed. Otherwise the arm is used normally in feeding. Photographs were secured showing the animal carrying food to its mouth with the affected hand (Plate 24, figs. 6 and 7).

November 6 (70 days): There is no change in the condition since the last note.

November 19 (83 days): There is an apparent recovery of abduction now, and the animal shows the movement distinctly when he is climbing the bars of his cage, especially when he is held by the legs to prevent him succeeding.

December 12 (106 days): Abduction of the arm is now still further developed.

December 21 (115 days): Abduction not quite as good as in the opposite limb.

January 16 (141 days): The monkey holds his arm up to receive food well above the head.

Physiological Examination.

January 19, 1911 (144 days): The following procedure was carried out:—

A. *The Spinal Accessory Nerve*—

This was exposed by an incision in the upper part of the neck, and was reached below the level of the digastric muscle. It was then isolated and stimulated with a weak faradic current. The incision was carried downwards over the posterior triangle of the neck, and over the shoulder and down the arm to the olecranon. Stimulation caused powerful contractions of the trapezius, elevation of the shoulder; contractions of the sterno-mastoid with movements of the head; and contraction of the deltoid, but no abduction of the arm. The deltoid was then uncovered by the removal of the integuments, and also the triceps and biceps were similarly exposed. It was then seen that the deltoid gave distinct contractions when the nerve was stimulated at the same point, the contractions being specially strong at its posterior part, but also taking place throughout the entire muscle. The deltoid was of good development and appearance and colour. There was no abduction of the arm when the deltoid contracted as a result of stimulating this nerve. The biceps gave no evidence of contraction, and there was no movement of the elbow. No contractions other than those mentioned were observed as a result of stimulating the nerve at that point. The galvanic current was then used to stimulate the nerve at the same point, and this time there were produced strong contractions of the deltoid, causing slight but distinct abduction of the arm. The biceps also this time gave slight contractions, and these were accompanied by slight flexion at the elbow and slight supination of the forearm.

Direct irritation of the deltoid produced vigorous contractions both when the faradic and when the galvanic currents were used, and the same result was got in the biceps and in the triceps.

B. *Brachial Plexus*—

Next the seat of suture was carefully exposed and it was seen that the plexus was involved in some new-formed tissue forming a mass between which and the inter-vertebral foramina through which the fifth and sixth normally issue there were no evidences of nerve regeneration. The seventh root was quite easily found and the eighth cervical and trunk of the first and second dorsal also. The following stimulations were done with a weak faradic current:—

1st. *Central Ends of the Fifth and Sixth Trunks.*—The electrode applied to the side of the vertebræ above the level of the seventh trunk at various points covering the situation of the normal points of emergence of the fifth and sixth produced no

movement whatever in the arm, or muscular contractions other than those produced in the neck muscles by the direct irritation.

2nd. *Peripheral Ends of the Fifth and Sixth Trunks.*—When the two trunks of the fifth and sixth were stimulated near the junction with the spinal accessory, which was shown by the horsehair suture, the result was as follows :—

The deltoid showed contractions most evident on the posterior part of the muscle, and therefore very similar to the contractions produced when the spinal accessory was stimulated. There did not appear to be any abduction of the arm produced, but there was very distinct rotation outwards of the humerus. In addition trivial contractions of the biceps were seen, but only very slight flexions of the forearm were produced. Stimulation with the galvanic current gave the same result.

3rd. *The Seventh Nerve.*—On stimulating this nerve with the faradic very trivial contractions of the deltoid were produced. There was moderate contraction of the biceps producing flexion of the forearm. Stimulated at another point on the surface of the nerve the result was contractions of the triceps extensor and extension of the forearm, and contractions of the extensor muscles in the forearm and extension strongly of the wrist. The same results were got when the galvanic current was used.

4th. *Trunks of the Eighth Cervical and First and Second Dorsal.*—When these trunks were stimulated with the faradic current there were contractions of the triceps, and extension of the forearm was produced. There was also strong flexion of the wrist and fingers. The wound was then closed.

January 20 : The animal was found dead this morning.

Post-mortem Examination.

The left plexus was found of the ordinary type.

The right plexus showed the proximal ends of the fifth and sixth roots very cicatricial and there was no evidence of regeneration. The peripheral ends were involved in a mass at the junction with the spinal accessory.

The muscular development of the arm was good, the general wasting of the muscles as compared with the other arm being very slight. This statement also applies to the deltoid.

Experiment VIII.—*Section of the Anterior Primary Divisions of the Fifth and Sixth Cervical Nerves and Suture of the Peripheral Segments of these to the Central Segment of the Divided Spinal Accessory.*

On August 6, 1914, in a young male *Macacus rhesus*, the same procedure was carried out on the right side as in the two preceding experiments. Before dividing the nerves they were stimulated with a weak faradic current. The spinal accessory gave the usual contraction of the trapezius. The fifth cervical, stimulated at various points, gave contractions of the deltoid, causing abduction of the arm, and contractions of the biceps, causing flexion of the forearm, and also a movement of external

rotation of the humerus was obtained. The same contractions and movements were obtained on stimulating similarly the sixth cervical.

August 7 (1 day): The arm is hanging by the side without any abduction being made. The forearm is in the position of maximum extension. No flexion movements can be seen. The movements of the hand appear almost normal.

August 9 (3 days): It is seen that the monkey can flex the forearm to the extent of a right angle in helping food to his mouth.

August 25 (19 days): The animal can put a piece of biscuit to his mouth with the affected hand. There appears to be nothing defective about the movement of the hand. There is good flexion of the forearm, but not so powerful as in the left arm. Supination of the forearm is deficient.

September 2 (27 days): No abduction of arm. Good use of flexors of elbow.

September 9 (34 days): There appears to be an improvement in the supination of the forearm, shown while the animal is feeding himself. There is no abduction of the arm. September 20 (45 days): No further improvement.

September 26 (51 days): The animal died unexpectedly to-day. He had not improved further since the last note.

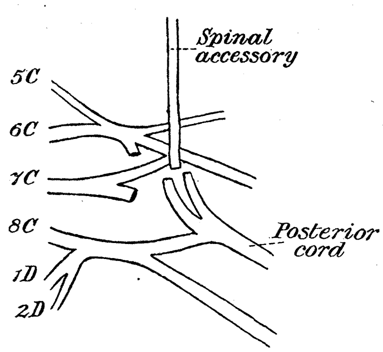
Post-mortem Examination.

There is no apparent reunion of the fifth and sixth cervical nerves. There is a clear and well-formed junction between the spinal accessory and the fifth and sixth cervical nerves. All the muscles of the limb are reduced in bulk as compared with those of the opposite side.

(*b*) Branches of three roots cut off from their centres and attached to the central segment of a nerve not belonging to the plexus.

Experiment IX.—*Section of Two of the Branches which pass to the Posterior Cord of the Brachial Plexus, the one from the Junction between Fifth and Sixth, and the other from the Seventh, and Suture of their Peripheral Ends to the Central Segment of the Divided Spinal Accessory.*

On October 26, 1909, in a small female *Macacus rhesus*, the left brachial plexus having been exposed, the two branches which pass to the posterior cord of the plexus, the one from the junction between fifth and sixth, and the other from the seventh, were cut, and their peripheral ends were united to the spinal accessory, previously divided, the suture being of horsehair. The wound was then closed.



The animal quickly recovered from the anæsthetic, and it was seen that the arm was held flexed at the

elbow. When the forearm was passively extended it was promptly flexed on being released. The arm was also held close to the body, there being an absence of abduction. There was paralysis of the extensor group in the forearm, the wrist being "dropped."

October 27 (1 day): No independent use is being made of the arm.

November 2 (7 days): The animal has distinct supination, but wrist drop is shown. There is loss of voluntary abduction of the arm and of extension at the elbow.

December 8 (43 days): There has been a great improvement since last note, as all the movements may now be said to be performed in a satisfactory way, except abduction of the arm, which has not yet exhibited itself.

December 28 (63 days): The remaining defect, namely, abduction of the arm, has now been recovered very fully, the animal being able to raise her arm well above the head. The arm is now used quite normally.

January 16, 1910 (82 days): As the monkey appeared to be ill it was decided to make an examination at once.

Physiological Examination.

The spinal accessory was exposed in the upper part of the neck anterior to the sterno-mastoid, and stimulated with the faradic current. This caused, in addition to contraction of the sterno-mastoid and contraction in the upper part of the trapezius, also contractions in the extensors, in the forearm, triceps, and deltoid. These movements were not of a very vigorous kind but were quite distinct. When the galvanic current was used the result was the same.

The wound was closed. The animal died the same day.

Post-mortem Examination.

The dissection showed the following arrangement:—

The right brachial plexus showed the ordinary type but the junction between the fifth and sixth roots was exceptionally close to the vertebræ, so that the separate trunks of the two nerves were exceedingly short.

On the left side the spinal accessory was found passing to the junction, at which there was the usual swelling, and to this swelling were attached distally the branches of the plexus. The severed branches had, however, made reunion between their proximal and distal ends.

The biceps of the left arm was almost as bulky as that of the right. There was not much difference in the two deltoids, but the affected triceps was much reduced in bulk, and so also was the supinator longus. The extensors in the forearm were greatly wasted and the flexors slightly. The supinator brevis was diminished in bulk and was paler than normal. The upper part of the trapezius was much thinner than that of the opposite side. The sterno-mastoid was not affected.

3. Tabular Statement of Results.—Experiments on Elimination of One or More Roots of the Brachial Plexus and Restoration by Means of Anastomosis.

No.	Nerves cut.	Central ends destroyed.	Central ends substituted for those destroyed.	Immediate result of section.	Date of commencing recovery.	Date when maximum recovery observed.	Wound.	Days living.	Physiological Examination.
I	Fifth and inner half of seventh cervical	Fifth cervical	Seventh cervical	Loss of abduction of arm. No other defect even at first	Regained power of abduction at 10 days	By 19 days perfect	*Per primam*	263	None made. P.M. Between fifth, sixth and seventh cervical a globular mass represents the fifth nerve turned down. The central end of fifth found with bulb in intervertebral foramen. Deltoid and biceps of two arms practically identical, *i.e.*, no wasting.
II	Sixth and outer half of seventh cervical	Sixth cervical	Seventh cervical	No abduction of arm. Reduced power, but not loss of flexion at elbow. Supination defective. Extensors in forearm weakened but not paralysed	36 days — increased flexion at elbow. 45 days—good power of abduction of arm. Raises arm above head. Feeds himself with the hand	51 days—all the movements regained	Do.	245	At 55 days. No reunion of central end of sixth. The distal sixth again cut and the result is *not* to throw the animal back to its original condition completely, and 17 days later able to abduct arm to right angles. Able to feed himself five days after the examination.
III	Fifth, sixth and seventh cervical	Fifth and sixth cervical	Seventh cervical	No abduction of arm. No flexion at elbow. Supination defective. Extensors in forearm defective. Fingers flexed, and cannot be properly extended	91 days — improved movements of the hand	126 days—normal use of hand, normal flexion of forearm, almost normal abduction of arm. Can use hand to carry food to mouth	Do.	224	Fifth and sixth central ends have not reunited. Stimulation of seventh cervical causes contraction of deltoid, biceps, triceps, abduction of arm, flexion and extension at elbow, and extension of fingers and thumb.
IV	Do.	Do.	Do.	No abduction of arm. No flexion at elbow. Loss of supination. Some awkwardness of movements of extensors of the fingers	79 days—some power of flexion of elbow	118 days—use of limb almost complete. Abduction at shoulder more than right angle. Flexion at elbow quite normal in range. Supination of forearm at least half of normal range	Do.	145	No reunion of fifth and sixth. Stimulation of seventh gives contraction of deltoid, biceps, triceps, extensors in forearm. Elbow extension and elbow flexion at different points. Stimulation of mass at junction, made at different points of mass, causes contractions of deltoid, biceps, triceps, and extensors of hand. This examination at 119 days and final physiological examination confirmed.

