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DETERMINATION OF INTRATHORACIC CONDUCTION TIME IN CARDIOVASCULAR AFFERENT FIBRES OF THE VAGUS NERVE

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The responses of cardiovascular sensory endings have been studied by several investigators, and in all known cases a specific natural stimulus has been accepted as the causal agent for stimulating a particular type of ending (see Heymans & Neil, 1958). For instance, it is believed that type A atrial endings are stimulated by a rise in atrial pressure (Amann & Schaefer, 1943; Jarisch & Zotterman, 1948; Whitteridge, 1948; Dickinson, 1950; Paintal, 1953*a*; Struppler & Struppler, 1955; see also Heymans & Neil, 1958), especially since the main burst of impulses in these receptors coincides with the a wave of the venous-pressure curve, and very often follows this curve closely (Whitteridge, 1948; Dickinson, 1950). Such conclusions are based on the tacit assumption, that the conduction time from the endings to the recording electrodes, usually somewhere along the cervical vagus, is insignificant, and that for practical purposes this may be ignored when correlating the changes in impulse activity to changes in intravascular pressure at the peripheral site in or near the heart. Occasionally an arbitrary allowance has been made for conduction time (Pearce & Whitteridge, 1951).

It is also assumed generally that the myelinated afferent fibres remain myelinated throughout their course and also that there is no significant reduction in the conduction velocity of the fibres in their intrathoracic course. This is a risky assumption, because Iggo (1958) has indicated that the conduction velocities of some vagal afferent fibres are greater in the proximal part of the cervical vagus and has suggested that some myelinated fibres may lose their myelin sheath in the distal part of their course.

In view of the above it was considered necessary to determine the intrathoracic conduction time of cardiovascular afferent fibres. This paper will describe the methods used for this purpose and the results obtained. It will be shown that, although there is hardly any reduction in intrathoracic

conduction velocity in some afferent fibres, there is some reduction in most of them, but there is probably little, if any, non-myelinated propagation in these fibres.

METHODS

Adult cats anaesthetized with chloralose 75–80 mg/kg after induction with ether were used throughout this investigation. The methods used for dissecting thin filaments from the vagus, recording their impulses and determining the conduction velocities of particular afferent fibres were essentially similar to those described earlier (Paintal, 1953*b*), except that a Tektronix oscilloscope was used in place of some of the apparatus described earlier. Attempts were made to keep the temperature of the cervical vagus close to 37° C, but in several experiments it deviated by about 1° C and in a few experiments by about 2° C. In such instances a temperature correction for conduction velocity was made, a Q_{10} of 1·3 being assumed (Paintal, 1953*b*).

E.c.g. lead 2 was recorded simultaneously. During part of some experiments the right arm electrode was replaced by an electrode in the right atrium provided by the tip of a catheter filled with 0·9 % NaCl solution. This yielded a prominent *P* wave large enough to trigger the sweep.

Atropine sulphate 1 mg/kg was injected intravenously whenever necessary.

In some experiments antidromic stimuli were applied to the vagus in alternate cardiac cycles (Fig. 5). Figure 1*A* shows a simplified block diagram of the circuit used to achieve this, and Fig. 1*B* the associated wave forms generated by the circuit, numbered to correspond to the stages in the block diagram. The circuit operated as follows: the P wave of the e.c.g. (1) triggered the sweep of the oscilloscope (2) and the start of the sweep provided a triggering pulse (3) which in turn triggered a variable saw-tooth generator (4). The duration of this saw tooth (i.e. 4) was adjusted to about $1\frac{1}{2}$ cardiac cycles (see Fig. 1*B*) so as to block every alternate triggering pulse from the trigger circuit (3). The start of the saw-tooth from (4) provided a triggering pulse (5) which triggered the stimulator (6) for stimulating the vagus.

In order to distinguish the sweeps with an antidromic stimulus from those without it, the two were displaced vertically, as shown in Fig. 5. This was done either by applying a suitable square wave from a square-wave generator (7) triggered by (5) into the input of the d.c. amplifier of the oscilloscope, as shown in Fig. 1*A*, or by using the switching circuit of the Tektronix 53/54C dual trace plug-in unit and connecting the preamplifier to both inputs of this unit, which was switched to 'alternate sweeps' operation so that the multivibrator of the 100 kc electronic switch was converted functionally into a flip-flop triggered by the fly-back of the sweep (for details see instruction manual of Tektronix 53/54 plug-in unit, Tektronix Inc., Portland, U.S.A.).

RESULTS

In the initial experiments intrathoracic conduction time was determined by stimulating the vagus or its branches in the thorax or by stimulating the region in the atrium or aorta wherein the receptor was located and recording the time of arrival of the evoked impulse at the recording electrodes. Since it was possible to locate the receptor precisely only after the heart had stopped, local electrical stimulation was carried out after cardiac stand-still had been produced by bleeding the cat. From the values of intrathoracic conduction time thus obtained, the intrathoracic conduction velocity was determined in the usual way after making

necessary corrections for the deviation of the mediastinal temperature from 37° C.

