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Comparison of sinoventricular conduction in children and adults using bundle of His electrograms

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Sinoventricular conduction was measured in 28 children aged 3 days to 12 years, during diagnostic catheterization by recording His bundle electrograms. All of them had congenital heart disease and selective His bundle electrograms are illustrated. Comparison of the increments of conduction in 30 adults confirmed that the longer PR interval with age was entirely due to slower atrioventricular nodal conduction and that internodal and His Purkinje system conduction were similar in the two groups. Intraventricular conduction was slower in adults. Concepts of the evolution of conduction with age based on the results are presented with particular regard to the functional maturity of the specialized conduction fibres at birth.

The recent advances in the study of myocardial conduction using the His bundle electrogram have mostly depended upon measurements in adults, and normal values of the increments of impulse conduction from the sinus node to the Purkinje myocardial junction are now available (Scherlag *et al.*, 1969; Bekheit *et al.*, 1971). In adults it can be assumed that the conduction fibres are mature both functionally and morphologically. There is histopathological evidence, however, that the conduction fibres are by no means mature at birth and that they undergo a process of cell death and moulding during the first two years of life (Dawes, 1968; James, 1970). It therefore appears important to obtain information about the function of the 'immature' conduction fibres in children, and especially in infancy. Only a few publications of His bundle recordings in children are at present available and they give conflicting evidence about the evolution of atrioventricular conduction with age (Brodsky *et al.*, 1971; Roberts and Olley, 1971). Accordingly, we present in this paper the results of His bundle measurements in a group of 28 children aged 3 days to 12 years, of which 14 were less than 2½ years of age, i.e. during the process of postnatal moulding of the specialized tissues. We recognize that the selective sample is small, but His bundle recordings require an invasive technique and are only justifiable during diagnostic catheterization as a supplementary measurement. As expected, therefore, our children had congenital heart disease. However they all had normal PR intervals in scalar tracings according to their age and heart rate (Alimurung and Massell, 1956; Walsh, 1968). The measurements in the children are compared with those in a selection of adults who had His bundle recordings during diagnostic catheterization, and whose scalar tracings also had normal PR intervals (120–200 msec). The increments of conduction responsible for the variation in the PR interval with age could thereby be identified. In particular, His bundle recordings in the children up to 2½ years of age are important in view of the morphogenesis of the Purkinje system at this period of life and, where appropriate, analysis of this age group is compared with that of the older children. The data therefore presented in this paper have two main interests. Firstly it allows new concepts to be formed about changes in atrioventricular conduction with age, and secondly it gives information about atrioventricular conduction at a critical time in childhood. The latter is not just of academic interest as it has been suggested that the 'immature' Purkinje fibres may in some way be related to tachyarrhythmias and contribute to sudden unexpected death in infants (James, 1968). Structural changes, however, have to be correlated with electrophysiological studies for meaningful interpretation of their functional significance. As our children had congenital heart disease, examples of His bundle electrograms will be illustrated in selected cases. All of them had normal sinoventricular conduction.

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Patients and methods

The His bundle electrogram was recorded in 28 children, age range 3 days to 12 years (mean age 3 years and 7 months). Fourteen of the children were under 2½ years and were of particular interest with regard to the morphogenesis of the conducting tissues. Ten of the children were between 2½ and 6 years and the remaining 4 between 7 and 12 years. They were all sedated with a mixture of pethidine, promethazine, and chlorpromazine for catheterization purposes. The technique described by Scherlag *et al.* (1969) was employed for His bundle recordings. Briefly, a No. 5 bipolar electrode catheter was introduced into the saphenous vein and its tip advanced under fluoroscopic control into the inflow tract of the right ventricle. The catheter was attached to an AC input preamplifier (Sanborn Model 350–2700) with a band-pass of 15–1500 Hz. It was manipulated until a rapid deflection (H wave) appeared in each beat on the oscilloscope between the atrial (A wave) and ventricular (V wave) electrograms. A simultaneous standard limb lead was also recorded at a paper speed of 100 mm/second using a Sanborn photographic recorder.

