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THE NERVOUS CONTROL OF THE CERVICAL OESOPHAGUS OF THE RAT DURING SWALLOWING

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The arrangement of the motor fibres to the cervical oesophagus in the common laboratory animals has been described by Hwang, Grossman & Ivy (1948). These workers have shown, by nerve stimulation and X-ray photography, that the motor fibres serving the cervical oesophagus emerge from the vagus either above or below the nodose ganglion, depending on the species, and enter the oesophagus from either a branch of the pharyngeal nerve or the superior laryngeal nerve. The dysphagia which follows section of these fibres in the dog and the degree of functional recovery which may occur has been described (Hwang, 1953).

During an analysis of the myelinated fibres of the superior laryngeal nerve of the rat (Andrew, 1956*b*) activity in the motor fibres to the cervical oesophagus was detected electrically, and a preliminary report of the discharges of nerve action potentials which take place during swallowing has been given (Andrew, 1956*a*). In the present paper an attempt is made to relate discharges of nerve impulses to and from the cervical oesophagus to other events in the act of swallowing.

METHODS

The experiments were performed on thirty rats. Anaesthesia was induced with trichloro-ethylene vapour and maintained by intra-peritoneal injection of 25% (w/v), urethane solution 5 ml./kg body weight.

Electrodes. The muscle action potentials were picked up with bipolar copper wire electrodes inserted into the muscle. The wires were enamel-insulated, except at the cut ends, and the tips were separated by a fraction of a millimetre. The wires (diameter 0·07 mm) were wound as a helical spring between the muscle and the input terminals of the amplifier. This arrangement permitted contraction of the muscle fibres to occur without a shift of electrode position and consequent change of action potential size. The electrodes were isolated from the control grids of the input valves by 0·001 μF polystyrene dielectric condensers. Nerve action potentials were picked up with silver wire electrodes.

Recording. The electrodes were connected to conventional capacity-coupled amplifiers and thence to double-gun recording cathode-ray oscillograph, monitor tubes and loudspeaker. The action potentials were recorded on moving bromide paper.

The dissection of the cervical oesophagus and its nerve supply. A mid-line incision was made on the ventral surface of the neck. The subcutaneous tissue was divided between the salivary glands. The sternohyoid muscle was cut transversely at its attachment to the hyoid bone and reflected back and cut short close to the sternum. The edges of the wound were tied back and the cavity so formed filled with paraffin oil. All further dissection was carried out beneath the oil surface. The omohyoid muscle was detached from the hyoid bone and in many experiments it was found convenient to detach the sternothyroid muscle from the thyroid cartilage. Features of the nerve supply have been described already (Andrew, 1956*b*).

Stimulation. The swallowing reflex was elicited by stimulation of the pharynx or epiglottis with the blunt end of a thin glass rod, introduced through the mouth. On a few occasions it was produced by injecting 1–2 ml. of air into the oesophagus from a thin flexible tube (diameter 1 mm) inserted through the mouth and upper oesophageal sphincter.

RESULTS

The ease with which the act of swallowing may be elicited and the vigour of the peristaltic wave in the oesophagus vary a great deal in the anaesthetized animal. This variation is partly accounted for by changes in the level of anaesthesia which occur during an experiment lasting a few hours. In this work two relatively constant events were selected as landmarks and included in records of oesophageal activity so as to relate the latter to the act as a whole. The two events selected were the inhibition of the activity of the cricothyroid muscle and the contraction of the thyrohyoid muscle (a laryngeal elevator); both of these occur during the pharyngeal phase of swallowing. The features of these two events will be described first and then the efferent and afferent discharges in the oesophageal nerve fibres will be related to them.

The inhibition of the cricothyroid motoneurones. The cricothyroid is an accessory respiratory muscle which is active even during quiet breathing; it contracts during inspiration. Some motor units discharge continuously throughout the respiratory cycle with a maximum frequency during inspiration, others phasically during inspiration only. When a swallowing movement occurs the outflow of motor nerve impulses is completely inhibited for 0·1–0·2 sec. Activity then restarts at a higher level than before the inhibition but rapidly subsides to the original level.