The intrathoracic conduction velocities of 7 arterial baroreceptor afferent fibres and type *A* and type *B* atrial fibres determined in this way were found to be about 40–60 % less than the conduction velocity of the

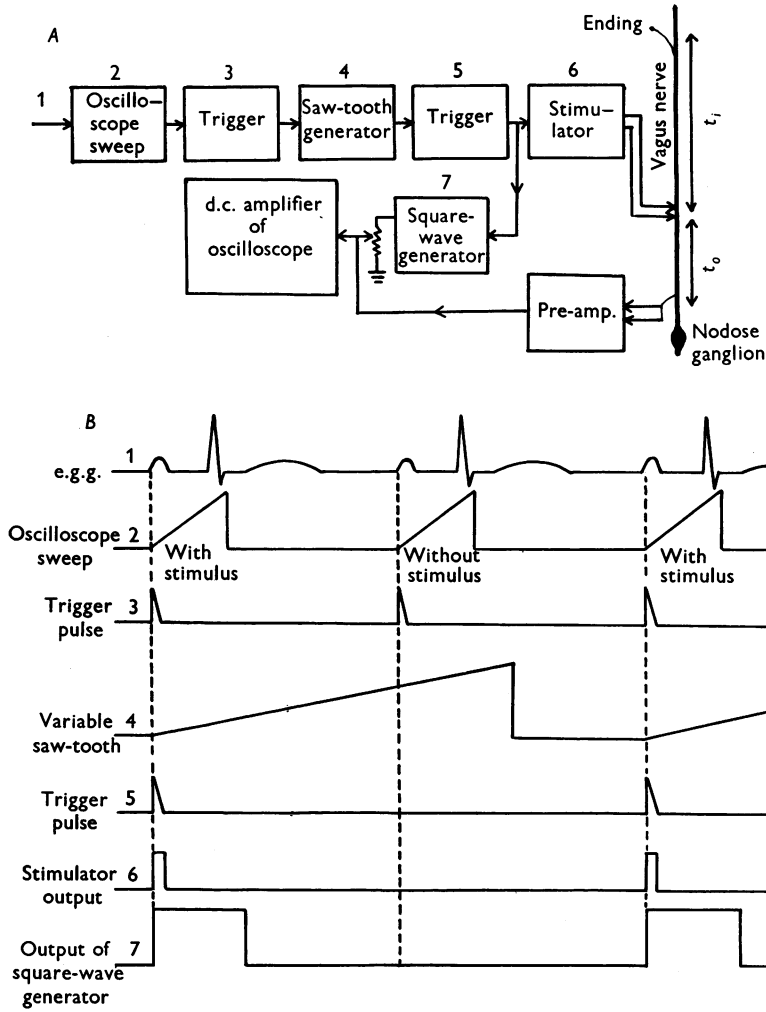

Fig. 1. Schematic block diagram of the circuit (*A*) and the wave forms generated by it (*B*) in the set-up used for stimulating the endings antidromically during every alternate cardiac cycle and simultaneously deflecting the sweep vertically by applying a square-wave voltage bias from the output of a square-wave generator (7), or by using a suitable switching circuit (see text). The wave forms in *B* are numbered to correspond to the sections of the circuit in *A*. A sample of the record obtained by this set-up is shown in Fig. 5.

fibre in the cervical vagus. Initially this reduction was attributed to asphyxia, but in one experiment the conduction velocity was determined while the heart was beating normally and in this instance also the intrathoracic conduction velocity was reduced, being 42% of that in the cervical vagus. The reduction in conduction velocity could not, therefore, be attributed to asphyxia, especially since cervical conduction velocity remained unchanged in all experiments, and so it was at first concluded that the conduction velocity was actually much lower in the distal part of the vagus.

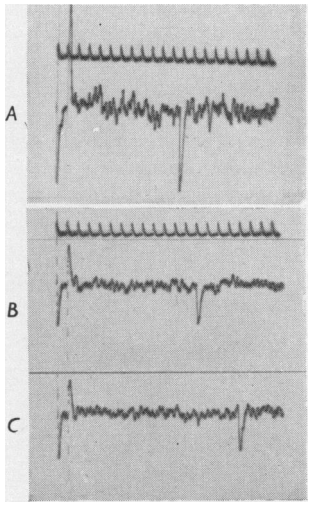

Fig. 2. Evoked impulses in a fibre from a right atrial type B receptor obtained by stimulating the atrium locally after cardiac standstill. Sweeps *B* and *C*, in which the gain was reduced to half that in *A*, were taken about 10 and 15 min after *A*, respectively. These show that total conduction time in the fibre increased with time and this method of determining total conduction time is therefore unreliable.

However, suspicion was later aroused when it was noted that in some cases the total conduction time from the peripheral site in the heart to the recording electrodes increased with time in the same fibre after cardiac standstill (Fig. 2) and conduction ceased in others at a time when the velocity in the cervical vagus was unaltered. This showed clearly that the results obtained by stimulating the fibre near its peripheral termination were variable under these conditions and it was therefore necessary to find other ways of determining intrathoracic conduction time.

While searching for a suitable method it was found that the natural cardiovascular stimuli such as atrial contraction in the case of type A endings and the aortic pressure pulse in the case of aortic-baroreceptors

yielded fairly reproducible impulse activity from one cycle to the next, provided respiratory fluctuations could be eliminated. Also the interval between the first and second impulses tended to be nearly the same from cycle to cycle (Figs. 3 and 5). In view of this observation it was decided to use the following method for determining intrathoracic conduction time. The description concerns type A atrial fibres.