V	Fifth, sixth, seventh, eighth cervical, and first and second dorsal	Eighth cervical and first and second dorsal	Fifth, sixth and seventh cervical	Complete paralysis of all movements of the arm and of sensation	69 days—apparently some sensation	Sensation present, but no recovery of motion.	Do.	133	Eighth cervical and first and second dorsal had formed reunion with the junction. Conductivity of the nerves regained.
VI	Fifth and sixth cervical and spinal accessory	Fifth and sixth cervical	Spinal accessory	Loss of abduction of arm. Weakened power of flexion of forearm. Hand can be put to mouth. Some loss of supination	107 days — distinct abduction of arm, and strong flexion at elbow	142 days—the arm appears normal. It is not easy to detect any defect. Can raise arm more than right angle, but perhaps not so powerfully as in case of other arm.	Do.	203	No reunion of fifth and sixth centrals. Spinal accessory stimulated gives contractions in the deltoid muscle.
VII	Do.	Do.	Do.	Loss of abduction of arm. Weakened power of flexion of forearm. Hand can be put to mouth. Some loss of supination	83 days — abduction of arm evident	115 days—little apparent defect in the movements of the arm.	Do.	144	No reunion of fifth and sixth central. Stimulation of spinal accessory causes contractions in deltoid, and abduction of arm and contractions of biceps, and the movements of flexion at the elbow and of supination take place.
VIII	Do.	Do.	Do.	Loss of abduction of arm. Weakened flexion of forearm. Supination defective	—	No recovery . . .	Do.	51	None. P.M. No reunion of fifth and sixth central ends.
IX	Branches of fifth and sixth and seventh cervical and the spinal accessory	Branches of fifth and sixth and seventh cervical	Do.	Loss of abduction of arm. Loss of voluntary extension at elbow. Wrist-drop, but extensors in forearm not quite paralysed. Flexion of forearm present. Some supination	43 days—weakness of extensors in forearm disappeared	63 days—all the defects recovered from. Able to extend at elbow and abduct arm.	Do.	82	Stimulation of spinal accessory gives contraction of deltoid, triceps, and extensors in forearm. It was found at P.M. that the central ends of the branches intended to be eliminated had reunited.

4. Comparison of the Results of the Various Experiments.

(1) *The Different Forms of Experiment.*

The procedure carried out in the nine experiments was varied in six different ways. They all agreed in the fact that a particular nerve or particular nerves had connection with the central nervous system severed, and attachment of the peripheral end or ends made to a neighbouring nerve or to neighbouring nerves. There were two groups of the experiments, namely, those in which attachment was made of the severed root or roots to another root or to other roots of the brachial plexus, and those in which attachment was made to a nerve not belonging to the brachial plexus, namely, the spinal accessory. Thus, in the former case, in any restoration which took place the muscles were still innervated through the cells appropriate to the plexus, whereas in the latter case the function had to be restored through cells not by nature related to the brachial plexus. To the first group belong Experiments I, II, III, IV, and V, and to the second, Experiments VI, VII, VIII, and IX.

The experiments varied again in the number of roots detached from the cord. In two one entire root only was thus severed, namely, Experiment I, in which the fifth was prevented from reuniting, and Experiment II, in which the sixth was the one affected. In these cases the nerve cut off from its centres was inserted into the seventh. In all the other experiments more than one root was cut and prevented from reuniting.

In Experiments III and IV the same procedure was done, namely, to divide the fifth, sixth, and seventh, prevent reunion of the central ends of the fifth and sixth, and attach the peripheral ends of all three to the central end of the seventh. In Experiment V all the roots of the plexus were cut, and the central ends of the eighth cervical and of the first and second dorsal left ununited, and the peripheral ends of all the roots joined to the central ends of the fifth, sixth, and seventh cervical nerves.

In the second group of experiments, in which the spinal accessory formed the central segment of the composite nerve, three of the experiments corresponded exactly, the peripheral segments being those of the fifth and sixth cervical nerves, namely, Experiments VI, VII, and VIII. In Experiment IX the peripheral nerve segments were the branch to the posterior cord of the plexus from the fifth and sixth and the branch to the posterior cord from the seventh.

(2) *The Immediate Results of the Nerve Sections.*

In Experiment I, where only the fifth root had been cut and a partial cut made in the seventh, the only movement apparently completely paralysed was abduction of the arm, and this only lasted for a short time.

In Experiment II, where only the sixth had been cut and a partial cut made in the seventh, the paralysis was more extensive, in proportion in a measure to the larger bulk of the sixth as compared with the fifth. Here the most marked loss was abduction of the arm, which could not be performed. In addition there was reduced

power of flexing the elbow, but this movement was not altogether lost. In addition it was noticed that there was defective supination.

The next most destructive operation on the plexus is found in Experiments VI, VII, and VIII, in which the fifth and sixth roots were cut for anastomosis to the spinal accessory. In all there was complete loss of abduction of the arm. In all there was loss of flexion at the elbow joint, but in none was this complete from the first, there being some power of voluntary flexion. Supination of the forearm also was defective in all.

Still more destruction was produced by the initial lesion in Experiments III and IV, where the fifth and sixth and seventh roots were divided. In both of these animals the same defects manifested themselves, loss of abduction of the arm, loss of flexion at the elbow, loss of or defective supination, and interference with the proper action of the extensor muscles in the forearm so as to cause a greater or lesser degree of awkwardness of movements of the fingers and hand.

The most destructive lesion was in Experiment V, where all the roots of the plexus were severed, and in that animal there was complete paralysis of all the movements of the arm.

In the case of Experiment IX, in which the branches to the posterior cord of the plexus from the fifth and sixth and seventh were cut, this produced loss of abduction of the arm, loss of extension of the elbow, and wrist drop as the most pronounced defects. The arm was held flexed at the elbow, owing to the flexors of the elbow being active while the triceps was paralysed.

(3) *The Earliest Sign of Recovery.*

The earliest sign of recovery from the defects shown immediately after the experimental lesion varied very considerably in the different experiments, the earliest being 10 days and the latest 107 days. On examination, however, it is seen that in a general way the dates are capable of being arranged into two groups, namely, one in which only a single root was divided, *i.e.* either the fifth (Experiment I) or the sixth (Experiment II), where the recovery started in 10 days and 36 days respectively, and one in which two or more roots were divided at the initial lesion, in which the earliest sign of restoration of movements appeared at a very much later period, namely, from 79 to 107 days. Of these there were the two groups, one where another part of the brachial plexus was made to act as the central segment, and in which the earliest sign of recovery of movements appeared at 79 and 91 days respectively (Experiments IV and III), and the other in which the spinal accessory was intended to supply that function, in which the earliest improvement occurred at 83 and 107 days respectively (Experiments VII and VI).

In the remaining two experiments, in which recovery of function occurred, the course of events was different. Thus in Experiment V, in which the entire plexus was cut, the only evidence of restoration of function consisted in a return of sensation

at 69 days, and in Experiment IX, where the branches of the roots were concerned, the earliest sign of returning voluntary movements occurred at 43 days.

(4) *The Maximum Result.*

There are two observations under this heading: first, the time at which the greatest degree of recovery was approximately attained, and second, the exact amount of recovery which this maximum result represented. These are best considered together.

As regards the length of time which had to elapse before the best result was attained, it was found that the date at which recovery commenced gave a very good index as to this. When recovery commenced early, the further improvement advanced rapidly, and the best result was soon attained. Thus in Experiment I, where recovery commenced at 10 days, it was only a few days until the amount of abduction of the arm, the only defect in the arm, had apparently made its complete recovery (Plate 23, figs. 1 and 2). As regards the degree of this recovery, it appeared to be as perfect as before the experiment, at least as regards range of movement, and so continued till the death of the animal at 263 days after the operation. In the case of Experiment II, again, where only 36 days elapsed before recovery commenced, it was only 15 days more, or 51 days from the commencement of the experiment, until the maximum or nearly the maximum recovery was attained. In this case also the amount of recovery left nothing to be desired (Plates 23, 24, figs. 3, 4, 5), as the animal appeared to use the limb as freely and as well as before the operation, all the movements lost or impaired having, at least as regards range of movement, been regained. In this animal also this recovery held good till its death 245 days after the operation. This, then, was the case when only one root had been divided and attached to the seventh.

In the experiments where two roots had been divided and their distal segments anastomosed to the seventh, the most notable difference from those in which only one was cut was, like the delay in commencing recovery, the delay in the recovery reaching its maximum extent. Thus in Experiment III the time required for this was prolonged to 126 days and in Experiment IV to 118 days, following the commencement of recovery at 91 and 79 days respectively. The degree of recovery also, although almost complete, could not be regarded as perfect or as so complete as in the case where only one root had been divided. The animals could certainly abduct their arms above the level of the head, and flex the elbows more than a right angle or normally, but the supination at least in one of the animals was not so completely restored, although it was sufficient to enable the animal to use the hand freely in feeding and in climbing.

When the same two roots (fifth and sixth) had been divided and anastomosed to the spinal accessory, the time necessary to get the maximum degree of restoration was in one case a little longer than when the attachment of the same two roots was made

to the seventh cervical, but in the other case about the same time. Thus in the two experiments in which the animals lived long enough to show this (Experiments VI and VII), this was reached on the 142nd and 115th day respectively. The delay in one of the experiments corresponded to the slightly later first appearance of improvement which that experiment exhibited. As regards the amount of recovery which took place in the two cases, it was not less than when the source of the new supply to the divided roots was another part of the plexus. Thus in both cases the power of abduction of the arm was so well recovered that the animals could hold up their arms well above the head, and the other affected movements were practically perfect, at least as far as regards range of movement.

In the special case of Experiment IX, the maximum amount of improvement was attained at 63 days, *i.e.* 20 days after the recovery commenced.

On comparing the time in the different experiments required for the development of the recovery from its commencement to a degree that was fairly complete, it is seen that there is a similarity between most of the experiments, with a marked difference in the case of the two in which one root only was cut. The following Table exhibits these results.

Number of experiment.	Roots divided.	Nerves to which distal segment or segments anastomosed.	Days elapsed till recovery showed sign of commencing.	Days elapsed from commencement of recovery till maximum result attained approximately.
I	5 C and ½7 C	7 C	10	A few days.
II	6 C and ½7 C	7 C	36	15
III	5 C, 6 C, 7 C	7 C	91	35
IV	5 C, 6 C, 7 C	7 C	79	39
VI	5 C, 6 C	Spinal accessory	107	35
VII	5 C, 6 C	,, ,,	83	32
IX	Branches of 5 C, 6 C, and 7 C	,, ,,	43	20

It is seen from this Table that the time required for the development of the recovery, once it had started, was about the same in the experiments, excluding the two in which only the one entire root was cut, and Experiment IX.

(5) *The Physiological Examination.*

An examination by stimulating the exposed nerves before the death of the animal was made in all except in the case of two in which the death of the animal occurred unexpectedly. In the case of the latter a *post-mortem* examination showed that there was no anatomical evidence of the reunion of the nerve or nerves which it was the object of the experiment to eliminate (Experiments I and VIII). In addition to these there was one experiment (Experiment IX) in which only a partial examination was able to be carried out, before the animal died. It was not therefore examined to settle the point whether any reunion of the nerves intended to be eliminated had taken

place, and on the day following, when the animal died, the *post-mortem* examination showed that there was evidence of anatomical reunion of the nerves which were intended to have remained ununited, so that the experiment was vitiated.

