

THE CONDUCTION OF THE IMPULSE FOR CARDIAC CONTRACTION

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INTRODUCTION

Following the foundations laid by Engelmann (1875, 1878, 1894, 1895, 1897, 1900, 1903), Gaskell (1882, 1883, 1900), MacWilliam (1885), His, jun. (1893), Tawara (1906), Keith & Flack (1907) and Lewis (1916, 1921), it is widely believed that the automatic rhythmicity of the hearts of vertebrates is myogenic in origin, and that the impulse for contraction is transmitted throughout the several cardiac chambers, and from one chamber to the next, by the muscle fibres rather than by nerves. In mammals and birds, special muscular structures exist which are held to conduct the cardiac impulse, namely, the sinu-atrial node, the atrioventricular node and the atrioventricular bundle with its two limbs and their terminal branches (the ventricular subendocardial Purkinje fibres). Keith & Flack (1907) believed that these elements are remnants of more extensive tissues of similar structure in lower vertebrates. Davies & Francis (1941) found that the hearts of poikilothermal vertebrates (Fishes, Amphibia, Reptilia) contain none of these structures and that the musculatures of the several cardiac chambers have uniform histological characters. They therefore concluded that the special structures in mammals and birds are neomorphic in nature, undergoing parallel development in these vertebrates, and that, if the cardiac impulse in poikilothermal vertebrates is conducted by muscle, it is the ordinary myocardium that is responsible. The myogenic conduction of the impulse from atria to ventricles in mammals has recently been challenged, particularly by Glomset & Glomset (1940), Glomset & Birge (1945, 1948) and Field (1951*a*), Glomset and his colleagues on the basis of their claim that in some mammals (dog, rhesus monkey and man) the atrioventricular (A.V.) node and bundle are either absent or feebly developed, and Field because in the A.V. bundle there are nerves which he suggested might be the agents that conduct the impulse. Many authors have noted the presence of nerves in the A.V. bundle of several mammals, while Cohn & Trendelenburg (1910) and Glomset & Birge (1948) stressed that in experimental lesions of the bundle, with resultant A.V. dissociation, the accompanying nerves are of necessity involved. Thus the experiments are not 'crucial' in determining which of the two elements of the bundle, muscle or nerve, conducts the impulse.

The present work involves a correlation between the time taken for the cardiac impulse to traverse the ventricles in mammals and birds and the degree of histological differentiation of the A.V. bundle and its branches, and it is submitted as collateral evidence in favour of the myogenic conduction of the impulse.

OBSERVATIONS

The *QRS* complex in electrocardiograms of mammals indicates the spread of the activation process throughout the ventricles; in birds, there is no preliminary *Q* deflexion in the electrocardiogram and the *RS* complex indicates this spread

(Lewis, 1916). Measurements were made of the duration of the *QRS* complex in several adult mammals and of the *RS* in two birds; they are expressed in hundredths of a second in Table 1. Some of the electrocardiograms were recorded by the present authors (sheep, cat, rabbit and wallaby). For some of the animals, measurements were made from published electrocardiographic records of other authors, e.g. cow (Alfredson & Sykes, 1942), man (Katz, 1941), dog, swan and pigeon (Lewis, 1916) and rat (Griffith & Jeffers, 1949). Electrocardiograms of the horse were obtained through the kindness of Prof. W. C. Miller, Equine Research Station, Newmarket.

Table 1. *The diameters of the muscle fibres of the atrioventricular bundle, the subendocardial Purkinje fibres and the ventricular myocardial fibres, the duration of the QRS complex in the electrocardiograms, and the heart rates (beats per minute) of a series of mammals and birds. The mammals and birds are respectively listed in order of decreasing sizes of the hearts*

Animal	A.v. bundle (μ)	Subendo- cardial Purkinje fibres (μ)	Ventricular myocardium (μ)	QRS (1/100 sec.)	Heart rate (calculated from e.c.g.)
Horse	35	88	12	7	44
Cow	30	40	12	9	71
Human	11	18	12	8	72
Wallaby	36	40	12	3.5	125
Sheep	30	40	12	3	180
Dog	12	18	12	4	180
Cat	9	15	12	4	240
Rabbit	10	14	12	3	187
Rat	9	13	12	2	300
Swan	35	44	9	3*	257
Pigeon	11	12	8	2.7*	182

* These figures refer to the *RS* complex, there being no *Q* deflexion in the bird (Lewis, 1916).