The time base was triggered by the prominent P wave of the e.c.g. (intracardiac lead II, Fig. 3) and the position of the first impulse was recorded in 4 or 5 cycles after stopping the respiratory pump (Fig. $3B_1$, B_2) and after injecting atropine into the cat. Next, an antidromic stimulus was applied as much before the first impulse as possible and the effect of this in delaying the appearance of the first impulse was noted in successive sweeps (Fig. $3B_3$, B_4). As expected, the antidromic stimulus depressed the ending, thereby delaying the initiation of the first impulse, and as it were re-setting the rhythm of the ending (see Matthews, 1933; Paintal, 1959*b*). The same procedure was then repeated several times after bringing the antidromic stimulus closer and closer to the first impulse (Fig. $3C_3$, C_4). The relation between the interval between the antidromic stimulus and the first impulse (abscissa) and the delay in the appearance of the first impulse following the antidromic stimulus (ordinate) was then plotted as in Fig. 4. Each point on this graph represents an average of 3–6 observations.

From this curve (Fig. 4) it is evident that when the stimulus was applied about 40 msec or more before the arrival of the first impulse at the recording electrodes, the appearance of the first impulse was delayed only a little, and that, as the antidromic stimulus was brought closer, the appearance of the first impulse was delayed much more. Bringing the antidromic stimulus still closer eventually caused the antidromic impulse to collide with the first impulse after its initiation at the normal time, so that the first impulse recorded then was in fact the second impulse of the normal train of impulses. For collision to take place the antidromic stimulus must be applied at an interval that is less than $2t_1+t_0$ before the normal time of appearance of the first impulse at the recording electrodes (see Fig. 2 in Iggo, 1958 and Fig. 3 in Paintal, 1959*a*), where t_1 is the conduction time in the fibre between the ending and the stimulating electrodes placed in the distal part of the neck, and t_0 the conduction time between the stimulating electrodes and recording electrodes near the nodose ganglion (Fig. $1A$). The aim of every experiment therefore was to determine the value of $2t_1+t_0$ from graphs such as those shown in Fig. 4, so that intrathoracic conduction time (t_1) could be derived. This entailed the following procedure which is described in detail.

First, it was assumed that intrathoracic conduction velocity could be less but not more than cervical conduction velocity, since there is no known instance of increase in conduction velocity in the peripheral part of nerve fibres. Accordingly, the minimum predicted intrathoracic conduction time was first computed by dividing the intrathoracic conduction distance by

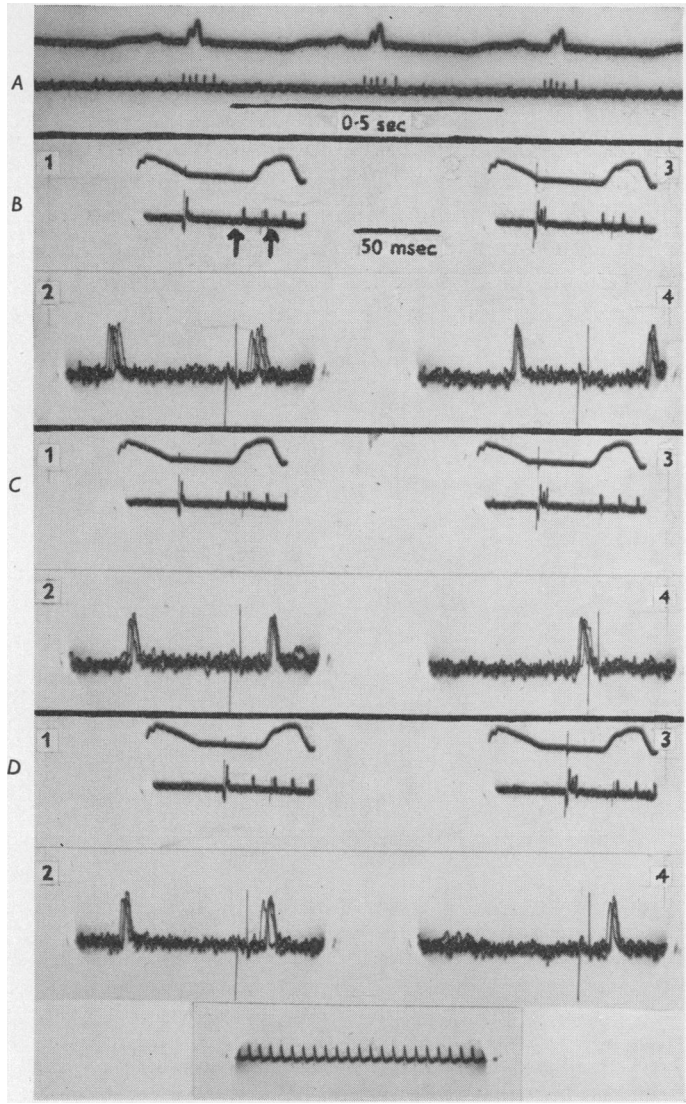

Fig. 3. Determination of intrathoracic conduction time in a left atrial type A afferent fibre. *A* is part of a continuous record with e.c.g. lead 2 showing the characteristic pattern of discharge. In *B* 5 superimposed sweeps were recorded at B_1 on one double-beam cathode-ray tube, and another set, B_2, on another cathode ray tube simultaneously. The sweeps in B_2 are an expanded part of the sweeps shown between arrows in B_1, and they show the first two impulses of the burst. In sweeps B_1, B_2, C_1, C_2, D_1, D_2 the stimulus to the vagus, which is seen before the first impulse in the upper sweeps only, was just subthreshold for the fibre. In B_3, B_4, C_3, C_4, D_3 and D_4 the stimulus was suprathreshold, so that an antidromic impulse was generated. In B_3 and B_4 the antidromic impulse arrived at the ending before the first impulse was initiated, thereby delaying the appearance of the first impulse a little (compare first impulse in B_2 and B_4). In sweeps C_3 and C_4 the antidromic stimulus was brought closer to the first impulse and this delayed the appearance of the first impulse still further; the second impulse is not seen in C_4. In D_3 and D_4 the antidromic impulse collided with the first impulse, so that the second impulse appeared at its normal time as compared with D_2. The vertical lines are electrical artifacts locked to the sweep. The millisecond time marks at the bottom are for the expanded sweeps.