The His bundle electrogram was also recorded using No. 5 or 6 bipolar catheter in 30 adults aged 15 to 69 years as a supplement to routine diagnostic cardiac catheterization. All of them had normal atrioventricular conduction (PR = 120–200 msec) and normal values for increments of conduction (Bekheit *et al.*, 1971). They were not receiving cardiac drugs.

The following measurements were made to define the difference in the increments of conduction in children and adults.

1) *PA interval:* internodal conduction time, measured from the onset of the P wave in the scalar lead to the initiation of the A wave of the His bundle electrogram.

2) *AH interval:* atrioventricular nodal (AV nodal) conduction time measured from the onset of the A wave to the onset of the H wave of the His bundle electrogram.

3) *HV interval:* His Purkinje system (HPS) conduction time, measured from the onset of the H wave to the onset of V wave of the His bundle electrogram.

4) *HS interval:* total intraventricular conduction time, measured from the onset of H wave to the end of the S wave of the scalar tracing.

5) *PR interval:* measured from the scalar tracing representing total atrioventricular conduction time.

The notation of the His bundle electrogram is shown in Fig. 1–5. Since the velocity of atrioventricular conduction is a function of ventricular cycle length, heart rate will be considered in the comparison between adults and children.

Results

Table 1 summarizes the anatomical defects and their distribution in the 28 children studied. It also shows the mean values for each group of congenital defect of the ventricular cycle length (VV interval), the PR interval, and its increments. Fig. 1–5 illustrate His bundle electrograms during the first 2½ years of life in children with Fallot's tetrad, transposition of the great vessels, atrial septal defect with persistent ductus arteriosus, single ventricle, and Ebstein's anomaly. In all of them the His bundle electrograms confirmed normal atrioventricular conduction. To our knowledge the child with tetralogy of Fallot is the youngest infant in whom a His bundle has been reported (Fig. 1).

Table 2 summarizes the comparison of atrioventricular conduction in the children and adults. The

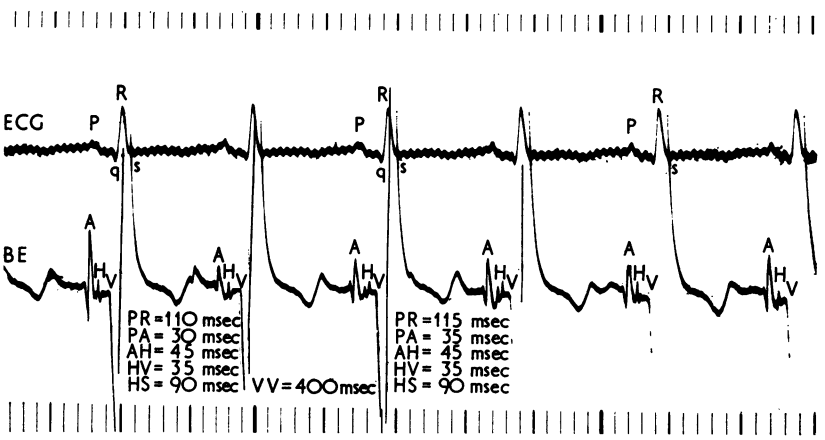

FIG. 1 *His bundle electrogram. Fallot's tetralogy. Girl aged 3 days. Normal conduction. Distance between 2 light lines equals 40 msec.*