The contraction of the thyrohyoid muscle. No activity could be detected in the muscle fibres between swallowing movements. Recordings from the central end of the motor nerve, which is very slender, did not reveal any activity in large fibres. Activity in small motor fibres could be detected in about half the preparations; it consisted of a low frequency discharge in one or two fibres. The frequency was usually slightly modulated by the respiratory cycle, the maximum occurring during expiration; increased respiratory activity tended to increase the discharge and to recruit additional small fibres. When a swallowing movement took place the discharge in small fibres accelerated to high frequencies, e.g. 200 impulses/sec and a short volley occurred in a number of large motor fibres. This volley lasted 0·1–0·3 sec. The rise in frequency in the

small fibres usually preceded the α fibre volley and the return to the resting level extended by a fraction of a second after the volley. In recordings taken from the whole motor nerve the events in the small motor fibres were obscured during the α fibre volley; however, clearer records could be obtained from branches given off close to, or within, the muscle. Fig. 1 shows the activity in motor fibres during a swallowing movement.

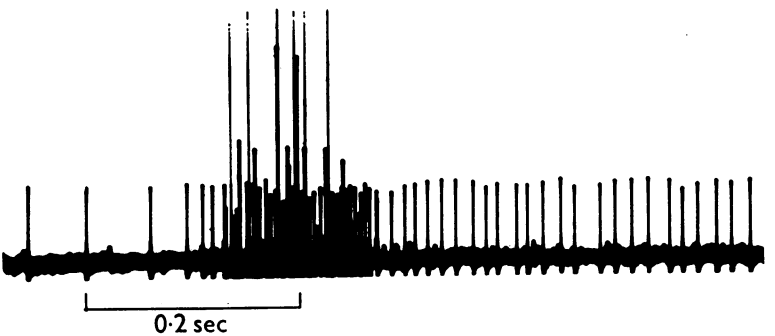

Fig. 1. Efferent nerve action potentials in a small branch of the motor nerve to the thyrohyoid muscle during a swallowing movement. The volley of six large action potentials corresponded to the contraction of the muscle during elevation of the larynx. It will be seen that the small action potentials began to rise in frequency just before the α fibre volley, discharged at a high frequency during the volley, and declined in frequency afterwards. The record does not give a true picture of the relative sizes of the action potentials as the peaks of the α fibre action potentials are beyond the top of the record.

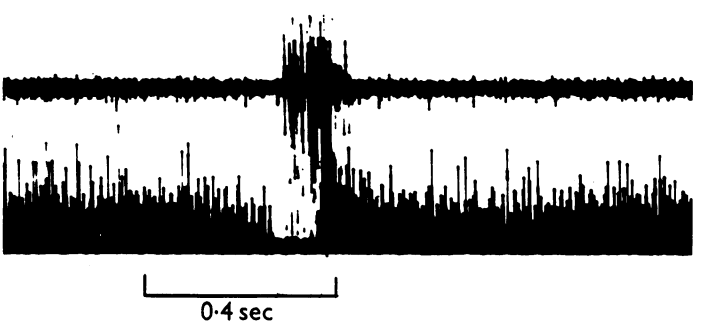

Fig. 2. Simultaneous recordings of the efferent nerve impulses in the motor nerves to the thyrohyoid muscle (upper record) and the cricothyroid muscle (lower record) during a swallowing movement. The outflow to the cricothyroid was inhibited for 0·1 sec, the multifibre volley to the thyrohyoid muscle lasted for 0·14 sec.

The time relation between the cricothyroid inhibition and the thyrohyoid excitation. The beginning of the inhibition of the cricothyroid activity and the beginning of activity in the large motor fibres to the thyrohyoid was almost simultaneous. The elevator muscle volley was usually slightly longer than the

cricothyroid inhibition and so overlapped the resumption of activity in the cricothyroid. Fig. 2 gives an example of simultaneous recordings from the central ends of the motor nerves to the two muscles.

The activity in efferent fibres to the cervical oesophagus

The efferent fibres in the rat are contained in two branches of the superior laryngeal nerve and are small myelinated fibres, 6μ or less in diameter. The anatomy of the nerve supply has already been described (Andrew, 1956*b*). In addition there is almost certainly a degree of overlap by the innervation zone derived from the recurrent laryngeal nerve. Activity in fibres taking this course is not considered in this paper.