the cervical conduction velocity of the fibre, and from this the minimum value for $2t_1+t_0$ was calculated. Thus in the case of the fibre of Fig. 4 the minimum value was 20·2 msec (in Fig. 6 it is 10·9 msec), and it was assumed that if the antidromic stimulus was applied less than 20·2 msec before the first orthodromic impulse, the antidromic impulse would collide with the orthodromic impulse and the first impulse recorded then would be the second impulse occurring at its normal time.

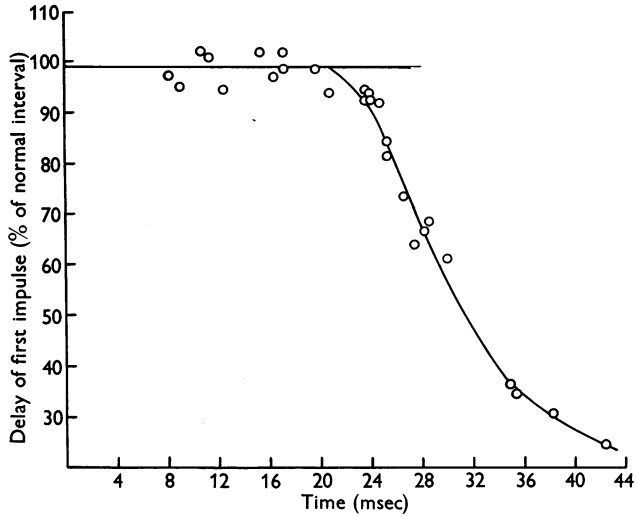

Fig. 4. Graph showing the delaying effect of an antidromic impulse on the initiation of the first impulse in the same receptor as is shown in Fig. 3. The abscissa represents the interval between the antidromic stimulus and the normal time of appearance of the first impulse obtained from sweeps such as those shown in B_1 and B_2. The ordinate represents the delay in the appearance of the first impulse expressed as a percentage of the normal interval between the first and second impulses. The horizontal line at 99 % represents the average moment of appearance of the second impulse after the antidromic impulse had collided with the first. The graph begins to slope downward at 20·5 msec, which represents the interval between the antidromic *stimulus* and the normal moment of appearance of the first impulse when the antidromic *impulse* has an even chance of colliding with the first impulse or arriving at the ending just before it is initiated. This interval $= 2t_1+t_0$. Minimum predicted value of this was 20·2 msec. For other details see fibre no. 7 in Table 1.

Secondly, the normal time of occurrence of the second impulse in relation to the first was determined from the sweeps with the antidromic stimulus subthreshold for the fibre, as in Fig. 3 B_2. This interval between the two impulses was regarded as 100 %. Thirdly, the antidromic stimulus was made suprathreshold, so that the antidromic impulse collided with the first orthodromic impulse, as in Fig. 3 D_3 and D_4, and the first impulse

recorded as Fig. $3D_4$ was therefore the second impulse of the normal burst. The interval between the collided first impulse and the second impulse was determined by assuming that the first impulse could have appeared at the same time as in Fig. $3D_2$ had it not collided with the antidromic impulse. This interval was expressed as a percentage of the normal interval (= 100 %), as described in the second step. If there were no fluctuations in impulse activity, this value would be 100 % in every case of collision, but owing to small variations in impulse activity due to slight cardiac slowing or to reflex effects it varied above and below 100 %, so that the points less than 20·2 msec in the abscissa in Fig. 4 are distributed in this manner. Fourthly, all the values for points on the abscissa less than 20·2 msec were averaged and a straight line drawn to represent this value, which is 99 % in Fig. 4 (97·4 % in Fig. 6). In view of these small differences from 100 % one could arbitrarily draw the line at 100 % but this is likely to introduce certain errors when computing conduction time (see below).

Finally, the point where the graph of Fig. 4 met this line was taken as the interval when the antidromic stimulus had to be applied so that the antidromic impulse had an even chance of colliding with the first impulse. This interval was equal to $2t_1+t_0$, which in Fig. 4 amounts to 20·5 msec. From this, the value for intrathoracic conduction time, t_1, was obtained, which in the case of Fig. 4 is 8·3 msec. If the antidromic stimulus was applied at an interval greater than 20·5 msec before the normal time of appearance of the first impulse at the recording electrodes, the antidromic impulse arrived at the ending before the first impulse was initiated, thus resetting it and delaying its arrival at the recording electrodes (Fig. 4). As is shown in Fig. 4 the amount of delay depended on the interval between the antidromic stimulus and the normal time of appearance of the first impulse, the greater the interval, the less the delay; this is to be expected. The initial part of the curve was linear in about half the cases, but in the others (e.g. Figs. 4 and 6) it was slightly curved, depending on the distribution of the points beyond the predicted limit for collision. Thus the initial curve in Fig. 4 is due to the point at 20·8 msec, in the absence of which this part of the graph would have been linear.