Measurements of the diameters of the muscle fibres of the a.v. bundle, the ventricular subendocardial Purkinje fibres and the ventricular myocardium were made on histological sections cut from adult hearts that had been uniformly treated by fixation in 10% formalin and impregnation in bulk by a silver-pyridine method (Blair & Davies, 1935). They were made directly, by means of a microscope eye-piece scale calibrated with a stage micrometer, on fibres which were cut longitudinally or transversely and through the central nuclei, excluding oblique sections and sections through the periphery of the fibres. Under these conditions the great majority of the fibres in each category were of the size stated in the table, though in each animal there was some range in the size of the fibres, the range being greater in the case of the Purkinje fibres than in the myocardial fibres. It was observed that the ordinary ventricular myocardial fibres in all the mammals examined showed a remarkable uniformity in diameter. On the other hand, the fibres of the a.v. bundle, as well as the subendocardial Purkinje fibres, show considerable differences in size from one mammal to another. In each mammal the subendocardial Purkinje fibres are larger than the muscle fibres of the a.v. bundle.

In the swan and pigeon, the ventricular myocardial fibres are smaller than those in the mammals, and the fibres of the a.v. bundle, as in the mammals, are smaller than the subendocardial Purkinje fibres.

DISCUSSION

Lewis (1921), under the title of 'The law of cardiac muscle', arranged the musculatures of different parts of the mammalian heart in sequence according to their properties as deduced from his experimental studies. For instance, in the dog both the diameter of the several fibres and the rate of conduction of the cardiac impulse in them were placed in the increasing order of A.V. node, ventricular muscle, atrial muscle, Purkinje fibres. This law applies to the different parts of one and the same heart, whereas the present work is a comparison between conditions in the hearts of different animal species.

From the results obtained, expressed in the table, the following comparisons may be made. First, among the mammals, the diameters of the muscle fibres in the A.V. bundle and of the ventricular subendocardial Purkinje fibres may be compared with the time taken for the cardiac impulse to traverse the ventricles (the *QRS* complex in the electrocardiogram). The *QRS* time (0.03 sec.) in the sheep is the same as that in the much smaller heart of the rabbit; the rate of conduction of the impulse is presumably, therefore, greater in the sheep. A notable difference between the two hearts is that the bundle fibres and Purkinje fibres in the sheep are about three times the size of those in the rabbit. The heart of the cow is much larger than that of the sheep; both the bundle fibres and the Purkinje fibres are respectively the same size in these animals, and the *QRS* time is three times as long in the cow (0.09 sec.) as in the sheep (0.03 sec.). The heart of the horse is larger than that of the cow, its bundle fibres and Purkinje fibres are larger, and the *QRS* time (0.07 sec.) is shorter than in the cow. The sizes of the bundle fibres and Purkinje fibres in general are related to the size of the heart, but that this is not necessarily so in all cases is indicated by a comparison of the human heart with that of the sheep. The human heart is much larger than that of the sheep, but the bundle fibres and Purkinje fibres of the sheep are much larger than in man; the *QRS* time in man (0.08 sec.) is much longer than that in the sheep (0.03 sec.). The *QRS* times in man, the cow and the horse are not markedly different, but the sizes of these hearts and the sizes of their bundle fibres and Purkinje fibres differ widely. The bundle fibres and Purkinje fibres in the cat are approximately the same size as those in the rabbit, but the *QRS* time is slightly longer in the cat (0.04 sec.), whose heart is bigger than that of the rabbit (*QRS*, 0.03 sec.). Likewise the bundle fibres and Purkinje fibres in man are about the same size as those in the dog, but the *QRS* time is much longer in the much bigger human heart.

The results expressed in Table 1 show that the duration of the *QRS* complex is not *solely* dependent on the size of the heart. For instance, the heart of the horse is very much larger than that of man, but the *QRS* time is actually slightly shorter, whereas the heart of man is larger than that of the dog and the *QRS* is also longer.