The activity in efferent fibres will be described for four functional states of the oesophagus. These states are (*a*) at rest between swallowing movements, (*b*) during a swallowing movement which is only a bucco-pharyngeal act, without a propulsive wave in the oesophagus, (*c*) during a swallowing movement containing a propulsive wave in the oesophagus, (*d*) during gagging movements. All the animals could be used to study (*a*) and (*b*), only about one quarter could be stimulated to produce regularly the full movement (*c*), and the movement (*d*) was only observed in lightly anaesthetized animals and was accompanied by ventroflexion of the neck and by jaw movements.

Activity at rest between swallowing movements. One or two fibres discharged at low frequencies (5–30 impulses/sec) and the frequency was usually modulated by the respiratory cycle. At its lowest detectable level the activity consisted of a few impulses only during inspiration. At higher levels of respiratory activity there was a continuous discharge in a few fibres with a maximum frequency during inspiration. These fibres will be referred to in subsequent descriptions as type 1 fibres. Motor units were detected in the wall of the fully innervated oesophagus at the level of the cricoid cartilage which showed activity similar to that detected in type 1 fibres. The fully innervated oesophagus at more caudal levels was inactive electrically. The mechanical action of the muscle was imperceptible to the eye during quiet breathing; it is of interest that Hwang *et al.* (1948) reported visible contractions of the cervical oesophagus of the dog during gasping respiratory efforts.

Activity during a bucco-pharyngeal swallowing movement. The activity in type 1 fibres was inhibited for a fraction of a second and then resumed at a raised level which slowly fell during the succeeding seconds; other fibres were usually recruited during this phase of post-inhibitory excitation. The phase of inhibition corresponded in time to the inhibition of the cricothyroid muscle. Fig. 3 shows the activity of a type 1 fibre during a swallowing movement.

Activity during a swallowing movement containing a propulsive wave. The type 1 fibres were inhibited as described in the previous section. In addition after the end of the inhibitory phase, another group of fibres discharged a short

volley. These fibres will be referred to as type 2 fibres. The recorded action potential size of the two groups was approximately the same, type 2 perhaps rather smaller. The volley was composed of shorter volleys in individual fibres dispersed temporally. The length of the multifibre volley was variable (0·2–0·8 sec), and the longer volleys corresponded to the more vigorous propulsive waves. Some propulsive waves did not traverse the whole length of the cervical oesophagus and consisted of little more than a twitch contraction of the upper end. By inserting electrodes in the oesophageal muscle at different levels and recording simultaneously the volley and the electromyogram of the propulsive wave as it passed the implanted electrodes, it was possible to conclude that the duration of the multifibre volley in type 2 fibres corresponded to the time the propulsive wave spent in moving along the cervical oesophagus. Fig. 4 gives an example of such a record. There was some evidence, however, that fibres taking another route, presumably through the recurrent laryngeal nerve, contributed to the muscle contraction at the caudal end of the cervical oesophagus. The recorded action potential size of the type 2 fibres could be improved by dissection of the motor nerve into smaller filaments and on a few occasions it was possible to record from two filaments simultaneously during the efferent volley and thus to display the displacement, in time, of the activity in different fibres. Fig. 5 shows an example of this type of record.

Activity during gagging movements. These movements were not studied in any detail, but records of oesophageal and elevator muscle activity obtained during gagging could easily be distinguished from those obtained during swallowing since (*a*) contraction occurred at both sites at the same time, instead of in sequence, (*b*) there was a general oesophageal contraction instead of a propulsive wave, and (*c*) the elevator contraction lasted much longer, e.g. for 1 sec.

The activity in afferent fibres from the cervical oesophagus

Recordings were made from filaments dissected from the oesophageal branches, and the peripheral end of the main trunk, of the superior laryngeal nerve. To reduce the afferent inflow from other regions, branch 1, which serves the upper larynx, was disconnected from the main trunk and in some experiments the ipsilateral recurrent laryngeal nerve, which contributes aortic baroceptor fibres to the superior laryngeal nerve by way of the communicating branch (Andrew, 1954), was also cut low in the neck. After section of both these afferent channels and removal of the sheath of the main trunk, impulses from the oesophagus were just detectable above the noise level as a low frequency multifibre resting discharge. The passage of a propulsive wave along the cervical oesophagus coincided with a multifibre afferent volley lasting about a third of a second.