In order to obtain the records from which the graphs such as that shown in Fig. 4 were constructed it was necessary to record the sweeps on two cathode-ray tubes, as in Fig. 3. In the simplest arrangement (Fig. 3) the P wave triggered the sweep and the interval between the subthreshold antidromic stimulus and the first impulse was recorded on superimposed sweeps on one beam of a double-beam cathode-ray tube (Fig. $3B_1$); on the other beam the e.c.g. was recorded. On the second cathode-ray tube (B_2 in Fig. 3) was displayed an expanded portion of the sweeps shown between

arrows in B_1, so that the position of the first re-set impulse and the second impulse could be determined more precisely. In each series, to start with, superimposed sweeps were recorded with the antidromic stimulus subthreshold for the afferent fibre (Fig. 3 B_1, B_2, C_1, C_2, D_1, D_2), and in the next series the stimulus was increased so that it was suprathreshold for the fibre (Fig. 3 B_3, B_4, C_3, C_4, D_3, D_4). The change in the position of the re-set first impulse could then be assessed from these two sets of superimposed sweeps as described already. A short-lasting artifact was introduced so

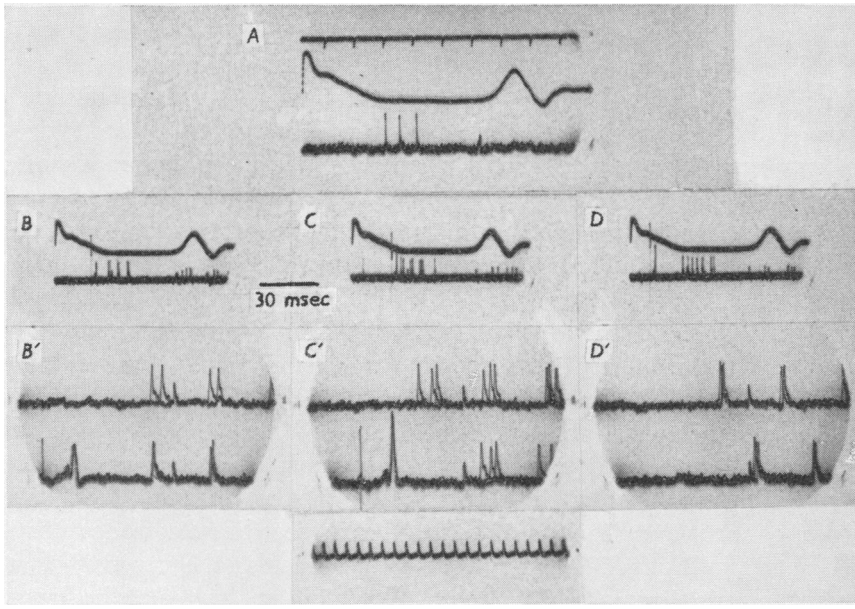

Fig. 5. Records showing the use of alternate sweep stimulation (see Fig. 1) for determining intrathoracic conduction time in a fibre from a left atrial type A receptor. Sweeps were triggered by the large P wave of intra-atrial lead 2, as in Fig. 3. *A* shows the normal pattern of discharge of 3 impulses in a burst. *B* shows 4 superimposed sweeps and *B′* 2 superimposed sweeps (expanded portions of sweeps in *B*) on each of two traces. The sweeps with an antidromic stimulus are displaced downwards as described in Methods. In *B′* the antidromic stimulus was subthreshold for the fibre, in order to show that the distribution of impulses in the two sets of sweeps is symmetrical. In *C* and *C′* the stimulus was suprathreshold, so that the antidromic impulse collided with the first impulse (note its absence in the lower sweeps of *C′*) and left the moment of appearance of the second impulse unaffected, as shown by the identical average moment of appearance of the second impulse in the upper and lower sweeps of *C′* with respect to the small electrical artifact. In *D* and *D′* the antidromic impulse arrived before the initiation of the first impulse, thus delaying the appearance of the first re-set impulse in the lower trace in *D′*. Millisecond time marks at the bottom belong to the expanded sweeps.

that it served as a convenient reference point from which to measure changes in impulse intervals (Fig. 3).

However, although the results obtained by the above arrangement were usually satisfactory, at times considerable difficulties arose when the normal interval between the first and second impulses changed suddenly, or when the triggering level of the sweep changed so that a different part of the P wave of the electrocardiogram triggered the sweep. If either of these changes took place, and especially if the interval between the first and

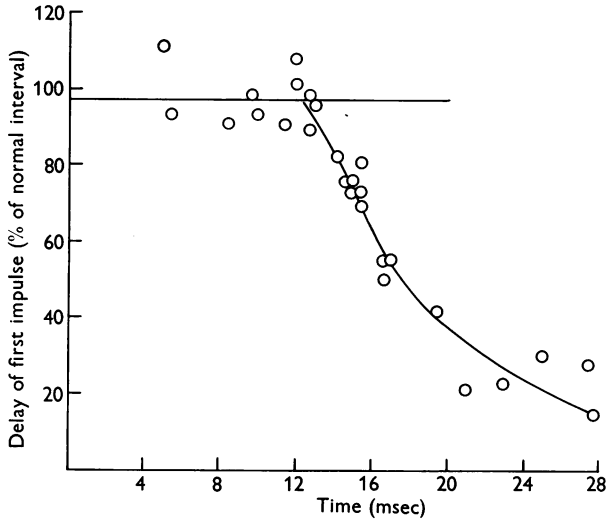

Fig. 6. Graph obtained from the experiment illustrated in Fig. 5. Minimum predicted value of $2t_i+t_0$ was 10·9 msec; value computed from graph is 12·0 msec. Computed t_i is 4·7 msec. For other information see fibre no. 12 in Table 1. Abscissa and ordinates as in Fig. 4.