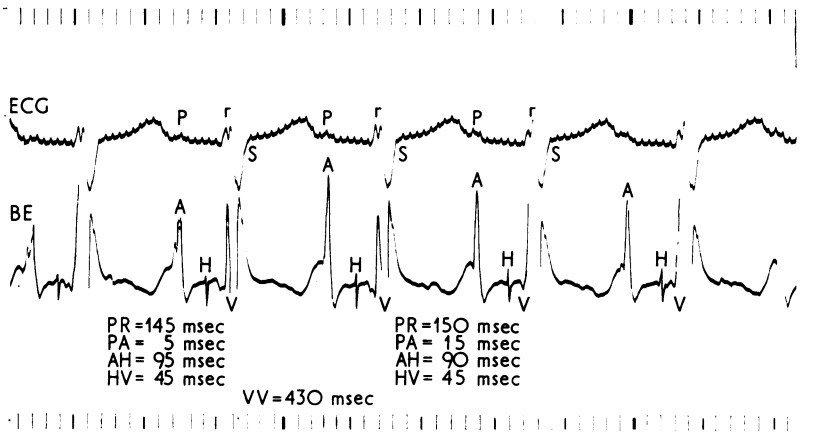

FIG. 2 *His bundle electrogram. Transposition of the great vessels. Boy aged 15 months. Normal conduction. Distance between 2 light lines equals 40 msec.*

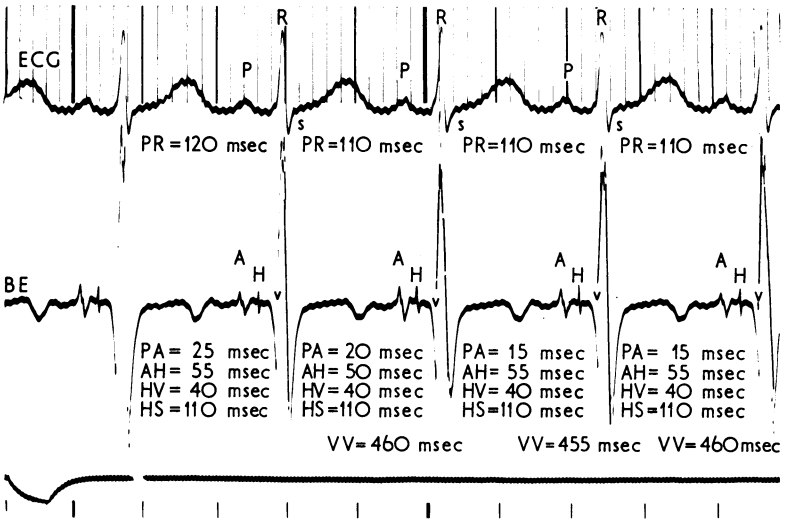

FIG. 3 *His bundle electrogram. Persistent ductus arteriosus. Girl aged 6 months. Normal conduction. Distance between 2 light lines equals 40 msec.*

significant differences were: (1) a shorter VV interval in children indicating a faster heart rate and (2) a shorter PR interval in children, due to a shorter AH interval. The factors influencing conduction in the two groups are now analysed separately.

Heart rate

The mean heart rate for the children was 114 beats per minute (range 75–158) compared with a mean heart rate of 68 per minute in adults (range 52–98), the difference between them being highly significant ($P < 0.0005$). Moreover, the mean heart rate in 14 children from birth to $2\frac{1}{2}$ years of age was 131 beats a minute compared with a slower mean rate of 106 beats a minute in the remainder of the children and the difference was also significant ($P < 0.005$).

Total atrioventricular conduction time (PR interval)

The mean PR interval for the group of children as a whole was 135 msec (range 110–152 msec), and in the adults the mean PR interval was 156 msec (range

TABLE 1

Anatomical defect	*No. of cases*	*PR (msec)*		*Bundle of His electrocardiogram studies*			
				VV (msec)		*Internodal conduction time (PA) (msec)*	
		Range	*Mean*	*Range*	*Mean*	*Range*	*Mean*
Persistent ductus arteriosus	7	110–155	134±4	609–438	554±16	16–34	24±3·6
Ventricular septal defect	6	110–140	130±3·2	426–590	490±13	21–34	23±3·2
Pulmonary stenosis with ventricular septal defect	4	120–146	134±3·4	340–596	456±17	5–30	23·5±3
Pulmonary stenosis with intact ventricular septum	3	120–137	131±4·6	380–642	551±18	22–30	26±3·4
Atrial septal defect	4	115–139	130±4·5	437–576	513±8	22–31	26±4·4
Transposition of great vessels with normal position of ventricles	1		146±3·5		456±5·2		22·5±3
Single ventricle	1		139±2·3		548±14		24±2·3
Ebstein's anomaly	1		111±2·1		450±1·6		46±1·6
Aortic stenosis	1		152±4·7		632±15		22±3·6

* Right bundle-branch block.