In all the other six experiments a complete examination was carried out, and the results showed that in five of these the nerve or nerves which were intended to be isolated had remained so, as on stimulating the central ends no contractions of any muscles in the arm occurred. In the remaining case (Experiment V) it was otherwise, as the examination showed that connections had been formed from the central ends, which were supposed to have been isolated, which on stimulation caused contractions to take place in muscles in the arm. This experiment was therefore vitiated. In the five experiments in which the conditions were proved to have been maintained throughout the experiment, as was intended, *i.e.* the central stumps intended to be eliminated remaining without connection to the anastomotic junction, further stimulation was made to ascertain the function fulfilled by the substituted central segment. In Experiment II stimulation of the seventh root above the point of insertion of the sixth, in addition to extension of the elbow joint, gave contractions of the deltoid and biceps, and stimulation of the peripheral segment of the sixth nerve caused contractions of the deltoid and biceps and triceps. The sixth was severed from the seventh and left in position, and, although the animal had not the same power of movement in the limb on the following day, yet recovery made rapid headway, and in about 17 days much of the loss due to the examination had been regained.

In Experiments III and IV the results of stimulation of the seventh were noted, and they showed a similarity in the two experiments. This gave in each case contraction of the deltoid, biceps, triceps, extension of the hand (IV) or fingers (III), according to the point of the nerve trunk which was touched by the electrode conveying a minimal current.

In the case of Experiments VI and VII, the first part of the examination consisted of exposing the spinal accessory well away from the seat of anastomosis to the plexus. It was therefore exposed in front of the sterno-mastoid, just below the level of the digastric. Stimulation caused in both cases contraction of the deltoid, which in one (Experiment VII) could be made strong enough to cause abduction of the arm, but in the other the contractions were not strong enough to do this. In addition, it was ascertained in Experiment VII that the biceps contracted under the same stimulation, causing some flexion and supination of the forearm. In addition to these contractions in muscles not normally belonging to the distribution of the spinal accessory, there were produced contractions of muscles normally supplied by that nerve, namely, the sterno-mastoid and part of the trapezius, showing that connections had been re-established with the trapezius.

In Experiment IX, in which the *post-mortem* examination rendered it probable that reunion had taken place in the brachial plexus, stimulation of the spinal

accessory in the anterior triangle of the neck, as in the other experiments of this type, caused in addition to contraction of muscles in the normal distribution of that nerve, also distinct contractions in the arm, causing contractions in the triceps and deltoid, and contractions in the extensors in the forearm.

5. General Considerations.

(1) *Methods of Observation.*

As regards the initial operation in the experiments, it is unnecessary to describe the technique which has been employed in order to secure the healing of the wound without infection, but in all such procedures, unless this is secured, any conclusion to be drawn from such experiment or operation must necessarily be liable to fallacy, as undue delays in restitution of function are most likely to be thereby caused, if indeed entire failure is not the result. In all these experiments the wounds have healed by first intention and the results have, therefore, been free from interference as far as this is concerned. On account of the fineness of the nerves it was found that the finest catgut procurable was too thick for the nerves, and therefore, in the majority of the experiments, horsehair was used and was found to serve the purpose admirably. At the examination it was found encapsuled at the seat of suture and was very useful in drawing attention at once to the exact situation of the anastomosis.

As regards the precautions taken to prevent reunion of the central ends, which were required to be eliminated, in some of the experiments for this purpose a silver wire plug was driven into the intervertebral foramina in order to lacerate the nerve, but in others this was not done and it was merely seen that a considerable gap separated the end of the central segment and the anastomotic junction. As a rule this sufficed, as in only two of the experiments had these precautions failed.

As soon as possible after the initial operation, a record was made of the nature of the paralysis resulting from the procedure. As a rule the amount of paralysis resulting was less than was expected to follow the lesion. The animals were then watched from day to day and any progress recorded. This was easier done in the animals which were tame, as they came forward to the front of the cage and allowed examinations to be made more easily. In all, however, observations were made either by offering food and thus inducing the desired movements, or, if that method failed, then by inducing movements of defence by endeavouring to capture the animal, with a noose. In almost all it was possible to train the animal when offered it, to take food with the affected hand instead of with the sound hand, by withdrawing it unless this was done. In this way information as to the progress was more easily obtained.

When recovery appeared to have reached its full extent a physiological examination was made except when this was prevented by the unexpected death of the animal. At this physiological examination the first procedure, when the brachial plexus was about to be exposed, was to apply a faradic stimulus to the central ends of the roots

which had been cut and kept ununited, when these stumps could be found, or in any case to the situation in which these stumps would have been expected in the event of them not showing their presence. This early stimulation was done in order to avoid any danger of cutting or stretching any communications which might have been formed, in which case their conductivity might have been destroyed, and they might thus have escaped detection. This is a very important part of the proceedings, as it is essential for every experiment to prove that any recovery which has taken place could not have been the result of a restoration of the old paths. After this had been done and the results recorded, restimulation was made at various stages of the exposure in order to make sure of the proper stimulation of these central ends. By means of this method only one failure was detected out of the six in which this investigation was carried out.

The next point to be ascertained was whether the trunk substituted for the eliminated central ends gave on stimulation contractions of the muscles normally supplied by the eliminated central ends. This trunk also was stimulated at the earliest point of the examination in order to avoid interference with the conductivity through cutting or stretching. On ascertaining and noting the resulting movements of the limb, further investigations were then made either at the same examination or in one case at a subsequent examination. In either case the muscles were exposed in the entire limb and the muscles which contracted on stimulation of the various nerves noted. In one case both plexuses were exposed simultaneously and the results of stimulation on the two sides compared.

In some cases the animals were allowed to live after the physiological examination in order to find out the effects of this on the recovered function.

A *post-mortem* examination was also always made in order to confirm by careful dissection the arrangement and distribution of the nerves. The muscles were also dissected out in order to ascertain the amount of wasting which they presented as compared with those of the other limb.

(2) *Comparison of Dates and Extent of Recovery with those of Experiments published in Parts I and II of this Research.*

As already pointed out the recoveries here recorded are capable of being divided into three groups: first, where it has commenced very early and progressed very quickly to an approximately normal degree, namely, 10 and 36 days respectively; second, where it came on a little later, namely, 43 days; and third, where it came on later still, namely, from 79 to 107 days. Following these commencements, the corresponding dates for a maximum result were as follow: first, where the earliest commencement occurred the maximum improvement followed in from a few days to 15 days; second, where motion commenced to be regained at 43 days this stage was reached 20 days later; third, when recovery did not commence till a date varying from 79 to 107 days the maximum result did not occur till the end of

115–142 days. The following Table shows these results along with similar results taken from the experiments recorded in the two preceding parts of this paper. The two experiments in which very early recovery occurred are placed by themselves, and also the experiment in which recovery commenced at 43 days.

Nature of the experiments.	Number of days which elapsed after operation before recovery commenced.	Number of days which elapsed after operation before recovery satisfactory.	Number of days during which this recovery was apparently progressing.
Anastomosis of the facial nerve to the spinal accessory or to the hypoglossal. Part I.	58	100	42
	32*	90	58
	105	116	11
	90	113	23
	45*	132	87
	84	107	23
Average . . .	69	110	41
Anastomosis of the limb nerves below the plexus in the dog. Part II.	96	126	30
	93	123	30
	81		
	59	79	20
Average . . .	82	109	27
Anastomosis in the brachial plexus, excluding experiments where function returned very early. Part III.	107	142	35
	83	115	32
	91	126	35
	79	118	39
Average . . .	90	125	35
Two plexuses where less than two roots were divided and where early recovery occurred.	10	19	9
	36	51	15
One where reunion vitiated the experiment.	43	63	20

(3) *Conclusions as to the Cause of Recovery of Function.*

As a result of comparison of the three sets of experiments it is seen that there is a correspondence between the dates of commencing recovery and of the development of that recovery to the stage at which it may be regarded as having reached its maximum, which has in every case amounted to a satisfactory recovery of the lost function. The correspondence in the dates of commencing recovery in the case of the experiments on the facial nerve with the other two sets would have been still

greater had it not been for two of the experiments, marked in the Table with an asterisk, which are recorded as having commenced at 32 and 45 days respectively. These are much earlier than the others, and it is possible that they are too early, as in the case of recovery after section of the facial nerve it is most difficult to determine accurately the date of commencing recovery. Commencing recovery in that case is judged from recovery of the orbicularis palpebrarum, and long before this develops there are reflex closures of the eye to a certain extent, which are brought about by causes other than restoration of the orbicularis palpebrarum (*vide* Part I), which make therefore the determination of real recovery through the facial nerve a matter of difficulty, and there is a possibility of error. If, then, these two cases be wholly excluded, the average becomes not 69, but 84 days, which very closely corresponds with the others.

The contrast with the experiments on the brachial plexus, where only one root was divided, is very marked, for in these cases the recoveries commenced very much earlier than in all the other experiments, excluding the cases of facial anastomosis just referred to. Also the date when the maximum result was attained was very much earlier than in any of the other recorded results. It may, therefore, be concluded that the cause of the recoveries in the two experiments was different from that in the others. In the case of the others the nerve sections performed resulted in paralysis in groups of muscles of an abiding nature of such a kind that restoration could result only from a re-establishment of the nerve supply of the affected muscles. This could be possibly brought about either by reunion of the cut nerves, or through the nerve to which the peripheral ends had been anastomosed. The physiological and *post-mortem* examinations showed in each case that the former was not the case, and, therefore, the latter must be held to have been the cause.

In the experiments, however, where early recovery took place only one entire root was divided, and although in one case examined at a later period it was shown that connections had been made through the seventh root, the recoveries recorded are too early for it to be held that these anastomotic connections were the cause of it or even indeed contributed to it, for the recovery took place before the anastomosis could have been effectively established. This is particularly the case where the fifth cervical root was the one divided, as the date given for maximum result of 19 days is clearly not sufficient for such a recovery through nerve anastomosis or indeed through reunion of a divided nerve. It is evident therefore that when the single root was divided, merely a transient paralysis was produced which in a few days was recovered from. It has been noticed in some of the experiments in which the animal has been allowed to live after the physiological examination, that although no nerves were cut a certain amount of paralysis resulted which soon passed off, so that it is probable that the handling of the plexus in exposing it may in itself produce a transient paralysis or paresis which is recovered from in a few days.