second impulses tended to fluctuate, then sweeps with a subthreshold antidromic stimulus could not be compared with those with a suprathreshold one, and the results had to be discarded. In order to overcome these difficulties it was arranged to stimulate the vagus during every alternate cardiac cycle (Fig. 5). This ensured a more constant stimulation of the vagus and it also enabled one to compare sweeps with and without an antidromic stimulus more or less in the same part of the respiratory cycle. Thus if there were any changes in the impulse interval or the triggering level, these changes would affect both sets of sweeps equally or almost equally. This arrangement required that there should be some method for distinguishing sweeps without an antidromic stimulus from those with one. The methods used for achieving this have been described under Methods and the type of records obtained is shown in Fig. 5. The graph constructed from such records is shown in Fig. 6.

In some cases the vagus was cut or crushed near the nodose ganglion, so that reflex effects of electrical stimulation of the vagus were prevented. However, with stimulation in alternate cardiac cycles this was not always necessary, because here stimulation was more or less constant. For the same reason it was sometimes not necessary to inject atropine into the cat.

It may be argued that instead of using the P wave to trigger the sweep the first impulse of the burst could have been used to trigger it, and the effect of the antidromic stimulus in re-setting the second impulse could have been used to obtain the same information about intrathoracic conduction time. However, this was usually not possible because the interval between the first and second impulses was too small, being usually less than 5–10 msec, so that even if the type A fibre had the maximum conduction velocity of 27 m/sec (Paintal, 1953*b*) throughout its length, and though the stimulus was applied immediately after the first orthodromic impulse, the antidromic impulse could still not be made to arrive before the normal time of initiation of the second impulse because the intrathoracic conduction distance was about 80 mm (t_1 = 3 msec) and the cervical conduction distance was about 50 mm (t_0 = about 2 msec). However, since the conduction velocity of aortic-baroreceptor fibres is higher (see Paintal, 1953*b*) and intrathoracic conduction distance concerned is also less, in the case of three such fibres the sweep was triggered by the first impulse and the effect of the antidromic stimulus on the second impulse was studied. Further, this was necessary in the case of arterial baroreceptors because the interval between the QRS of the e.c.g. and the first impulse of the burst is often long, being sometimes 80 msec, so that slower sweep speeds had to be used which reduced the accuracy of the measurements. This also applies to type B atrial receptors, in which the latency of the first impulse after the QRS is even greater. However, using the first impulse to trigger the sweep and noting the effect of the antidromic stimulus in delaying the second impulse has the disadvantage that there is a limited interval within which to examine the re-setting effects of the stimulus determined by the impulse interval and the conduction velocity of the fibre. Therefore only a small part of the curve relating to the interval between the stimulus and the first impulse (abscissa) and the delay in the second impulse (ordinate) can be obtained.

In column 4 of Table 1 the intrathoracic conduction times of 12 afferent fibres computed by the above methods have been tabulated. The results show that in 7 fibres the difference between the minimum predicted conduction time and that computed from the graphs was 0·5 msec or less. In 2 fibres it was greater than 0·5 msec but less than 1 msec; in 2 it was less than 1·3 msec and in only one fibre the difference was as large as 5·4 msec.

The intrathoracic conduction distances used for calculating the predicted intrathoracic conduction time (column 3 in Table 1) were measured from the cathode of the stimulating electrodes placed low in the neck to the middle of the left or right atrium with a pair of calipers. Precise location of the ending was not attempted. The measurements were made in the absence of any external attachments to the heart tending to increase or decrease the distance from the electrodes. Attempts were made to

TABLE 1. Intrathoracic conduction times and conduction velocities in cardiovascular afferent fibres

Serial no.	Location and type	Intrathoracic conduction time at body temperature (msec)		Difference between columns 4 and 3 (msec)	Cervical conduction velocity at 37° C (m/sec)	Intrathoracic conduction velocity at 37° C (m/sec)	
		Predicted minimum (msec)	Computed from graphs (msec)			Computed from column 4	Determined by local stimulation
1	SAR	0·8	< 0·8*	< −0·0	46·1	> 43·7	—
2	SAR	1·2	< 2·4*	< +1·2	38·8	> 19·2	—
3	SAR	1·5	1·9	+0·4	28·9	23·2	—
4	SAR	2·0	3·3†	+1·3	24·6	14·9	22·4
5	LAA	4·9	5·8	+0·9	18·4	15·7	—
6	LAB	5·9	< 6·6*	< +0·7	16·7	> 14·9	17·2
7	LAA	8·2	8·3	+0·1	12·5	12·4	—
8	RAA	5·1	4·6	−0·5	15·2	16·9	12·8
9	RAA	3·4	3·9	+0·5	26·2	22·8	—
10	RAA	5·5	10·9	+5·4	14·5	7·3	10·8
11	LAB	5·2	5·2	±0·0	15·7	15·8	15·5
12	LAA	4·2	4·7	+0·5	18·5	16·6	—

* Graphs incomplete; † computed with open chest; SAR, systemic arterial baroreceptor; LAA, left atrial type A receptor; LAB, left atrial type B receptor; RAA, right atrial type A receptor.

measure the distances while the heart was beating, but in a few cases the distances were measured after the heart had stopped. This apparently did not make any difference in the measurements. Since the cathode of the stimulating electrodes was usually situated about 1 cm rostral to the apex of the chest, an allowance for this must be made if figures for the exact intrathoracic conduction time are desired. This amounts to a reduction of 10–12 % in the figures given in column 4 of Table 1.