TABLE 2

No. of cases	*Age*	*PR (msec)*		*Bundle of His electrogram studies*					
				VV (msec)		*Internodal conduction time (PA) (msec)*		*AV nodal conduction time (AH) (msec)*	
		Range	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*
Adults (30)	15–69 yr	120–190	156±3·8	590–1365	880±31	5–45	32±3·6	55–125	83±3·2
Children (28)	3 dy–12 yr	110–146	135±5	380–860	527±14	5–45	29±4	50–105	67±3
t test		P<0·0005		P<0·0005		0·15<P<0·20		P<0·0005	

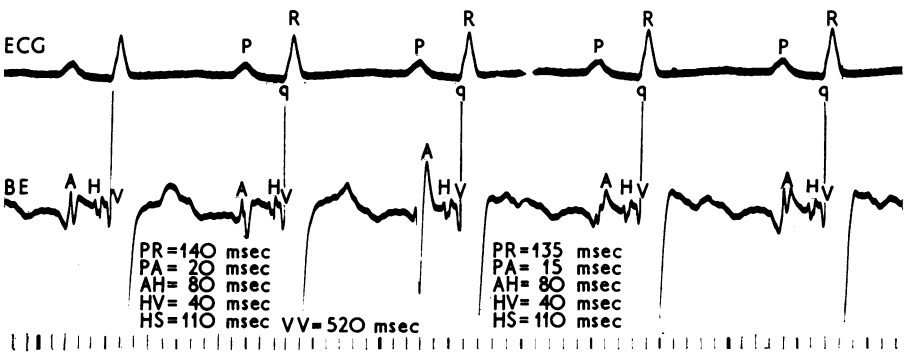

FIG. 4 *His bundle electrogram. Common ventricle. Boy aged 2 years. Normal conduction. Distance between 2 light lines equals 40 msec.*

120–190 msec). The slower atrioventricular conduction in the adult group was highly significant (P<0·0005). However, in the 14 children up to 2½ years of age, the mean PR interval was 131 msec, and in the remainder 137 msec but the difference between the older and younger children was not significant (P<0·1>0·05). Therefore, the faster heart rate in the younger children was not associated with any

AV nodal conduction time (AH) (msec)		*His Purkinje conduction time (HV) (msec)*		*Total intraventricular conduction time (HS) (msec)*	
Range	*Mean*	*Range*	*Mean*	*Range*	*Mean*
50–77	67±2·6	35–45	41–	105–125	112±1
45–73	66±3·4	35–40	38–	100–125	115±1·2
50–105	75±3·5	35–40	38–	90–120	108±1
55–67	62±4	35–45	40–	90–120	108±1
50–74	64±2·6	40	—	110–130	123±2*
	84±4·2		40–		128±2·4
	75±3·5		40–		114±2
	56±1·6		40–		125±1·4
	66±4·4		40–		113±3·5

His Purkinje conduction time (HV) (msec)		*Total intraventricular time (HS) (msec)*	
Range	*Mean*	*Range*	*Mean*
35–45	41–	110–140	131±1·4
35–45	43–	90–125	115±1·7
0·40 < P < 0·50		P < 0·0005	

significant change in the total atrioventricular conduction time up to the age of 12 years.

Internodal conduction (PA interval)

The mean PA interval in the children was 29 msec (range 11–45 msec) compared with a mean value of 32 msec in the adults (range 10–45 msec). Internodal conduction time was not significantly different in children and adults ($P < 0{\cdot}2 > 0{\cdot}15$). The slower total atrioventricular conduction in the adults therefore could not be attributed to any change in sinus impulse conduction from the sinus node to the atrioventricular node.