In all the mammalian hearts examined the ordinary ventricular myocardial fibres are the same diameter (12μ); it is only the fibres of the bundle and the Purkinje fibres which vary markedly in size. In each heart the subendocardial Purkinje fibres are larger than the bundle fibres; in man, cat, rabbit and rat the bundle fibres are actually smaller than the myocardial fibres and closely resemble them in histological structure. There thus appears to be a progressive differentiation, both as regards size and structure, of the fibres in the ventricular part of what is termed

'the conducting system' by those who hold the orthodox conception of the myogenic conduction of the cardiac impulse.

In general, it is seen that in hearts of unequal size, where the duration of the *QRS* is shorter in the larger heart, the fibres of the 'conducting system' are larger in the bigger heart (e.g. horse or cow compared with man; sheep compared with dog); where in hearts of different sizes the *QRS* is about the same, the bigger heart contains larger fibres in the 'conducting system' (e.g. dog and cat); and where in hearts of different sizes the fibres of the 'conducting system' are the same size, the *QRS* is longer in the bigger heart (e.g. cat and rat; cow and sheep). These comparisons in mammals suggest that there is a correlation between the diameter of the muscle fibres in the 'conducting system' and the rate of spread of the cardiac impulse through the ventricles.

This correlation also holds good in the case of the two birds examined. The heart of the mute swan (*Cygnus olor*) is very much larger than that of the pigeon; the fibres of its 'conducting system' are more than three times as large as those of the pigeon and its *RS* is only slightly longer.

The heart rates of the animals shown in Table 1 were calculated from the electrocardiograms; in each animal the rate is obviously subject to wide fluctuations. That in one and the same animal a varying heart rate does not influence the duration of the *QRS* complex is indicated, in man, by cases of sinus bradycardia and of tachycardia, in both of which the *QRS* is of normal duration. Electrocardiograms of horses at rest and after 20 min. severe exercise were loaned to the authors by Prof. Miller, and analysis of these shows that the durations of the *QRS* in the tracings of the hearts that had their rates accelerated by the exercise were the same as those of the resting animals.

Electrocardiographic records of a crocodile, *Crocodilus niloticus* (juvenile), were made by Davies, Francis & King (1951). The ventricles of this reptile have no A.V. bundle or Purkinje fibres, and the myocardial fibres are smaller (8μ) than those in the adult mammals examined in the present work. Although the heart of this animal is about the same size as that of an average-sized cat, the *QRS* complex in the electrocardiogram is much longer (0.13 sec.) than that in the cat (0.04 sec.), and indeed, longer than that in the mammals with much larger hearts. The slower rate of transmission in the crocodile, however, might in part be due to the lower body temperature (28° C.).

The above correlations are consistent with the orthodox view that in mammals and birds the cardiac impulse is conducted through the ventricles by the muscle fibres of the A.V. bundle and the peripheral Purkinje fibres, and they are submitted as evidence in support of that view.

Gasser & Grundfest (1936, 1939) have shown that the rate of conduction of an impulse in mammalian medullated nerve fibres is proportional to the diameter of the axis cylinders. In the present work a correlation has been made between the rate of spread of the cardiac impulse and the diameter of the fibres of the 'conducting system'. If these muscle elements are the true conductors of the impulse, the correlation may indicate that the phenomenon of conduction in them is a surface phenomenon as is known to be the case in nerves.

Finally, it is necessary to consider the nature of Purkinje fibres. The fibres

originally described by Purkinje (1845) are the very large fibres seen, for instance, beneath the endocardium of the sheep or cow, and characterized by irregular distribution of cross-striated myofibrillae and of the multiple nuclei within the fibres (Blair & Davies, 1935). Such fibres are also present in the a.v. bundle of some animals, e.g. horse, cow, sheep, wallaby and swan in the series examined in the present work. But in some animals the fibres of the a.v. bundle are smaller than (man, cat, rabbit and rat), or about the same size as (dog) the ordinary ventricular myocardial fibres, and rather closely resemble the latter in histological structure. Also in the rabbit and rat the subendocardial 'Purkinje fibres' are only very slightly larger than, and differ only slightly in structure from, the myocardial fibres. Nevertheless, the bundle and peripheral fibres in all these animals appear to be homologous, and in the absence of any alternative name even the small peripheral fibres are generally referred to as 'Purkinje fibres'. The term 'neuromyocardium', as applied to the fibres of the bundle or the peripheral fibres, suggested in the Birmingham Revised Terminology (1933) is, in the opinion of the present authors, unsuitable and misleading as an anatomical term with structural implications.