SHERRINGTON (15, p. 125) found that "monkeys in which the fifth, sixth, eighth and

first roots were singly in different individuals severed and allowed to degenerate displayed no obvious impairment of the movements of the limb, either immediately after the operation or when the operation wound had healed." This is more than can be said in the two experiments of my series which involved the division of one entire root only, namely the fifth and the sixth, as paralysis was exhibited in both, lasting for an appreciable time, namely, when the fifth was cut till the lapse of 10 days, and when the sixth was cut not commencing to recover for 36 days, but in neither was this the only lesion, as in both the seventh root was also cut half through in order to permit of an efficient anastomosis. The sixth root was in every experiment considerably thicker than the fifth, and therefore from this point of view it might have been expected that more abiding results would follow its section. Apart from that, however, a difference in the two experiments which may have contributed to making the paralysis more severe when the sixth was divided was that the seventh in the former was divided on its inner half and in the latter on its outer half. When, therefore, the section of one and a half roots was made in such a way that the sections were contiguous the result may have been more severe than when one and a half uninjured roots intervened between the sectioned fifth and the hemisection of the seventh. It is clear, therefore, that the recovery in these two experiments was not due to the anastomosis, but to the multiple supply of the affected muscles, enabling these muscles to continue to function. This is further explained by the work of FORGUE and LANNEGRÂCE (4), who showed that each muscle which was under the supply of more than one root received that supply in such a way that the separate roots did not supply separate sections of the muscle but that the supply of each root was uniformly distributed. They state that "dans tout muscle les fibres tributaires de la même racine sont disseminées dans l'épaisseur de l'organe et non cantonnées dans une zone spéciale." They showed also that on stimulation of a root a complete contraction and not a partial one is caused in the muscle and that on sectioning a root of the plexus it is found that in the muscles innervated by it, degenerated fibres are found scattered among sound nerve fibres throughout the muscle. These observations then give the explanation of recoveries which take place after section of a single root or less than two as in Experiments I and II, at a date too early to be adequately explained as a restoration through the nerve. The temporary paralysis may be a mere inhibition of the voluntary power, following upon the exposure and handling of the plexus.

It is obvious therefore that in forming any conclusion as to the cause of a recovery following an operation of anastomosis in the case of the brachial plexus, it is very necessary clearly to understand the distribution of the roots of the plexus and to take these into consideration. It is, therefore, necessary to consider the different views which have been put forward as to the distribution of the roots of the plexus.

(4) *Previous Investigations on the Distribution of the Nerve Fibres of the Roots of the Plexus.*

Following the earlier inquiries into the functions of the plexus in rabbits and in man, for an account of which reference may be made to SHERRINGTON (10), the more recent investigations fall into three groups, namely, the experimental, the anatomical, and the clinical. The experimental method consists of stimulation of the roots of the plexus by the faradic current, and observation of the resulting movements or contractions in the exposed muscles, and of section of one or more roots and observation of the resulting paralyses and ultimately of the degenerated fibres in the muscles. This is the method by which FERRIER and YEO (1, 2) investigated the plexus in the monkey, the results of which were published in 1881. Also SHERRINGTON (15) employed this method in the same animal.

The anatomical method consists of dissecting out the bundles of the nerve fibres running in the nerve trunks, and these may be traced from the muscles up through the plexus. These dissections have been made in the human subject and consequently are specially important in respect of enabling comparison to be made between the plexus of man and that of the monkey, from the latter of which the evidence by stimulation has for the most part hitherto been obtained. HERRINGHAM (6) published in 1886 the results of his dissections, and BOLK (16) in 1898 made an important investigation by the same method. FORGUE and LANNEGRÂCE (3, 4) in 1884, and HARRIS (21, 22) in 1904, published results obtained partly by the one, and partly by the other method.

Clinical observation forms a third source from which valuable information has been derived. There are different ways in which information may be obtained from this source. Thus the results of injuries of the spine causing paralysis of the spinal nerves have enabled THORBURN (7, 8, 9), KOCHER (14), and others, to make contributions to the subject. The disadvantage, however, here is that this does not necessarily give a correct estimate of the localisation of function in the roots of the plexus, as fibres derived from cells in the cord do not necessarily leave the cord at the level of these cells.

In another class of cases, however, namely, lesions of the plexus itself, valuable information has recently been obtained due to surgical treatment in such lesions. Thus it is necessary for the proper management of these operations to ascertain the condition of the affected roots by stimulation, and the information obtained in the course of these examinations is of physiological value. Another source of information obtained at these operations is that the situation of the lesion is revealed when the plexus is exposed for operation. Information obtained during stimulation suffers, however, from the defect that only the movements produced and the contractions of such muscles as can be felt by palpation to contract can be ascertained at these examinations. HARRIS has made observations by this method, and these are incorporated in his results obtained by other methods.

In making a comparison of the results of the various investigators this can be done by comparing the lists which they have prepared showing the various muscles to which the different roots of the plexus are distributed. FERRIER and YEO describe specially the movements of the limb caused on stimulation, but in addition enumerate the chief muscles contracting. SHERRINGTON describes for each muscle, whether it contracted regularly or occasionally on stimulation of the root, and also noted whether degenerated fibres were found regularly or occasionally in the muscle after section of the root, and in some these were found although the muscle gave no response on stimulation. HARRIS again gives two lists of muscles, as he holds that there is such a variation in different plexuses as to justify a separate description of the two extremes, the one the prefixed type, and the other the postfixed. All the others have given only one table, some indicating slight variations.

On comparing, then, the results of FERRIER and YEO, FORGUE and LANNEGRÂCE, HERRINGHAM, SHERRINGTON, and BOLK, it is seen that there is a very great agreement in their findings, but when these are compared with the results of HARRIS it is seen that there are important differences, a few of which may be enumerated. In the first place the lists of the various authors bring out the multiple supply of each muscle from more than one root, but in this respect the results of HARRIS give some important muscles as exceptions to this rule. The representation of the deltoid is put by all in the fifth and sixth cervical, only FORGUE and LANNEGRÂCE and SHERRINGTON enumerate the seventh as either occasionally or partially supplying the muscle. HARRIS, however, in his prefixed type puts the deltoid fibres in the fourth and fifth, and in his postfixed type entirely in the fifth. In the case of the biceps and brachialis anticus these are placed by all in the same roots as supply the deltoid, the seventh again participating according to FORGUE and LANNEGRÂCE and to SHERRINGTON. With this localisation HARRIS agrees, as far as concerns his postfixed type, but in the case of his prefixed type he places them entirely in the fifth. As regards the supply of the supraspinatus it is placed by HARRIS in the same position as the deltoid, again in his postfixed type a single root supplying the muscle. BOLK attributes this muscle to the fourth and fifth, but none of the others place it so far forward as the fourth. In the case of the external rotators, infraspinatus and teres minor, the identical supply is given for the two, these muscles, according to HARRIS, being under the control of a single root of the plexus, namely, the fifth, in the case of his postfixed type. HERRINGHAM, SHERRINGTON, and BOLK place them in the fifth and sixth, HERRINGHAM noting the sixth as an occasional contributor, and SHERRINGTON adding also the seventh root to the supply. As regards the supinator brevis in his postfixed plexus, HARRIS places it in the fifth and sixth, agreeing with FERRIER and YEO, and with SHERRINGTON and BOLK, who have also referred the seventh to the supply of this muscle, the former giving the chief supply to the sixth. HARRIS, however, in his prefixed type of plexus places the supply of this muscle entirely in the fifth.

The triceps is quite differently treated in HARRIS's tables than in any others. As regards this muscle all others have placed it in the seventh and eighth, SHERRINGTON and BOLK placing it in the sixth also, and FERRIER and YEO and SHERRINGTON in the first dorsal also. HARRIS has, however, placed it in his postfixed type in the sixth and seventh, and in his prefixed type in the fifth, sixth, and seventh.

In other respects the tables of HARRIS do not so materially differ from those of others. His chief difference is thus in his estimate of the fifth and sixth. To the fifth or fifth and fourth he attributes in a prefixed type of plexus 13 muscles, and even in the postfixed plexus the fifth is the sole supply of the deltoid, teres minor, supraspinatus, infraspinatus, rhomboids, and subclavius. The fifth is thus given an importance which no other author has accorded it. These results, however, refer to man and not to the monkey, for in a paper published jointly with LOW (19) it is stated "Experimental stimulation also of the fifth root (anterior division) in *rhesus* produced well-marked contractions in both parts of the deltoid and biceps, infraspinatus, supinator longus and brevis, and in the extensor carpi radialis longior. All these muscles contracted on stimulation of the sixth root also, but for certain reasons we consider the brachial plexus in man in its upper portion to be prefixed nearly a whole root as compared with *Macacus rhesus*, and less for its lower portion." It may, therefore, be taken from this that the differences in HARRIS's localisation do not refer to the case of Macacus but to the human plexus. In the investigations which have been compared, however, there are two sets of observations, namely, those of HERRINGHAM and those of BOLK, both of which refer to the human plexus. With reference to his view quoted above as to the extent to which the plexus in man is prefixed as compared with that of Macacus it is found that his localisation of the muscles in the lower roots agrees more closely with that of others. Thus the flexores sublimis and profundus digitorum are supplied, according to him, through the eighth cervical and first dorsal, and this agrees with all the others, SHERRINGTON attributing it also to the second dorsal, and all excepting FERRIER and YEO finding them represented in the sixth also. Thus instead of placing these muscles higher he places them lower than do the majority of other investigators.

HARRIS and LOW (19) refer to a case published by MARKOE (5) in 1885, which "clearly proves that in man the deltoid, spinati, biceps, and brachialis anticus derive their whole motor supply from the fifth cervical root." This case was one in which there was loss of power to abduct the arm or to flex the forearm, and limitation of supination, following an accidental wound in the neck. The deltoid, supra- and infraspinati underwent atrophy, and the biceps and brachialis anticus to a lesser extent. The parts were exposed by operation and extensive cicatricial tissue found. The fifth nerve was isolated above the scar, and traced down to the plexus. The scar was cut out and the nerve drawn together. He states that the proximal end was small in comparison to the distal. Improvement followed this operation, flexion of the forearm and abduction of the arm being regained.

In this case, although the fifth root was found divided and was sutured, there was scar tissue also found and there is no proof that this had not involved the sixth nerve also, which might recover after its removal. Also the fact that the central end of the fifth was found small in comparison with the distal end throws doubt on the accuracy of the observation, as central ends of ununited nerves are not less in thickness than their peripheral ends, but if there is any difference it is in the opposite direction.

The more important features of the plexus made out by the investigations already mentioned are as follow.

The great majority of the muscles supplied through the brachial plexus are supplied by several roots. This was pointed out by FORGUE and LANNEGRÂCE. SHERRINGTON also, as already mentioned, calls attention to the absence of paralysis on sectioning the fifth or sixth or eighth cervical or first dorsal, and he also states that in one monkey with only the eighth and fifth left intact the "impairment of the limb was not very great." This is due to the participation of so many segments in the supply of each muscle. The same overlapping was shown by SHERRINGTON (13) to occur in the case of the sensory nerves. Thus he says that in root territories in the skin "in some cases so many as seven posterior roots above and below had to be severed." The motor supply is thus of the same nature as far as overlapping is concerned.

A second important point with reference to this multiple supply of each muscle is that the nerve roots, as a rule, each supply not a limited area, but are distributed throughout the muscle. This was noted by FORGUE and LANNEGRÂCE, and also by RUSSELL (12) in the case of the dog, and by others. It is this which explains the observations of SHERRINGTON that one root can be divided without producing paralysis of any muscle.

A third point is that each root supplies muscles of different action, sometimes opposed. This has been demonstrated by all the investigators. Thus the stimulation of a root causes a movement which is that of the muscle supplied by the fibres which predominate in the root, but by stimulation of the same root with a minimal current and a fine electrode the different fasciculi to different muscles may be stimulated separately, and stimulation of the same root may thus be made to produce contractions of (say) flexors alone or extensors alone. These movements, however, as pointed out by FORGUE and LANNEGRÂCE, are mechanical, and differ from a voluntary movement which is under the influence of the synergic fibres of more roots than one. "Une racine," they state, "n'a ni spécialité d'action, ni spécialité de distribution." The same was found by RUSSELL in the case of the dog, and he points out also that in two roots the same muscle is unequally represented, so that a strong stimulus causing the predominating movement may produce only one particular movement for one root, as the contiguous root on stimulation, although causing contraction of the same muscle, may have these contractions

overcome by stronger contractions of an opposing group of muscles whose fibres predominate in that root.