Atrioventricular nodal conduction (AH interval)

The mean AH interval in the group of children studied was 67 msec (range 55–105 msec) compared with a mean value of 83 msec (range 55–125 msec) for the adults. The difference between the two groups was highly significant ($P < 0{\cdot}0005$). Slowing of atrioventricular nodal conduction therefore plays a significant part for the longer PR interval in adults compared with children. The mean AH interval for children up to 2½ years was 68 msec compared with a mean value of 67 msec between 2½ and 12 years, and the difference between them was not significant ($P < 0{\cdot}4 > 0{\cdot}35$).

His Purkinje system conduction (HV interval)

The HV intervals ranged between 35–45 msec for both children and adults with mean values of 41 msec and 43 msec, respectively. The difference be-

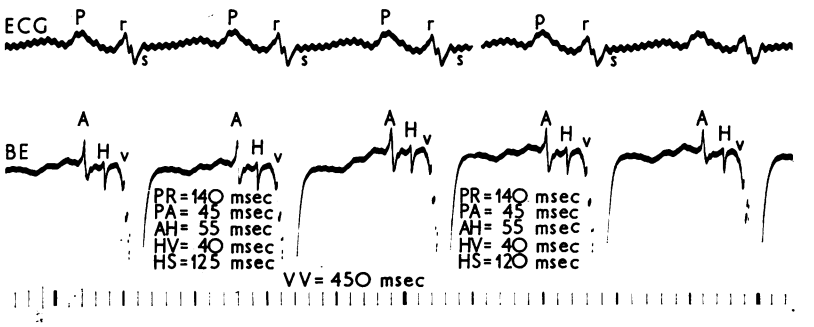

FIG. 5 *His bundle electrogram. Ebstein's anomaly. Girl aged 2½ years. Normal conduction. Distance between 2 light lines equals 40 msec.*

tween them was not significant ($P < 0{\cdot}5 > 0{\cdot}4$). There was therefore no difference in the velocity of conduction in the His Purkinje system in children and adults.

Total intraventricular conduction (HS interval)

The mean HS interval in the children (excluding 6 cases with right bundle-branch block) was 115 msec (range 110–125 msec), compared with 131 msec in the adults (range 110–140 msec). The difference between the two groups was highly significant ($P < 0{\cdot}0005$). Moreover, the mean HS interval in children up to 2½ years was 106 msec, compared with a mean value of 118 msec in the remaining older children aged 2½ to 12 years, and the difference between them was also highly significant ($P < 0{\cdot}0025 > 0{\cdot}0005$). Thus total intraventricular conduction time tends to lengthen with age.

In summary, the heart was significantly faster during the first 2½ years of life than in children aged 2½ to 12 years and significantly slower in the adults than in the children up to age of 12 years. The PR interval was shorter in the children than in the adults, but it did not alter significantly from birth to the age of 12 years. The lengthening of the PR interval with age was exclusively due to slower atrioventricular nodal conduction, internodal atrial conduction and His Purkinje system conduction having the same range of values for children and adults. Lastly, the total intraventricular conduction time increased significantly after the age of 2½ years and was also longer in the adults than children as a group. These results are illustrated graphically in Fig. 6.