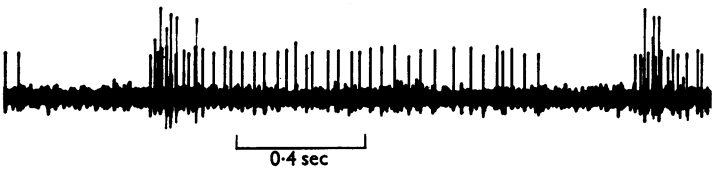

Fig. 3. An example of the discharge in type 1 efferents in a filament dissected from the central end of the oesophageal branch of the superior laryngeal nerve. The two pauses in the tonic discharge corresponded to the pharyngeal phases of two swallowing movements. Note the recruitment of an additional fibre in the phase of post-inhibitory excitation.

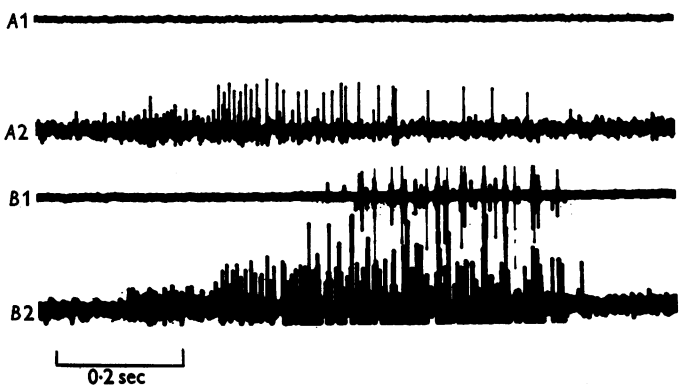

Fig. 4. *A* 1 and *A* 2 are simultaneous recordings of the oesophageal electromyogram at the level of the 7th tracheal ring (*A* 1), and efferent nerve impulses in a filament dissected from the central end of the oesophageal branch of the superior laryngeal nerve (*A* 2), during a swallowing movement which did not contain a propulsive wave. *B* 1 and *B* 2 are recordings taken shortly afterwards during a swallowing movement which *did* contain a propulsive wave. The electrode positions were not changed between the two swallows. *A* 2 thus shows the activity of type 1 fibres, and there is no activity shown in the electromyogram. *B* 2 shows the activity of both type 1 and type 2 fibres and the electromyogram corresponds, in time, with the additional multifibre activity seen when *A* 2 is compared with *B*2. The electromyogram is due to the contralateral innervation.

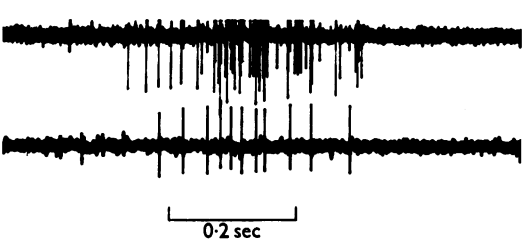

Fig. 5. Simultaneous recordings from two filaments dissected from the central end of the oesophageal branch of the superior laryngeal nerve during a swallowing movement containing a propulsive wave. The activity of four or five type 2 fibres can be distinguished; the individual volleys overlap in time.

To obtain action potentials of satisfactory size it was necessary to use very slender filaments. The recorded action potential size of the afferent fibres illustrated in this section is larger than that of the efferents in the preceding section; this, however, is not evidence that the afferent fibres are of larger diameter, but rather indicates the greater technical difficulty in making functional single fibre preparations from the type 2 efferents than from the afferents. The greater difficulty arose because the efferents are active only for a short period of time and in a limited number of anaesthetized animals.

Resting discharge. There was a continuous discharge in small fibres at low frequencies (4–15 impulses/sec). The discharge frequencies were determined by the intraoesophageal pressure, increased pressure leading to increased frequencies. Thus the introduction of 1–2 ml. of air through a tube inserted through the pharynx raised the resting frequency. The endings responsible for the discharge were located by probing the wall of the oesophagus. The ending zones of individual fibres were localized and were found to be confined to a particular level of the oesophagus. The sphincter region was innervated and probe tests here caused discharges in two or three fibres simultaneously. Endings were detected as far caudally as the dissection permitted, i.e. to the upper margin of the sternum, which corresponds to the 10th or 11th tracheal ring.