It has also been shown that variations in individual plexuses occur, but that these are never of great importance, and that such variation consists in a slight shifting upwards or downwards of fibres to a contiguous root, and that fibres running normally in a particular root are not found when altering their position exceptionally to be present in a root further removed than to the root which is next to the root in question. Thus HERRINGHAM found the circumflex nerve usually to be supplied partly from the fifth and the sixth, but in some cases from the fifth alone, and other varieties of the same nature in the case of other branches of the plexus.

Finally, with regard to the resemblances between the brachial plexus of man and monkey the evidence appears to be that the resemblance is very close. FERRIER and YEO, in discussing this aspect of the subject, state that the "brachial plexus in the monkey corresponds in its constitution, configuration and distribution almost exactly with that of man." SHERRINGTON also states that "the similarity between the two is almost minutely exact." He shows, however, that there are slight differences, these being caused by a slight prefixture of the plexus in the case of man, and he states that "the most salient point of difference appears in the motor distribution of the second thoracic root, which is not generally considered to contribute to the brachial plexus in man." He also shows that the correspondence between man and monkey is confirmed by the comparison between the skin fields in Macacus experimentally found and those observed clinically by THORBURN, HEAD, MACKENZIE, STARR and KOCHER.

The statements just quoted from authors who have investigated the subject experimentally are confirmed by a comparison between their results and those obtained by dissection of the human plexus, namely, by HERRINGHAM and by BOLK. HARRIS, however, takes a different view of the matter, and is of opinion, from the results of his dissections and stimulations, that the differences between man and monkey are greater, holding that the prefixture of the plexus in man is to such an extent as to involve an entire root of the plexus.

As regards the anatomical teaching with reference to the human plexus, in the last edition of CUNNINGHAM'S 'Anatomy,' it is stated that the plexus "in some cases" receives a slender branch from the fourth cervical nerve, and that "in many cases" the second thoracic nerve contributes by an intrathoracic communication with the first thoracic nerve. In the monkey this branch is constant and fairly large.

(5) *The Author's Investigation on the Distribution of the Plexus in Macacus and in Man.*

The number of exposures, by surgical operation, of the brachial plexus which I have made during the past 13 years, I find to be 38. Of these one was for Erb's

paralysis of the usual type following injury in the adult, and the remainder for Duchenne's birth paralysis of the upper extremity. One of the latter involved both plexuses, and caused on both sides complete plexus paralysis, all the roots having been torn. All the other cases were unilateral, and all were of the "upper" type, involving paralysis of abduction of the arm, loss of power of flexion at the elbow, loss of supination, loss of external rotation of the arm, and in some cases loss of power of the extensors which occupy the back of the forearm. This, then, is the common type of the injury as described by DUCHENNE. The ages at which these cases were operated upon varied from two months to 19 years, but the great majority were aged two to three months, which I still consider to be the time of choice for this operation. At these exposures of the plexus, observations made at the time in order to determine the remedial procedure required have at the same time shown the nature of the distribution of some of the roots of the plexus. This evidence has been of three kinds: first, as to the nature of the lesion and the roots involved; second, in certain cases where excision of the lesion was practised, the results of these excisions; and third, the results of stimulation of the exposed roots. Each of these sources of information will now be considered.

1st. *The Nature and Situation of the Lesion.*—Excluding the case where the scar was found to involve the entire plexus on both sides, I have seen and operated upon 35 cases of Duchenne's paralysis and one of Erb's paralysis, in all of which the type of paralysis was that which I have just described. In the majority of these cases it was found at the operation that the lesion had been a rupture of the nerve trunks, and that these trunks were joined by a scar, while in the remainder it was found that the nerves had lost their conductivity, not by rupture, but by compression in a scar, which in some cases was very fine and ring-like, and in others very extensive. The situation of this scar, or this cicatricial compression, has always been the same in these cases, namely, at the junction of the fifth and sixth nerves. Sometimes the nerve to the subclavius has been recognisable, and in other cases it has not been seen. The fifth and sixth cervical nerves have usually been traced upwards from the lesion, and have shown a healthy appearance above the lesion. The seventh nerve has not apparently been involved in any of these cases.

2nd. *Results of Excision of the Scar.*—The operation performed has been of two kinds, which of the two depending on the nature of the lesion. If that was compression of the nerve trunks, then removal of the scar alone was practised. In the event of a scar being found on the nerves, then the two trunks (fifth and sixth cervical) were cut above the lesion and the three nerves issuing from the scar at the seat of lesion were also cut. These nerve trunks were the suprascapular, the branch to the outer cord of the plexus, and the branch to the posterior cord of the plexus joining with that from the seventh root. After this excision the three peripheral ends were joined to the two central ends, namely, to the anterior primary divisions of the fifth and sixth cervical nerves. For the purpose of considering the distribution

of the roots of the plexus, the importance of the procedure in the operation when excision was practised lies in the fact that both fifth and sixth roots were divided. In an older patient, in whom partial recovery had occurred, it might be expected that section of the fifth and sixth roots would cause an addition to the paralysis, but hitherto I have in these older cases confined the operative intervention to removal of compressing scars. Of the many excisions in infants, however, none have shown increase of the distribution of the paralysis after the operation, although that has involved the excision of the segment of junction of the fifth and sixth nerves. This has an important bearing on the question, for if the lesion which brings about this form of paralysis is due to the destruction of the fifth root alone, and the sixth had in these cases only been apparently damaged, then the excision of the undamaged sixth, and therefore the destruction of a root contiguous to that which had already been destroyed, would, in accordance with what is known of the brachial plexus, bring about an evident addition to the paralysis already present. HARRIS considers that the sixth root in man contains a very large proportion of afferent fibres, but, even granting this, there would still be a certain number of motor fibres present, the division of which would produce an addition to the muscular paralysis.

3rd. *Results of Stimulation of the Roots of the Plexus in Macacus and in Man.*—In making these observations I have used a minimal faradic current and a fine electrode, so as to ascertain the effect of stimulating the fibres to separate muscles or groups of muscles. Any increase of current was unsatisfactory, as it gave a stimulation of the entire root, and the movement produced was that of the muscles, the fibres to which predominated in the root. There is also the danger, in the event of using too strong a current, of overflowing to neighbouring nerves and complicating the observations. In stimulating the roots by a minimal current the effects of the stimulus may be different at different examinations during the operation, and this is due to failure to touch exactly the same spot with the electrode at the different examinations. If, however, care is taken to repeat the stimulus always at exactly the same spot, then the results always correspond. It was also noticed in some cases that it was impossible to get the same movement by stimulating along the nerve in the same straight line, the particular movement being elicited only from one small area, as if the bundle of nerve fibres in question had come more to the surface in that small area, and elsewhere ran more in the centre of the trunk.

Another point has been made out in (*a*) scars which have been formed between torn nerve ends and which contain some fibres in which conductivity is present, causing a partial recovery, and in (*b*) scars in Macacus between the nerve ends which have been experimentally anastomosed, that the result of stimulating these scars by minimal currents is not to produce general muscular contractions, but the effects, as in the case of the nerve trunks, depend on the spot at which the stimulus is applied. Thus if at one point of the scar contraction of the flexors and flexion is the result, at another point contraction of the extensors and extension may be the result. This

shows that in the bonds of union the nerve fibres passing to muscles arrange themselves into separate bundles, each bundle going to special muscles or groups of muscles just as in the nerve trunk itself.

Another point which was seen is that although a muscle undergoes contraction as a result of stimulation of a root, *e.g.*, the fifth, it does not necessarily follow that this muscle will become paralysed on section of that root, as it also is supplied by the contiguous root. This is in accordance with the work of others quoted above. The conclusion is that recovery of function taking place soon after section of a root may be due to the normal supply through another root.

In the following Table the results of stimulating the nerves in Macacus and in Man are placed together so as to enable a comparison to be made in the two so far as the observations have been able to be made in the case of Man. In exposing the plexus for treatment of injuries in Man I have always used the method of stimulating in order to ascertain the condition of the injured trunks and to determine the procedure, but I have not until recently recorded the results during the operation, as in such cases the stimulations are made for purposes of diagnosis, and it has not been found possible to record more than in a general way from memory after the operation what the results were. Recently, however, I have, while making the stimulations, dictated the results in the same way as is done in experimental work, and these have been immediately recorded in writing. These records have now been made in six cases of Duchenne's paralysis, and the age at operation is noted in each case. These are placed under six examinations made in Macacus, one of the monkeys having the results recorded for both plexuses (Experiment IV).

In the case of the experiments in Macacus, only the roots are admitted to this comparison which were not affected by the anastomosis. Sometimes the results were obtained at the time of performing the initial lesion, and at other times they were obtained at the physiological examination. In the case of the roots joined in the experimental anastomosis, the effects of stimulation were usually an expression of the distribution, not only of the normal root, but also of that of the root which had been anastomosed to it. These are therefore unfitted for comparison.

The results of stimulation and of excision of the sixth root in the human plexus are of importance in consideration of the view that the ordinary type of Duchenne-Erb paralysis is due to a lesion of the fifth cervical nerve alone, which appears to have gained many adherents. All the cases included in the Table showed the ordinary type of Duchenne's paralysis, and in these, then, the sixth nerve, according to the view referred to, ought to have been normal. As a matter of fact, it was always found that the lesion had involved not only the fifth, but also the sixth, and, in consequence, the contractions and movements elicited on stimulation of the roots represent spontaneous recovery either in progress or having become arrested, in every case, however, imperfect. When these contractions were found to be caused by stimulation of the roots, there is no case where the fifth did not

OBSERVATIONS of the Results of Stimulation of Roots of the Brachial Plexus in Macacus (six experiments) compared with those in Man (six cases).

Fifth Cervical Nerve.

	Experiment or Case.					
Macacus (undamaged nerves)	Expt. II	Deltoid contractions	—	—	—	External rotation arm
	Expt. IV, right	do.	Abduction of arm	Biceps contractions	Flexion at elbow	do.
	Expt. IV, left.	do.	do.	do.	do.	do.
	Expt. V.	do.	do.	do.	do.	—
	Expt. VIII	do.	do.	do.	do.	do.
Man (damaged nerves)	Heron, age $\frac{5}{12}$	—	—	—	—	do.
	Todd, age $\frac{6}{12}$	do.	—	do.	—	—
	Brown, age $\frac{2}{12}$	do.	—	—	—	do.
	Cuthbertson, age $\frac{2}{12}$	—	—	—	—	—
	Wilson, age 2.	do.	do.	do.	do.	—
	Dowie, age 19.	do.	do.	do.	do.	—

Sixth Cervical Nerve.

	Experiment or Case.										
Macacus (undamaged nerves)	Expt. IV, right.	Deltoid contractions	Abduction of arm	Biceps contractions	Flexion elbow	External rotation arm	—	—	—	—	—
	Expt. IV, left	do.	do.	do.	do.	do.	Coraco-brachialis contractions	Extensors in forearm contractions	Extension of hand	Supination	Shoulder pushed forward
	Expt. V	do.	do.	do.	do.	—	—	—	—	—	—
	Expt. VIII	do.	do.	do.	do.	do.	—	—	—	—	—
Man (damaged nerves)	Heron	—	—	—	—	do.	—	—	—	—	—
	Todd	do.	—	do.	—	—	—	—	—	—	—
	Brown	do.	—	—	—	do.	—	—	—	—	—
	Cuthbertson	—	—	—	—	—	—	—	—	—	—
	Wilson.	do.	do.	do.	do.	—	—	—	—	—	—
	Dowie	do.	do.	do.	do.	—	—	—	—	—	do.