Some authors have considered that Purkinje fibres are embryonic fibres of arrested development, though Field (1951*b*) maintained that this does not mean that the fibres are really embryonic but merely that they have been held up in development and failed to acquire their full complement of striated myofibrils. Many others, including the present authors (Davies & Francis, 1941, 1946), considered them to be specialized fibres on one or more of the following grounds. At no stage in its development does the ordinary myocardial fibre have the structure of a fully formed Purkinje fibre, so that the latter cannot be considered to be embryonic heart muscle or to be muscle arrested in its development. The Purkinje fibre develops from an undifferentiated cardiac mesenchymal cell and proceeds along its own line of development to become a fully mature Purkinje fibre, increasing in size and differentiating in structure, and becoming an entity which, it is believed, is capable of conducting an impulse at a faster rate than the myocardium, the latter becoming specialized in structure in association with its prime function of contraction. In cold-blooded vertebrates no such differentiation takes place, the musculature having uniform histological characters throughout the heart. It is in this sense that the present authors (Davies & Francis, 1941) suggested that the elements of the 'conducting system' of mammals and birds are neomorphic, undergoing parallel evolution in these animals and, as is generally believed, having the physiological property of a more rapid rate of conduction than ordinary cardiac muscle. Another observation in favour of considering Purkinje fibres (and nodal fibres) as specialized structures is the age changes seen in the sizes of the different muscle fibres in the marsupial heart (Davies & Francis, 1942). The fibres of the sinu-atrial and atrio-ventricular nodes attain their full size and structure in the foetus (pouch stage) of the wallaby, and are then considerably larger than the ordinary cardiac muscle fibres, the latter only attaining their full growth later. The fibres of the a.v. bundle in the foetus are already much larger than those of the myocardium; they subsequently continue to increase in size, and in the adult they are also much larger than the myocardial fibres even though the latter have also considerably increased in size. Similar changes have been noted in the dog by the present authors. There thus

appears to be a differential rate of development between the fibres of the 'conducting system' and those of the ordinary myocardium.

Field (1951*b*) suggested that the changes in structure that Purkinje fibres in the sheep undergo during their development result from the relative inactivity of these fibres compared with the myocardial fibres, and that the changes are a differentiation (in its strict sense) rather than a specialization (implying a definite function). The present work, which indicates that a correlation can be made between the size of the fibres and the rate of spread of the cardiac impulse, is consistent with the view that the Purkinje fibres, varying in size and structure from animal to animal, are specializations related to the relative rate of conduction of the impulse.

The recent extensive experimental investigations in dogs by Sodi-Pallares, Rodriguez, Chait & Zuckermann (1951) showed that the spread of the impulse in the ventricular septum is in conformity with the distribution of the branches of the two limbs of the A.V. bundle. Davies, Francis & King (submitted for publication) found that the limbs of the bundle in the dog contain no nerves, and this observation, coupled with the work of Sodi-Pallares *et al.*, is submitted as strong evidence in favour of the conduction of the cardiac impulse by the bundle and its branches, rather than by nerves as other authors have suggested.

The results obtained in the present work suggest that it is possible to relate the time taken for the cardiac impulse to spread through the ventricles (*QRS* complex in the electrocardiogram) both to the degree of histological specialization attained by the muscle fibres of the 'conducting system' and to the size of the heart. In none of the animals examined was any exception found to this general thesis. The measurements of the muscle fibres in the hearts of the mammals and birds were not made from the same individuals as those from which the electrocardiographic records were taken; hence the correlations made above are expressed throughout only in general terms rather than as exact mathematical ratios.

SUMMARY

1. In a series of mammals and birds, the time taken for the cardiac impulse to traverse the ventricles, estimated from electrocardiograms, has been correlated both with the diameter of the muscle fibres of the A.V. bundle and of the ventricular subendocardial Purkinje fibres and with the sizes of the hearts.

2. The results are submitted as evidence in favour of the orthodox view that the impulse is conducted by the muscle fibres of the 'conducting system' of the heart.

3. Reasons are given for considering Purkinje fibres to be structures specialized for a particular function.

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