Effects of respiratory movements. These effects on the resting discharge were variable. Sometimes during quiet breathing no modulation of the discharge frequency was detectable. In other experiments, when the oesophagus contained trapped air and mucus, the movements of the contents towards the thoracic portion during inspiration, as a result of decreased intrathoracic pressure, visibly deflated the cervical oesophagus and a reduction of the resting discharge occurred. A third variant occurred when vigorous breathing and an empty oesophagus caused longitudinal stretching during inspiration and an increased discharge in some fibres.

Effect of a bolus in the oesophagus. To stimulate the oesophagus in a normal fashion, a bolus of moist cotton-wool was introduced through the upper sphincter. It was found convenient to attach the bolus to the end of a thin glass rod so that it could be positioned manually. Slowly adapting endings connected to small fibres were stimulated and high frequencies of discharge (200–300 impulses/sec) could be produced when the bolus was pushed into the innervation zone of a fibre. The discharge frequency fell sharply as the bolus passed out of the innervation zone. In Fig. 6 the resting discharge of an ending is shown together with its adapted response to a small bolus of cotton-wool.

Effect of a propulsive wave. The propulsive wave exerted a powerful transient stimulant action as it swept through the innervation zone of an ending. Fig. 7 shows an example of the discharge of an ending located at the level of

the eighth tracheal ring as a propulsive wave passed. This preparation also contained fibres connected to endings at a different level of the oesophagus and these discharged a short volley in advance, temporally, of the response of the other fibre. The endings can thus supply information of the propulsive wave, in addition to positional information of a static bolus. To check that the stimulation of the ending did correspond, in time, with the passage of the propulsive wave through the ending zone, the following type of experiment was performed. The position of the ending zone of an electrically recognizable fibre was determined by probe tests, electrodes were inserted into the wall of the oesophagus at this level, a propulsive wave was elicited, and simultaneous recordings made of the electromyogram and the afferent discharge. Fig. 8

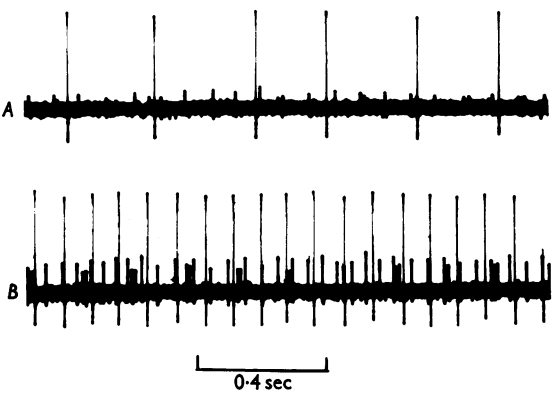

Fig. 6. Afferent nerve impulses from the oesophagus in a filament dissected from the superior laryngeal nerve. The ending discharging the large impulses was at the level of the 7th tracheal ring. Recording *A* shows the adapted resting discharge of 4 impulses/sec, recording *B* shows the adapted discharge from the same ending in response to a small cotton-wool bolus (diameter 3 mm) in the cervical oesophagus. When this record was taken the bolus had been in place for 5 min.

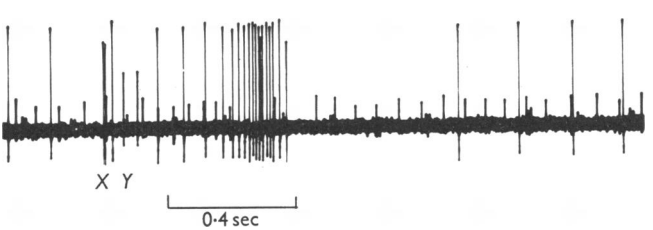

Fig. 7. Afferent nerve impulses from the oesophagus in a filament of the superior laryngeal nerve during the passage of a propulsive wave. The largest nerve impulses are from an ending at the level of the 8th tracheal ring. Its resting frequency of about 6 impulses/sec rose to about 100 impulses/sec as the propulsive wave passed the ending zone; a post-excitatory pause of ½ sec duration followed. The pairs of impulses in positions marked *X* and *Y* corresponded to the time of starting of the propulsive wave at the sphincter and were presumably discharged by endings in that region.

shows a record from such an experiment. It will be seen that the contraction of the muscle corresponded to the phase of maximal stimulation of the ending. The impulse frequency of the discharge, however, began to rise before the muscle became active.