Seventh Cervical Nerve.

	Experiment or Case.												
Macacus (undamaged nerves)	Expt. IV, right .	Triceps contractions	Extension of elbow	Extensors in forearm contractions	Extension of fingers	—	—	—	—	—	—	—	—
	Expt. IV, left .	do.	do.	—	—	Flexors in forearm contractions	Flexion of hand	Pronation	—	—	—	Internal rotation arm	—
	Expt. VI . . .	—	—	—	—	—	—	—	Biceps contractions	Flexion at elbow	—	—	—
	Expt. VII. . .	do.	do.	do.	Extension of hand	—	—	—	do.	do.	Deltoid slight contractions	—	—
Man (undamaged nerves)	Heron	do.	—	do.	do.	—	—	—	—	—	—	—	—
	Cuthbertson . .	do.	do.	—	—	—	—	—	—	—	—	—	—
	Wilson. . . .	do.	do.	do.	Extension wrist + digits	do.	Flexion of digits	do.	do.	—	—	—	Shoulder pushed forward
	Dowie	do.	do.	do.	Extension of hand	do.	Flexion of hand	do.	do.	Flexion at elbow (slight)	—	—	do.

respond, while the sixth responded, which would have been so had the lesion been confined to the fifth, the sixth remaining uninvolved. It is unnecessary here to consider the question from the surgical standpoint as to the probability or otherwise of the spontaneous recovery ultimately reaching the state of a useful or of a perfect recovery.

The results, therefore, of stimulating these trunks are of physiological interest, both when the result was positive and when it was negative, in the latter case showing that there was a total loss of conductivity, and therefore a participation in the lesion. The purpose of the Table being to make a comparison between Macacus and Man, the results of stimulating the lower roots of Macacus are not included, as I have not had opportunities of recording results of stimulation of the lower roots in Man. The Table shows in the case of the fifth cervical root a very close correspondence between the two, as every contraction and movement seen in Macacus was also seen in Man, and nothing more or less. In the case of the sixth root the similarity is also very great. In the case of Macacus additional contractions and movements are recorded, but it is clear that in so far as concerns the extensors of the hand and supination these must have been represented in the cases, as paralysis of the latter was present in all and of the former in some of the cases. In the case of the seventh root the most frequent contraction and movement, that of the triceps, corresponds in the two, and this is also the case for the extensors of the hand. As regards the remaining effects, flexion of the hand, pronation, and contraction of the biceps are seen in both.

This evidence, although fragmentary, is in favour of the views of FERRIER and YEO, and of SHERRINGTON and others, of the close correspondence of the brachial plexus of the Monkey to that of Man.

(6) *Importance of a Knowledge of the Distribution of the Plexus in Determining Procedure in Forming Anastomosis for Surgical or for Experimental Purposes.*

This question is of vital importance in the consideration of anastomosis of the roots of the plexus both from the surgical and from the physiological point of view. From the surgical standpoint it is important; for if the sixth root is also involved in the paralysis of the Duchenne-Erb type, then an anastomosis of the fifth, or part of the fifth, made into the sixth could not be followed by a recovery due to the surgical procedure. Recovery certainly might follow, but this would be due to the partial spontaneous restoration, which so often results in these cases even after long intervals, but which certainly would not have been promoted by the surgical intervention.

As regards the physiological standpoint it was first pointed out by HOWELL and HUBER (11) that in nerve-crossing experiments a satisfactory answer could not be got by crossing nerves which supplied synergic muscles, as the section of one of the

nerves supplying synergic muscles still left one group of muscles which were synergic with the paralysed group to carry out the function. This in the dog's leg was done so well as to make definite conclusions from the experiments impossible. They suggested therefore that it was necessary that the nerves which were to be crossed should contain fibres to antagonistic muscles. The difficulties in applying this principle to the brachial plexus are still greater, on account of the admixture of fibres in the roots of the plexus and of more than one root supplying each muscle, this double or treble supply also not being confined to one section of the muscle, but overlapping so that each part of the muscle is, as a rule, under the control of more than one root. The only way to overcome that difficulty is to anastomose not one root but more than one, and thus to produce a definite paralysis by involving all or practically all of the fibres to the affected muscle groups.

Recently BARILE (34), whose extensive series of experiments in dogs has led him to the conclusion of the possibility of successful substitution of one nerve for another in the supply of the muscles, has insisted on the importance of making these anastomoses in as extensive a surface as possible, and has pointed out that the anastomosis requires to include not only the efferent but also the afferent fibres in order that co-ordinated movements may be regained. If then these divided roots are in this way united to a neighbouring root or to the spinal accessory, and if restoration of co-ordinated movements occurs, then, all the experimental conditions having been proved to have been maintained, the recovery may fairly be attributed to the anastomosis. Where, however, the anastomosis consists of attaching one root or a part of a root to another, it would be an unwarranted conclusion that any recovery occurring was the consequence of the procedure adopted.

6. GENERAL CONCLUSIONS.

1. The brachial plexus of Macacus and that of Man are practically identical, at least as regards the fifth, sixth and seventh cervical nerves, the variation being of the nature of a prefixture of the plexus in Man, but not to the extent of an entire root.

2. In Macacus, section of the fifth nerve alone paralyses no muscle and limits no movement, although it may weaken some.

3. In Macacus, section of the sixth and part of the seventh disturbs the function of the limb to an appreciable extent, but the disturbance can be compensated for and the movements regained, although probably with diminished strength, without reunion of the roots and without aiding the recovery of function by anastomosis.

4. In Macacus, section of both fifth and sixth nerves almost entirely or entirely paralyses the deltoid, but not entirely the flexors of the elbow or the supinators; but in Man, section of these two roots not only completely paralyses the deltoid, but also the external rotators of the arm, the flexors of the arm to such an extent

at least that they cannot produce flexion, and also the supinator brevis to such an extent that it cannot produce supination, and in some cases also paralyses the extensors in the forearm.

5. In Macacus, in order to paralyse completely not only the deltoid but also the flexors of the elbow and the supinator brevis, it is necessary to divide the fifth, sixth and seventh nerves, as apparently more of the fibres to the flexors of the elbow pass in the seventh nerve than in the case of Man.

6. In Macacus, the paralysis resulting from section of the fifth and sixth may be largely restored by anastomosis of the peripheral segments of the two roots to the seventh cervical nerve or to the spinal accessory, and the resulting restoration of the muscles does not materially differ in date of onset, in progress, or in ultimate result in the two cases.

7. The time taken for restoration of function by means of anastomosis is approximately the same in the case of the brachial plexus in Macacus, and in the case of the limb nerves distal to the plexus in the Dog, and in the case of the facial nerve in the Dog and in Macacus.

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8. EXPLANATION OF PLATES.

PLATE 23.

Fig. 1 (Experiment I).—Photograph taken 11 days after the operation, showing recovering power of abduction of the arm as the monkey raises its arm to receive a morsel of food.

Fig. 2 (Experiment I).—Shows the same animal as the previous figure 19 days after the operation. There is seen to be a normal range of abduction of the arm. At this date the one arm was used as freely as the other.

Fig. 3 (Experiment II).—Photograph taken 17 days after the operation, showing the position in which the animal has carried his arm since the nerves were cut. So far no abduction had been noticed in the arm, but there was some power of flexion at the elbow joint.

Fig. 4 (Experiment II).—Photograph taken 40 days after the operation, showing recovery of flexion at the elbow joint, displayed while he is defending himself against attempts to throw a noose over his head.

FIG. 1.

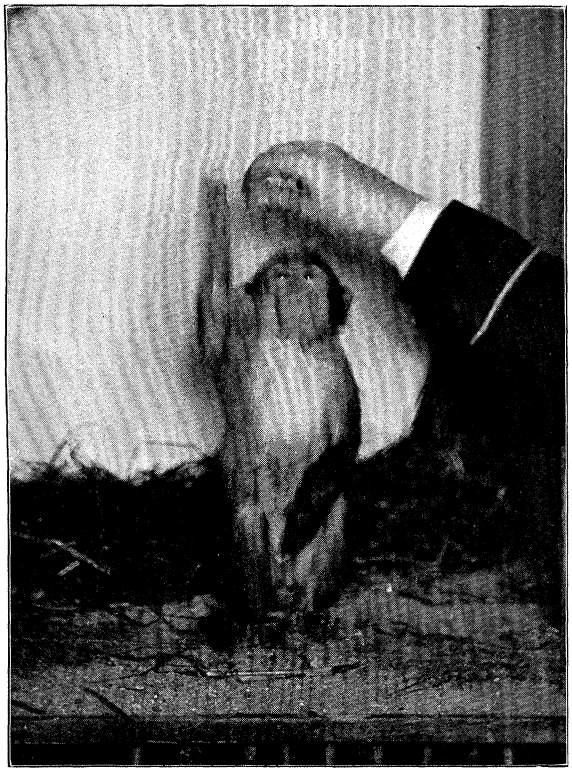

FIG. 2.

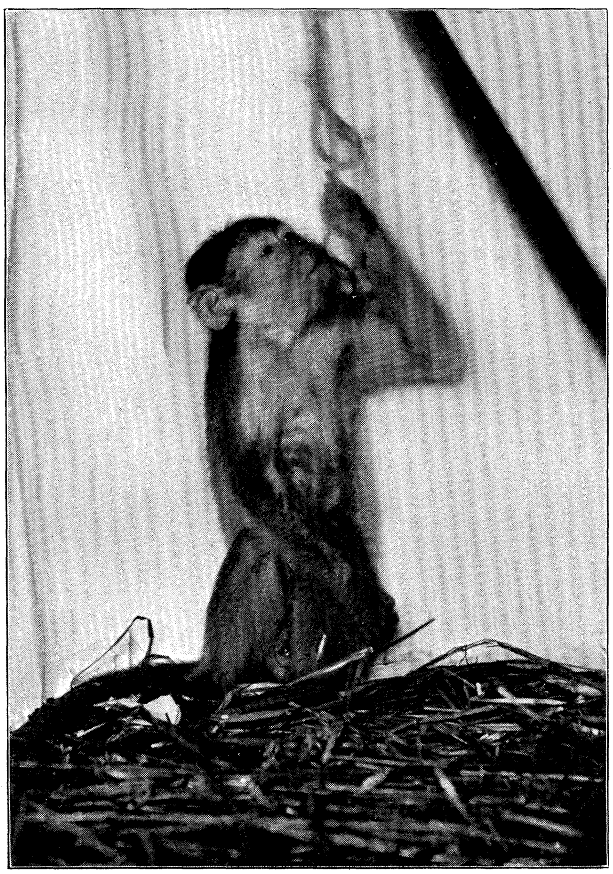

FIG. 3.