It is possible that the conduction velocities may have been slightly underestimated, since the conduction distances were measured as the shortest distance between two points. However, at present no estimate can be made of the amount of tortuosity of the fibres from the vagal trunk to the endings.

Errors arising from initiation of the impulse at some distance from the

cathode (Rushton, 1949) have also to be kept in mind in the case of faster conducting fibres especially when the conduction distance involved is small, e.g. fibres 1–4 (Table 1), in which the intrathoracic conduction distance was 43–45 mm. However, the results suggest that this error is not likely to be significant.

In Table 1 are also given the results of determining intrathoracic conduction velocity by stimulating the fibre peripherally in the thorax while the heart was beating in four experiments and after cardiac standstill in one (fibre no. 4). In the case of the atrial fibres the stimulating electrodes were applied in the region where the veins enter the atria. Stimuli of 1 msec duration were used because pulses of shorter duration yielded inconstant responses. The threshold was usually about 8–12 V, and depended on experimental conditions such as the presence of blood and movement of the tissues. By moving the stimulating electrodes about locally, the most sensitive area was found and the conduction distance from the recording electrodes to this point was measured for determining the conduction velocity. As can be seen from Table 1, the intrathoracic conduction velocity determined in this way agreed closely with the cervical conduction velocity in 3 out of 5 fibres. In fibre no. 8 it was clearly less than the conduction velocity computed from the graphs of the reset impulse (column 7), thus confirming the earlier conclusion that the intrathoracic conduction velocity determined in this way may not be representative of the true conduction velocity of the fibre with intact chest. However, this does not mean that the method itself is defective, because it is very likely that the velocity of the fibre fell after the chest was opened owing to fall in temperature, pressure, etc. The main defect of this method is that it provides no information about the conduction velocity of the fibre between the peripheral stimulating electrodes and the endings.

On the other hand, in fibre no. 10, although the directly measured conduction velocity was less than the cervical conduction velocity it was clearly greater than the conduction velocity computed from the graphs. This shows, first, that the intrathoracic conduction velocity was less than the cervical conduction velocity even with intact chest, and secondly that it was probably still lower in the course of the fibre from the peripheral stimulating electrodes near the great veins to the ending, a distance of about 24 mm, because the conduction velocity computed in this case was about 7·9 m/sec as against 10·8 established electrically.

DISCUSSION

Since in four fibres the computed intrathoracic conduction time exceeds the predicted minimum conduction time by less than 0·1 msec (fibres nos. 1, 7, 8 and 11 in Table 1), it follows that there was no obvious reduction in

intrathoracic conduction velocity in these four fibres, a fact confirmed by the results of local electrical stimulation in one fibre (no. 11, in Table 1). Marked reduction in conduction velocity (50 %) was present in only one right atrial fibre (fibre no. 10 in Table 1) and although it seemed to be reduced by 40 % in another fibre (no. 4, Table 1) this should be looked upon with suspicion, because the intrathoracic conduction time was computed after opening the chest. In two fibres the velocity was reduced by 11 % (fibres nos. 6 and 12 in Table 1) and between 13 and 20 % in three other fibres (fibres nos. 3, 5 and 9). It may therefore be concluded that although the intrathoracic conduction velocities of about a third of the cardiovascular afferent fibres is the same as their cervical conduction velocities, it is reduced by varying amounts in about half of them. Only in a small number of fibres (about 10 %) is it reduced by about half. Also it can be concluded that there must be very little non-myelinated conduction, because even if the reduction in conduction velocities is attributed entirely to non-myelinated propagation, still this cannot exceed 1–2 mm in most of the fibres and rarely can it (if at all) amount to 5–10 mm.

If the results are taken as a whole it can be concluded that the actual intrathoracic conduction time in about 85 % of the fibres from the atria will not exceed the minimum predicted value by about 1 msec. Therefore, if the cervical conduction velocity of a particular afferent fibre is known and the location of its ending is also known, the actual moment of initiation of impulses at the ending can be calculated with some confidence. If a measure of the conduction velocity of a particular fibre is not available, but its receptor is in the atria, and if the impulses are recorded near the nodose ganglion, then it may be assumed that the total conduction time from the ending to the recording electrodes will range from 4 to 19 msec, and there will be a 70 % chance that it will be less than 10 msec, allowing for a small amount of slowing in the chest. This is because (1) the mean conduction distance from the middle of the left atrium to the nodose ganglion measured with a pair of calipers averaged 138 mm in 13 cats (range = 120–152 mm; S.D. = 9), and from the middle of the right atrium it averaged 128 mm in 9 cats (range = 188–138 mm; S.D. = 8), and (2) the conduction velocity of atrial afferent fibres (type A and type B) ranges from 8 to 27 m/sec (Paintal, 1953*a*). Further, in the present investigation the conduction velocities of 35 atrial afferent fibres (19 type A and 16 type B) were determined and the mean conduction velocity averaged 18 m/sec in both. On pooling the earlier results with the present ones, it was found that 75 % of the atrial fibres had a cervical conduction velocity greater than 15 m/sec.