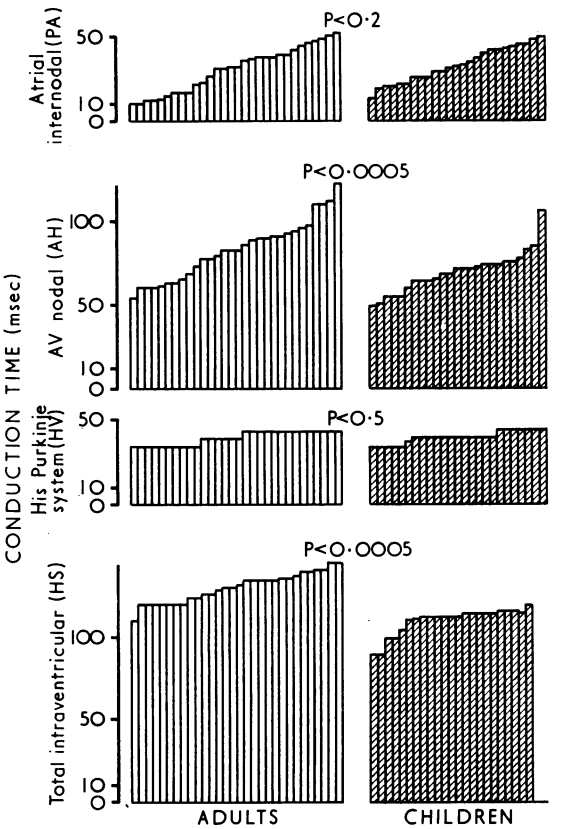

FIG. 6 *Comparison of the increments of conduction in adults and children. AV nodal conduction (AH interval) and intraventricular conduction (HS interval) alone are significantly shorter in children.*

Discussion

The results of our observations of myocardial conduction in children provide a basis for discussion of the possible mechanisms involved in the evolution of the specialized conducting system of the heart. Knowledge of the development of the sinoventricular conduction system in the foetal heart is scanty and observations in animals correlating development of the Purkinje system with electrical activity are few. It is of great interest that an electrocardiographic pattern similar to that of an adult can be recorded in a chick's heart shortly after fusion of the paired primordial cardiac tubes, which would correspond to a human foetal heart of about 5 weeks (Patten, 1956). At this stage of development there is no bundle of His, and the sinus and atrioventricular nodes are not yet incorporated into the cardiac tube from the sinus venosus. In addition, there is an isoelectric PR interval when the atrial and ventricular tubes are anatomically continuous. These factors have to be borne in mind when relating function to structure of conduction fibres in the fully developed heart. With the formation of the endocardial cushions the atrioventricular junction of the cardiac tube becomes constricted until ultimately the only functional connexion between the chambers is the bundle of His and remnant fibres which persist as accessory pathways. The suggestion is that the specialized conducting fibres represent the remnants of the primitive primordial cells which retain the special function of rapid conduction. The delayed conduction in the atrioventricular groove is present before the incorporation of the atrioventricular node and the mechanism involved is unknown, as is the normal delay in atrioventricular conduction in the mature heart (Scherf and Cohen, 1964). As already mentioned, there is evidence that the morphogenesis of the specialized conduction system is incomplete

at birth and the main bundle of His undergoes a process of cellular involution and moulding during the first two years of life. We will now present our ideas based on the results of His bundle electrograms in the light of our concepts of the function of the specialized tissues in childhood.

The faster sinus rate in children compared with adults is well known (Alimurung and Massell, 1956; Namin and Miller, 1966). In our children the fastest heart rates occurred from birth to 2½ years of age. The increased sinus discharge rate appears to depend upon increased sensitivity of the sinus pacemaker cells to circulating catecholamines (James, 1970), for the adrenergic innervation of the heart is not completed until some months after birth, whereas cholinergic innervation is acquired early in foetal life (Navaratnam, 1965; Friedman *et al.*, 1967). Our results confirm that the shorter PR interval in children compared with adults was exclusively due to increased velocity of the sinus impulse conduction in the atrioventricular node. The rate of conduction in the atria and His Purkinje system was the same in the two groups. As already noted above, the AH interval did not vary significantly in the children up to 2½ years of age and between 2½ and 12 years, in spite of the difference in heart rate. Nevertheless, when the mean AH intervals are plotted against the heart rates in the children and adults, heart rate rather than age appears to be more important as a factor which prolongs atrioventricular conduction (Fig. 7). Thus the AH interval of 90 per cent of the children