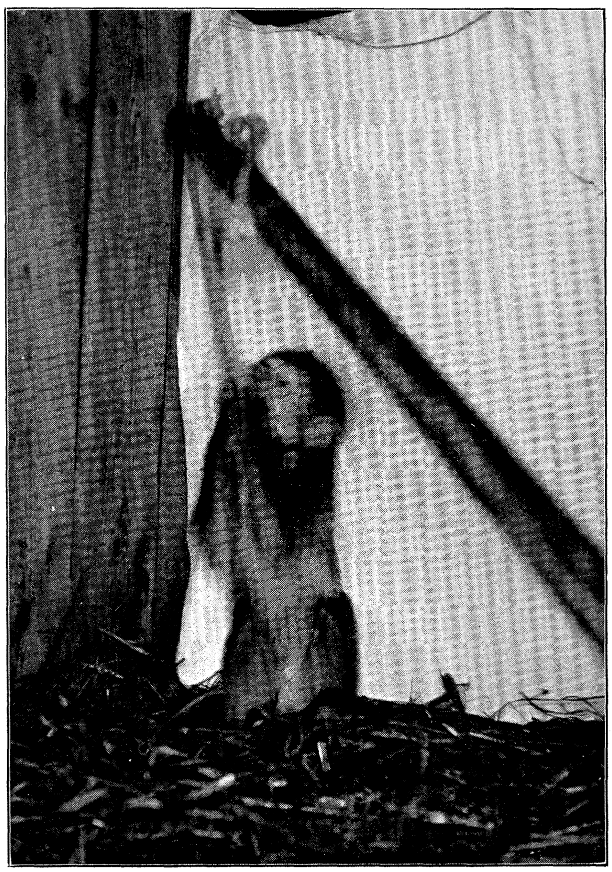

FIG. 4.

FIG. 5.

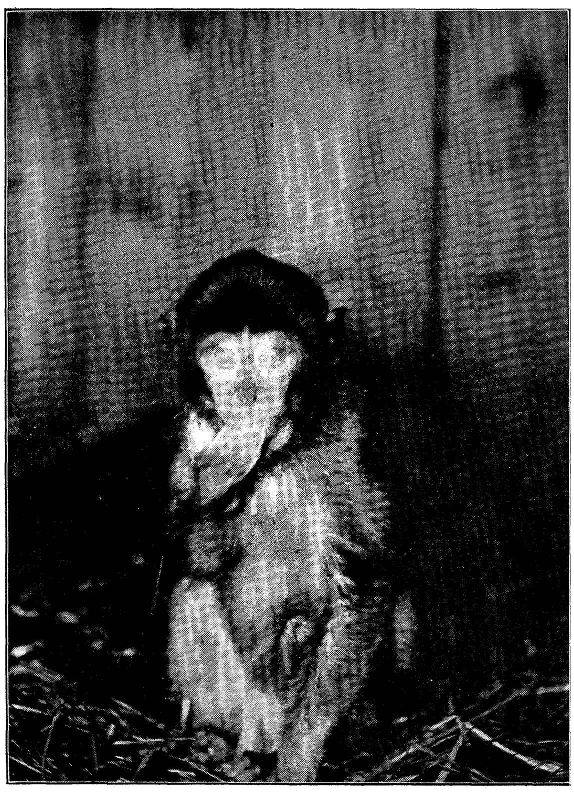

FIG. 6.

FIG. 7.

Plate 24.

Fig. 5 (Experiment II).—Photograph 46 days after the operation, showing recovery of abduction of the arm.

Figs. 6 and 7 (Experiment VII).—Section of the anterior primary divisions of the fifth and sixth nerves, and attachment of the peripheral segments of these to the central segment of the divided spinal accessory nerve. Photographs of the animal taken 21 days after the operation, showing that at this early date the animal uses the arm for feeding, being able to do so by the power of flexion at the elbow which he has retained. There was no abduction of the arm, and this did not commence to recover till 83 days after the operation. The flexion of the elbow shown in the photograph was not due to the anastomosis, but was retained notwithstanding the section of the fifth and sixth.

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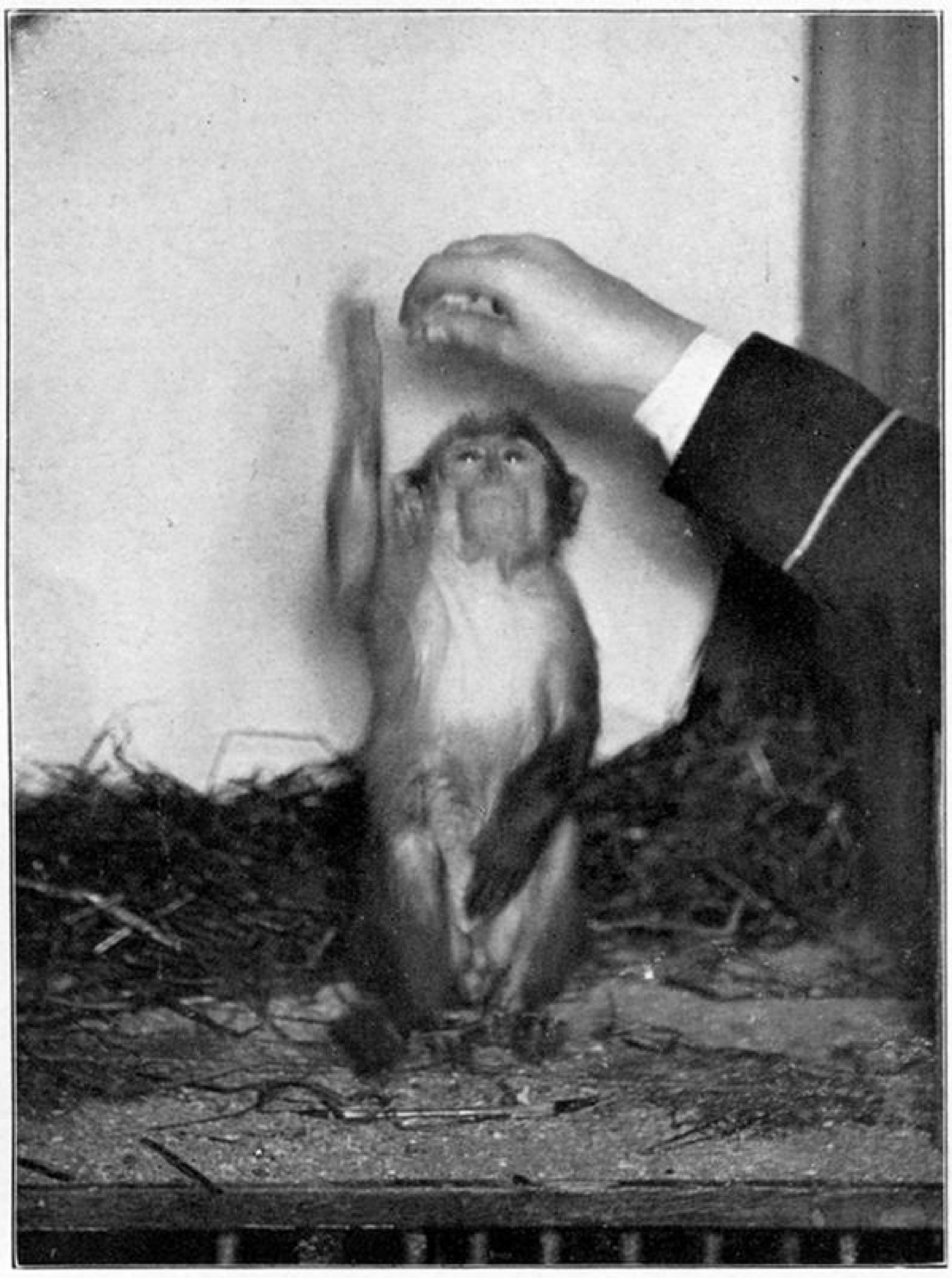
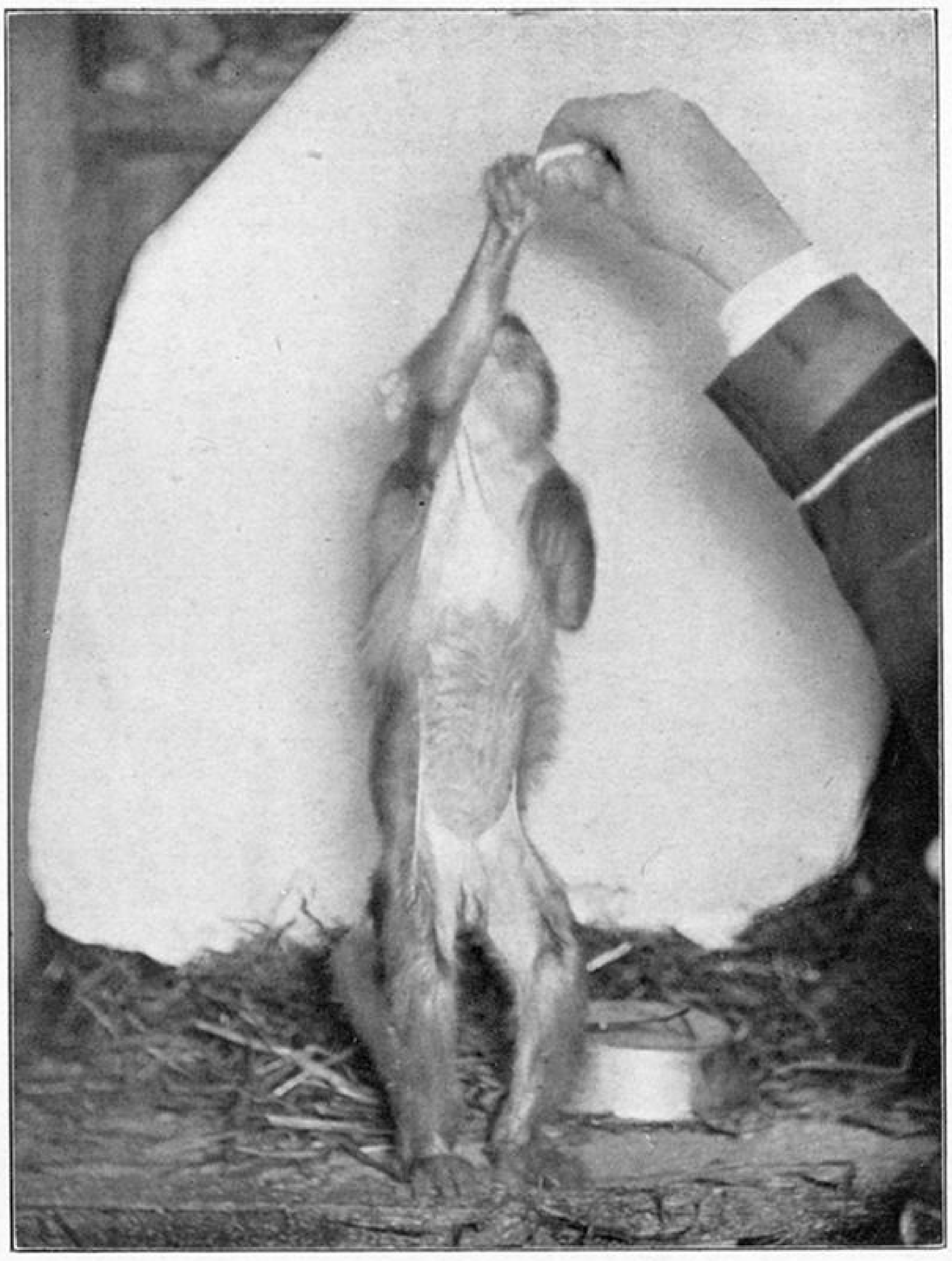


Fig. 2.