Effect of gagging movements. Discharges occurred synchronously with the general contraction of the cervical oesophagus associated with gagging movements.

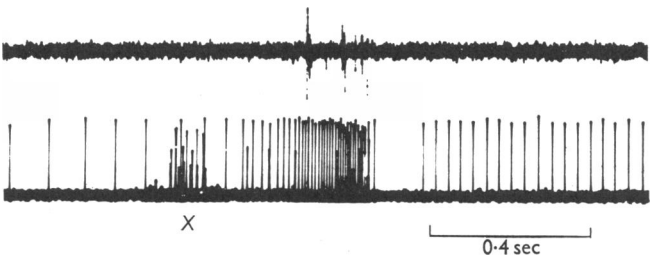

Fig. 8. Simultaneous recordings of the oesophageal electromyogram at the level of the 8th tracheal ring (upper record) and afferent nerve impulses from the oesophagus in a filament of the superior laryngeal nerve (lower record). The large nerve impulses were from an ending at the level of the 8th tracheal ring; it will be seen that the phase of maximum stimulation corresponded, in time, to the activity in the oesophageal muscle at that level. The volley of impulses in three other fibres at point marked *X* corresponded, in time, to the beginning of the propulsive wave at the sphincter and was presumably discharged by endings in that region.

DISCUSSION

The activity of muscles which participate in the bucco-pharyngeal phase of the act of swallowing has been studied electromyographically by Doty & Bosma (1956) in the dog, cat and monkey. From their published results it appears that the general features of the activity of the thyrohyoid and cricothyroid muscles in the dog are similar to those in the rat, except that the thyrohyoid muscle is quite inactive between swallowing movements in the rat, whereas in the dog it shows a low level of activity which is inhibited just before and after the contraction associated with the elevation of the larynx.

An attempt has been made in Fig. 9 to show, in diagrammatic form, a summary of the efferent and afferent activities during a swallowing movement. As has already been indicated, some variation was found between animals in the duration and vigour of the muscular contractions and in the same animal during the course of an experiment. In particular, the vigour of the propulsive wave varied unpredictably and in many animals could not be elicited regularly. These differences are well known; Meltzer (1899) drew attention to the effect of the level of anaesthesia. It should be explained that in this diagram the activity in efferent and afferent fibres is displayed differently; in the case of the type 2 oesophageal efferents, the blocked-in area represents the duration of the multifibre volley, in the case of the oesophageal afferent, the activity of

a single fibre is shown. It is suggested that the multifibre volley in the afferent fibres is composed of such activities in individual fibres temporally dispersed; an indication of this has been given in Figs. 7 and 8.

The absence of detectable resting activity in the muscle below the level of the sphincter is of interest as it is sometimes implicit in descriptions of oesophageal activity that the propulsive wave is preceded by a zone in which the resting muscular activity is reduced. Visual observation indicates that the oesophagus is distended just in front of the ring of constriction but the eye cannot discern whether this is associated with an inhibition of resting tone or

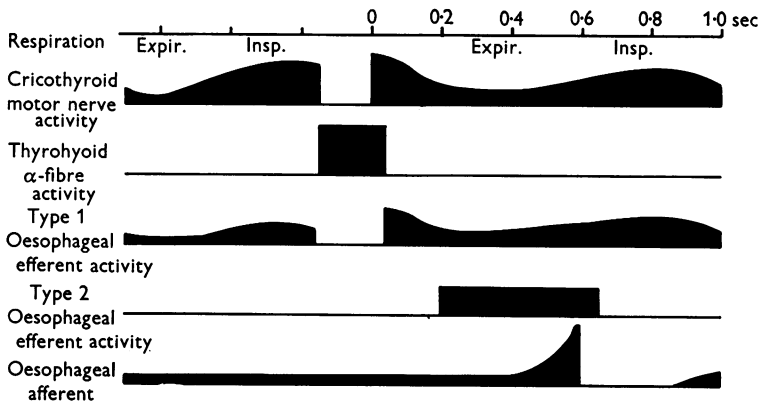

Fig. 9. A summary, in diagrammatic form, of the events in afferent and efferent fibres during a swallowing movement containing a propulsive wave. The type 2 efferent activity shown is the duration of the multifibre volley. The oesophageal afferent activity indicated is that from a single ending at the caudal end of the cervical oesophagus, discharges from endings nearer the sphincter would be displaced to the left.