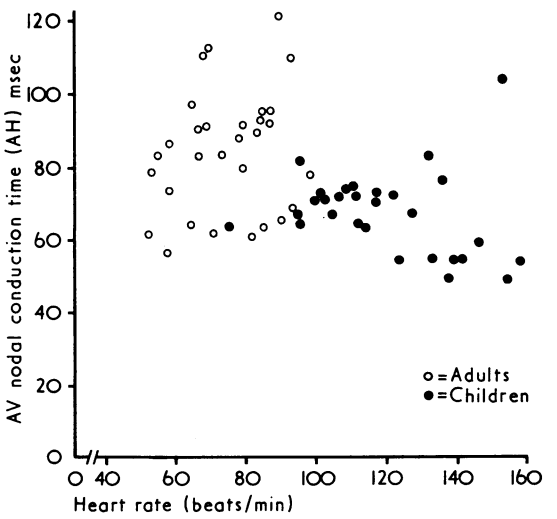

FIG. 7 *Relation of AV nodal conduction to heart rate in children and adults. Note tendency of faster heart rate and shorter AH interval in children.*

was less than 80 msec at heart rates between 98 and 158 beats a minute; whereas in 60 per cent of the adults, the AH interval exceeded 80 msec at much slower rates between 54 and 98 beats a minute. The explanation may be a hypersensitivity to circulating catecholamines of the atrioventricular node resulting in accelerated conduction in the same way as it causes increased rate of discharge of the sinus pacemaker. Such conditions are certainly more likely to be operative during the first two years of life when the heart has not acquired full development of its sympathetic nerve supply. An alternative explanation of rapid atrioventricular conduction in infants may be the persistence of embryonic remnants connecting the atria and ventricles which bypass the atrioventricular node before they are 'phased out' by degenerative changes.

It is of importance to note that in our studies the internodal and the His Purkinje system (HPS) conduction time did not differ in children from adults. This suggests the intriguing concept that the specialized atrial conducting pathways, and the His Purkinje conduction fibres are functionally mature and stable from the early neonatal period. Despite the extensive postnatal structural changes demonstrated by James (1968) and Dawes (1968) in the Purkinje fibres during their morphogenesis in the first two years of life, our measurements do not support the hypothesis put forward by James that such morphological changes have potential functional significance. James (1968) suggests that the process of 'moulding and shaping' of the specialized bundles may result in depressed conduction with increased susceptibility to potential lethal arrhythmias. However, in our children, conduction, far from being suppressed, was highly efficient in the atrioventricular node, and neither was there any slowing of His Purkinje system (HPS) conduction, which was the same as in the mature hearts of adults. It appears, therefore, that involutional structural changes in the conduction fibres in our cases did not result in any abnormal conduction in any increments, and thus they provide a less certain basis for the theory that arrhythmias may be the mechanism of unsuspected neonatal cot deaths in apparently healthy children. Many more studies of His bundle electrograms during the first two years of life are required for correlation with the morphogenesis of the specialized conducting tissues before its full functional significance can be assessed.

We would like to make some comments on atrioventricular conduction in septal defects. In the primordial cardiac tube before either the sinus node or the atrioventricular nodes are incorporated into the developing heart from the sinus venosus, impulses are delayed before the development of the

endocardial jelly. The latter is ultimately organized into the endocardial cushions dividing the atria from the ventricles. This delay persists between the same chambers in the developed heart, and its mechanism is unknown (Scherf and Cohen, 1964). The constriction at the atrioventricular junction and the growth of the contractile myocardial fibres leave atrioventricular conduction to remnants which may represent the fibres of the primordial cardiac tube. These embryonic remnants may assume the function of rapid impulse conduction. Ten of the children studied had septal defects (Table 1). The PA and HV intervals in atrial septal defects did not differ from those in ventricular septal defects. The preferential atrial pathways seemed to function normally in the former and the His Purkinje system in the latter. The main bundle of His is closely related anatomically to the fibrous skeleton of the heart, and additional His bundle studies are required to determine the site of block which has been reported in ventricular septal defect.