Some of the curves obtained from the re-set first impulse were almost linear, but most of them had a more gradual slope in the latter part as in

Figs. 4 and 6. This was because, when the antidromic stimulus was applied at a relatively greater interval before the normal initiation of the first impulse, the depressant effects of the antidromic impulse wore off largely before the initiation of the orthodromic impulse, so that there was only a slight delay in its initiation. When the stimulus was brought closer, the depressant effects of the antidromic impulse became more effective, so that the delay in the initiation of the first impulse increased. Thereafter, there occurred a somewhat linear increase in delay with further reduction in the interval between the antidromic stimulus and the normal time of initiation of the first impulse (curve between 26 and 34 msec in Fig. 4).

The chief defect in the present method used for determining intrathoracic conduction times is that it is a tedious process involving several hundred measurements in each case, and the method can be used with success only in those cardiovascular endings which yield almost identical trains of impulses in at least 3–4 successive cycles. Further, if the method of antidromic stimulation in alternate cardiac cycles combined with the recording of the corresponding sweeps as in Fig. 5 is not used, it is necessary that the trains of impulses should be similar in successive respiratory cycles. Also it is necessary that the interval between the electrical event of the heart, triggering the sweep, and the first impulse of the burst should not be too large, so that variations in the electromechanical events of the heart can be avoided. Thus it is not convenient to use this method in the case of type B atrial endings which have a late systolic discharge (Paintal, 1953*a*). In such cases one could trigger the sweep by the first impulse of the burst and note the re-setting effects of the antidromic stimulus on the second impulse. However, for this it is necessary that the interval between the first and second impulses should be larger than $2t_1+t_0$ and if one assumes that a type B fibre has a typical cervical conduction velocity of about 15 m/sec, it implies that the interval between the first and second impulses should be greater than 18–20 msec in order that some reliable observations on re-setting may be made. Type B endings discharging at such a low frequency, about 50 impulses/sec, are not common.

From the above reasoning it should also become clear that the interval between the electrical event of the heart triggering the sweep, and the first impulse, should be greater than $2t_1+t_0$, i.e. it should be at least 20 msec in the case of a fibre with a cervical conduction velocity of about 15 m/sec. For this reason it will not be possible to use this method in the majority of ventricular receptors if the sweep is triggered by the Q wave; in such cases the P wave could be used to trigger the sweep.

Another defect in the method is that one cannot say at exactly what interval between the antidromic stimulus and the appearance of the ortho-

dromic impulse at the recording electrodes collision took place, because the initial part of most graphs (e.g. Fig. 4) has a gradual downward slope and there is sometimes considerable scatter of the points on the graph. Part of this scatter is due to the fact that the interval between the antidromic stimulus and the normal moment of initiation of the first impulse in the absence of re-setting is not known. Only an estimate of this interval can be obtained from sweeps without, or with, the antidromic stimulus subthreshold for the afferent fibre (Figs. 3 and 5). However, the error involved in the computed intrathoracic conduction time is probably not more than about 0·5 msec in most cases, because it is possible to establish the beginning of the downslope of the curve correctly within 1 msec, as in Figs. 4 and 6. Confirmation of the results can be obtained by local electrical stimulation which, though it has its own defects, as shown in this investigation (Fig. 2), can nevertheless be of value, as in the case of fibre No. 4 in Table 1. Here it is suggested that there was probably either some error of about 1 msec in the computed value of intrathoracic conduction time in this case, or that there was marked reduction in the conduction velocity in the distal part of the fibre.

The information gained from this investigation has proved to be of considerable value in establishing the causative relation of a particular mechanical stimulus to the discharge of impulses produced by it.

SUMMARY

1. In cats with the chest intact a method of determining intrathoracic conduction time in certain cardiovascular afferent fibres from the receptor ending to the apex of the chest is described. The method which yields satisfactory results consists of plotting a graph of the interval between an antidromic stimulus and the first impulse of the burst (abscissa) against the delay in the appearance of this impulse (ordinate) caused by the stimulus, and determining from this graph the time taken by the antidromic impulse to arrive at the ending.

2. Out of 12 fibres the values in 7 of them computed in the above way deviated from the minimum predicted value by 0·5 msec, or less; in 4 it exceeded the predicted values by 0·5–1·3 msec and in only 1 it exceeded it by 5·4 msec.

3. Certain technical details aimed at eliminating errors due to fluctuations in impulse activity are described. The best arrangement is one in which the antidromic stimulus is applied in alternate cardiac cycles, and sweeps with the stimulus, which are suitably distinguished from those without it, are recorded during the same exposure (Fig. 5).

4. It is concluded that the intrathoracic conduction velocity with intact chest is not reduced in about a third of the fibres; it is reduced by 10–20 %

of the cervical conduction velocity in about half of them and in only a few is it reduced by half or more.

5. The results indicate that in the majority of the fibres from type A and type B atrial receptors the total conduction time from the ending to the nodose ganglion will not exceed the minimum predicted value by about 1 msec.

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