is due entirely to passive inflation. The records from low cervical sensory endings (see Figs. 7 and 8) indicated a rising stimulus as the propulsive wave approached. The present results, which of course are only applicable to the cervical oesophagus with predominant striped musculature, only give evidence (the pause in the discharge of the type 1 efferents) for an inhibition of resting tone at the sphincter region.

The increased activity of type 1 fibres during augmented respiration may be a response to prevent the entry of air into the oesophagus. As is well known, a sharp increase in the negative pressure in the thorax, such as may be produced in man by making an inspiratory effort with a closed glottis, can draw air past the upper oesophageal sphincter.

In the majority of experiments described the cervical oesophagus had been partly denervated, since it was necessary to cut the oesophageal nerves on one side in order to make suitable preparations for recording nerve impulses. No conclusion was reached as to the extent to which the oesophageal electro-

myogram was altered by the partial denervation; it was present on the denervated side and the propulsive wave was not altered qualitatively, though it seems likely that it had been weakened. Similarly, possible effects of the partial efferent denervation on the discharge of the sensory endings have to be considered. Further information on the arrangement of the innervation is clearly desirable.

The discharge of the sensory endings was observed under two conditions; first, the steady stimulus produced either by the resting intra-oesophageal pressure (during *quiet* breathing the changes transmitted from the thoracic portion of the oesophagus were not important) or by the steady distortion of the oesophageal wall produced by a bolus; and secondly, the transient stimulation due to a propulsive wave. Results obtained under steady conditions showed that the endings were stimulated by stretch and were slowly adapting. The stimuli used did not exclusively stimulate either the circular or longitudinal elements in the wall, but the potency of the small bolus suggests that some endings are associated with circular elements and the fact that some endings discharged with inspiration during vigorous breathing, when the oesophagus was stretched in its long axis, implicates endings associated with longitudinal elements. The discharge from an ending zone as a propulsive wave passed through it indicated a vigorous stimulation during the contraction of the muscle of the wall with a marked post-excitatory depression during the relaxation of the muscle. This suggests that the sensory ending is in series with the contractile elements. Whether the latter are functionally differentiated from the rest of the muscle, as in the skeletal muscle spindle, is not clear.

The deployment and properties of the sensory endings detected are quite compatible with the view that they form the sensory basis of secondary peristalsis since they could supply the necessary continuous positional information of a bolus in the cervical oesophagus. The introduction of a bolus into the oesophagus proved to be a very potent stimulus for these endings; action potential discharges of 200–300 impulses/sec could be obtained. Whether these endings play any essential part in primary peristalsis is not certain. Hwang (1954) studied the peripheral nervous pathways for secondary peristalsis of the cervical oesophagus of the dog by nerve section methods and came to the conclusion that the afferent fibres coursed through the upper recurrent laryngeal nerve to the communicating branch and thence to the superior laryngeal nerve. In the rat some of the afferents go directly to the branches of the superior laryngeal nerve, but apart from this, these experiments support his conclusion.

SUMMARY

1. Activity in afferent and efferent fibres serving the cervical oesophagus has been studied in the rat at rest and during swallowing movements.

2. Two types of efferent were detected, the first innervated the upper oesophageal sphincter region and carried a tonic discharge which was briefly interrupted during the pharyngeal phase of a swallowing movement, the second was responsible for the propulsive wave in the cervical oesophagus.

3. Slowly adapting stretch-sensitive endings connected to small myelinated fibres were detected in the wall of the cervical oesophagus. These produced a resting discharge which was influenced by the intra-oesophageal pressure. They responded with an increased discharge to the presence of a bolus in the cervical oesophagus. They may form the sensory basis for secondary peristalsis.

4. The propulsive wave stimulated the sensory endings as it passed through their zones of innervation. The progress of the propulsive wave along the cervical oesophagus is thus signalled by the sequential stimulation of the endings.

I wish to thank Professor G. H. Bell for his interest in this work.

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