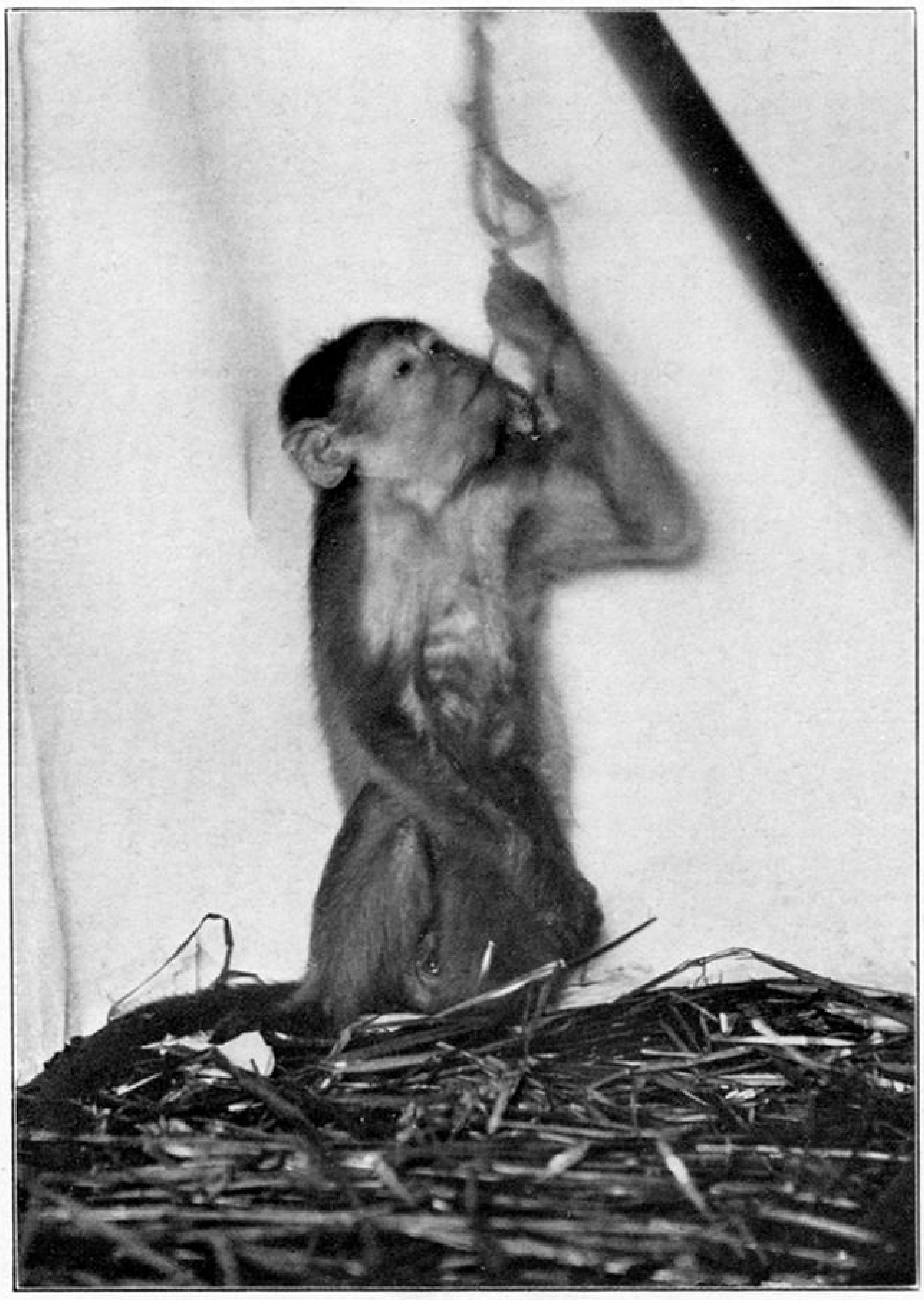


Fig. 3.

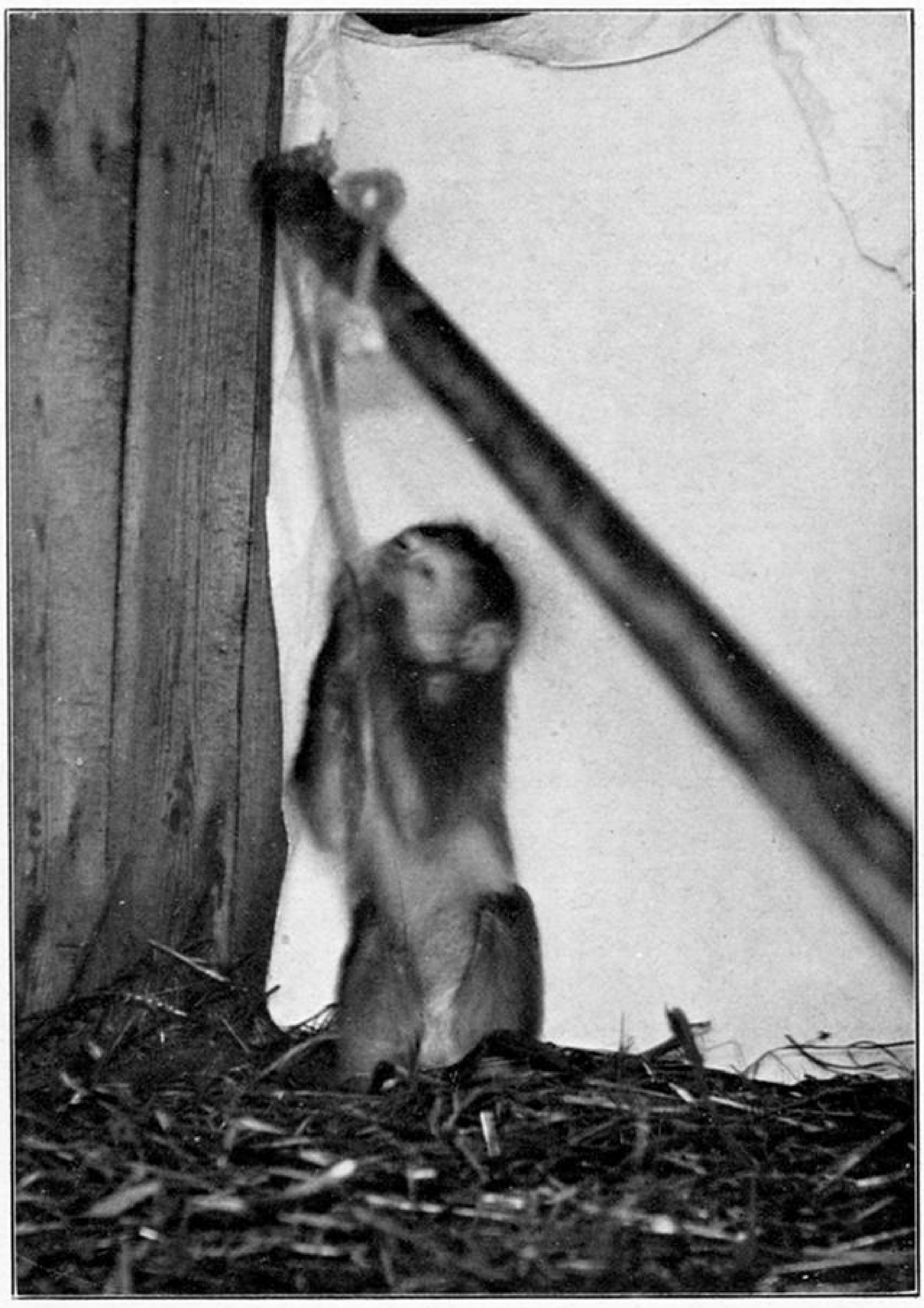


Fig. 4.

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Fig. 5.

Fig. 6.

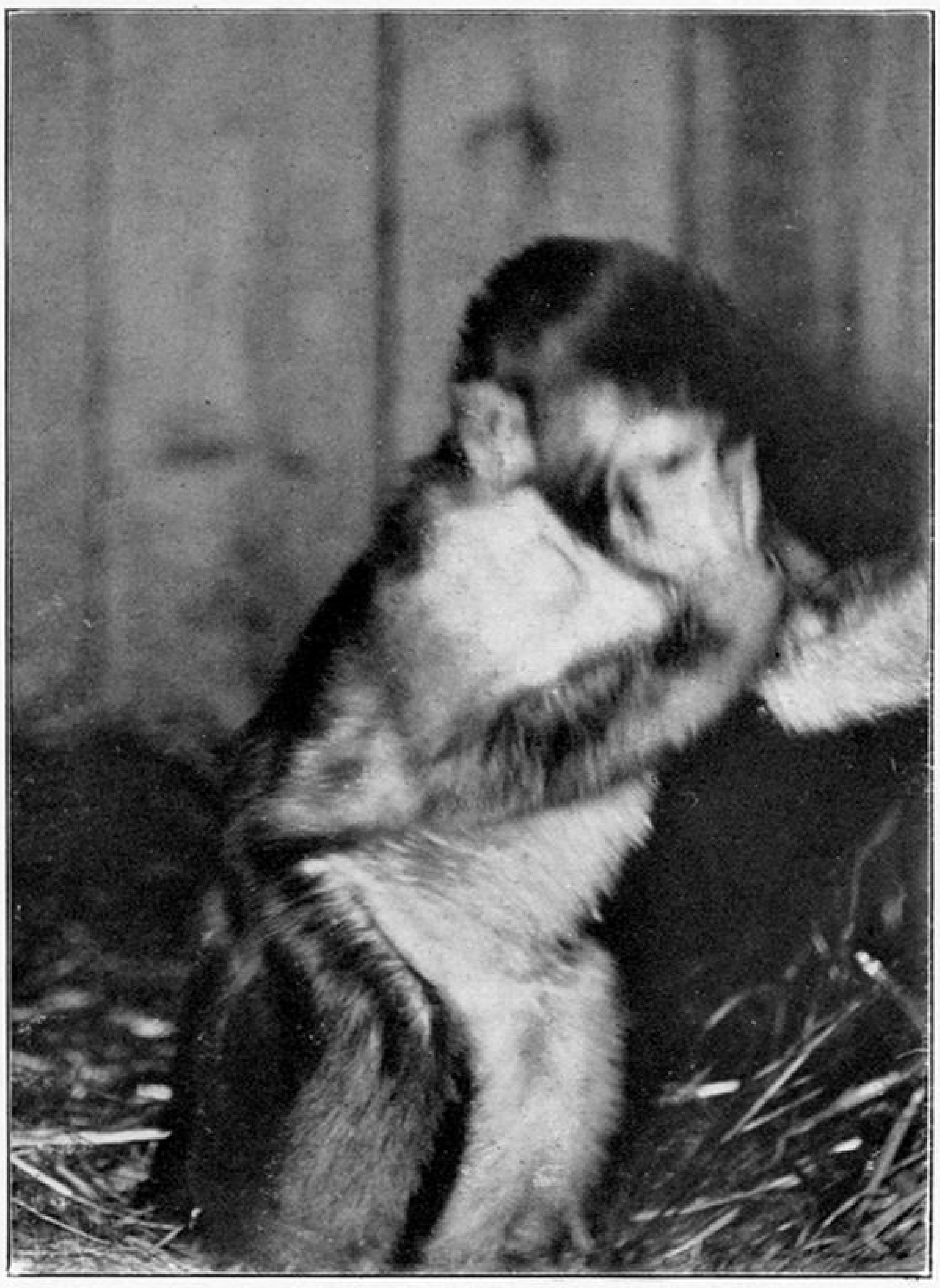

Fig. 7.

Plate 24.

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Figs. 6 and 7 (Experiment VII).—Section of the anterior primary divisions of the fifth and sixth nerves, and attachment of the peripheral segments of these to the central segment of the divided spinal accessory nerve. Photographs of the animal taken 21 days after the operation, showing that at this early date the animal uses the arm for feeding, being able to do so by the power of flexion at the elbow which he has retained. There was no abduction of the arm, and this did not commence to recover till 83 days after the operation. The flexion of the elbow shown in the photograph was not due to the anastomosis, but was retained notwithstanding the section of the fifth and sixth.