Total intraventricular conduction time in our measurements consists of two components: (1) HV interval, measured from the onset of depolarization of the main bundle of His to the arrival of the sinus impulse at the Purkinje myocardial junction or gate; and (2) from the gate to the completion of ventricular activation. Since the first component did not vary in children and adults, it follows that the significantly longer total intraventricular conduction time in adults was due to the second component. The immediate suggestion is that the significant factor is the greatly increased bulk of ventricular muscle with age. In support of this concept we found that the mean HS intervals of those aged less than $2\frac{1}{2}$ years was significantly shorter than those above it, yet ordinary contractile muscle is a slow conductor of impulses (Grant, 1957). It seems unlikely that in the normal adult heart the impulse leaves the Purkinje system, thus causing prolongation of the QRS interval. A possible explanation is that the growth in thickness of the ventricular myocardium causes a stretching of the conduction fibres with resultant slower conduction.

Finally, Fig. 8 illustrates our concepts of evolution of sinoventricular conduction with age. They are based on the premises that the Purkinje fibres in both atria and ventricles are functionally mature at birth, and that changes in conduction with age are entirely related to the properties of the atrioventricular nodal cells.

In summary, from our observations of myocardial

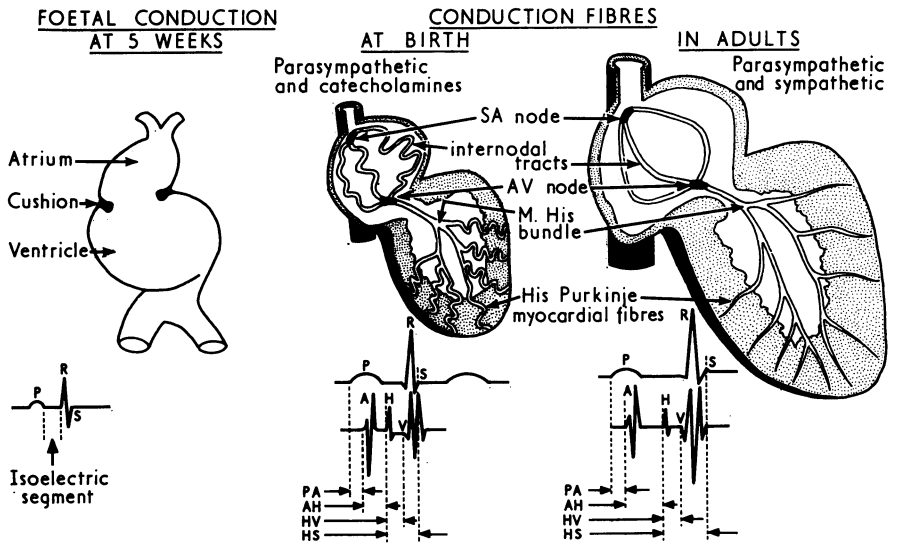

FIG. 8 *Evolution of sinoventricular conduction. Note foetal P wave and QRS complexes with isoelectric PR interval before AV node is incorporated in the conducting pathway from sinus venosus. At birth sinus rate is dominated by circulating catecholamines compared with autonomic balance in adults. The conduction pathways are shown fully developed at birth, with uncoiling in the adult heart, i.e. internodal (PA interval) and His Purkinje system (HV interval) are not altered by age. The difference in conduction is entirely due to AV nodal delay in adults (longer AH interval). The Purkinje fibres in the myocardium of adults are straightened and stretched to explain longer intraventricular conduction (HS interval). M. His bundle = main His bundle.*

conduction in children, we offer concepts about the evolution of the conduction system in the heart. It appears that impulse formation and conduction is well developed about the fifth week of foetal life before the sinus and atrioventricular nodes are developed and before the Purkinje fibres are histologically recognizable. During the formation of the atrioventricular cushions and the development of the contractile myocardium the remnant of the primordial cells functions as the specialized conducting fibres. After birth the specialized fibres continue the process of involution histologically, but from a functional point of view they are mature at birth. They form discrete pathways in the atria and ventricles which can adapt themselves to the growth of myocardial fibres. No linear strain is placed upon them in the atria or in the bundle or in its branches, but the terminal filaments may be stretched by the thickness of the ventricles which account for the longer ventricular activation time in adults. The atrioventricular node is an incorporated structure which has different conduction properties whose variations produce the difference in the PR interval with age.

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