

THE NORMAL ECG IN CHILDHOOD AND ADOLESCENCE

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1626

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An electrocardiogram (ECG) may be requested as part of the investigation of a wide range of problems in paediatrics, often in patients who have no clinical evidence of cardiac disease. Frequently the request is made by practitioners with no particular expertise in cardiology. The basic principles of interpretation of the ECG in children are identical to those in adults, but the progressive changes in anatomy and physiology which take place between birth and adolescence result in some features which differ significantly from the normal adult pattern and vary according to the age of the child. Correct interpretation of the ECG is therefore potentially difficult and a detailed knowledge of these age dependent changes is critically important if errors are to be avoided.

Extensive tables or centile charts of normal values in relation to age of patient are available.^{1–3} There is the potential for computer support in the interpretation of the paediatric ECG,^{4, 5} sparing the interpreter the need to consult these tables or memorise large quantities of age dependant variables. However, there is published evidence⁶ which shows that some abnormalities are missed both by computer interpretation and by paediatric emergency department doctors. Equally, daily practice suggests that computer generated reports not infrequently identify an abnormality where none exists.

ELECTROCARDIOGRAPHIC VARIABLES

Until recently the most comprehensive study of electrocardiographic variables in childhood was that of Davignon¹ based on measurements made on 2141 white children in Quebec, Canada. Normal limits for 39 variables were presented as centile charts ranging from the 2nd to the 98th centile. These invaluable tables and charts are quoted in many major paediatric cardiology texts currently available, but some limitations must be recognised in the application of the data in practice today. Normal values for males and females were not separated. It may be inappropriate to apply these normal values to non-white individuals and it is possible that there may be relevant physiological differences in, for example, height and weight and perhaps age at puberty between present day children and those studied 25 years ago.

Some technical matters may also be relevant. The frequency content of the ECG decreases with age. This fact may be of particular importance in recording and interpreting the ECGs of younger children. In 1990 the American Heart Association recommended 500 Hz as the minimum sampling rate and 150 Hz as the minimum bandwidth for recording the paediatric ECG.⁷ A more recent systematic investigation⁸ of frequency content, band width requirement, and sampling rate suggests that a minimum sampling rate of 1000 Hz and a minimum bandwidth of 250 Hz is required. The ECGs in the Davignon study¹ were digitised at a sampling rate of 333 Hz. This sampling rate is probably inadequate for the high frequency content of the ECG in young children. Most modern ECG recorders will sample at > 500 Hz or greater and observers should be aware of this fact when interpreting an ECG generated by such equipment.

The more recent studies^{2, 3} used sampling rates of 500 or 1200 Hz. It is possible that this difference in recording technology will have played some part in the observed differences in normal ranges between Davignon and more recently published studies. In 2001 Rijnbeek³ and colleagues published tables of new normal limits for the paediatric ECG. Careful study of this detailed paper is recommended as there are significant differences in the normal ranges of many variables from the data of Davignon. It is arguable that some of the traditional criteria used in paediatrics for the diagnosis of ventricular hypertrophy and QRS or QT interval prolongation should be revised in the light of these new findings.

NORMAL RANGES OF CLINICALLY IMPORTANT AGE RELATED VARIABLES ON THE RESTING 12 LEAD ECG

P wave

The P wave amplitude does not change significantly during childhood and at any age amplitudes in excess of 0.025 mV in lead II should be regarded as exceeding the upper limit of normal.

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Voltage criteria for atrial hypertrophy should only be applied when the patient is in sinus rhythm with a frontal P wave axis of between 0–90°.

Q wave

In most leads where a significant Q wave appears (II, III, aVF, V5, V6) there is a trend for the amplitude to double over the first few months of life, reaching a maximum at about 3–5 years of age and declining thereafter back towards the initial value of the newborn period. In the study of Rijnbeek the upper limit of normal Q wave amplitude is significantly higher than that recorded by Davignon (table 1). Thus Q waves of up to 0.6–0.8 mV would fall within the normal range for children in the 6 month to 3 year age range.

QRS complex

The relative right ventricular hypertrophy of the neonate regresses over the first few months of life. This change is reflected in the appearance of the QRS complex of the ECG. The mean frontal plane QRS axis of the neonate is around 75° with a range from 60–160°. There is a relatively rapid change in axis over the first year of life and from this age onwards the mean frontal QRS axis will be around 65–70° with a range from 0–110°.

The amplitude of R waves in the right precordial leads of normal children decreases with age while the amplitude increases in the left precordial leads. Similar but inverse changes occur in respect of the S wave amplitude. There is substantial individual variation in the rate at which these changes occur. On average the R/S ratio in V1 remains > 1 up to about 3 years of age but will remain > 1 in some normal individuals even into the 8–12 year age group. The absolute values for R and S wave amplitudes are in general greater, often significantly so, in the studies of Macfarlane and Rijnbeek as compared with Davignon (table 2). For example, the upper limit of R wave amplitude in V6 in the 12–16 year age group was 3.05 mV (Rijnbeek) as compared with 2.3 mV (Davignon). However, in some leads, notably V4, the R wave amplitudes are greater in the earlier study.

It is recognised that in children the ECG, when compared with the gold standard of ultrasound, is a relatively poor method of identifying left ventricular hypertrophy with low specificity and sensitivity. In a recently reported study⁹ electrocardiographic criteria for left ventricular hypertrophy were present in 15% of children with a normal left ventricular mass on ultrasound (specificity 85%), while only 12 of 62 children with an abnormal left ventricular mass also had left ventricular hypertrophy on the ECG (sensitivity 19.4%). In

this study the normal standards used were those of Davignon. I am not aware of any similar comparison having been made using the normal values of either Macfarlane or Rijnbeek.

All of this suggests that the traditional amplitude criteria for ventricular hypertrophy in children should be reviewed and if necessary amended.

T wave

Throughout childhood the T wave pattern, particularly in precordial leads, is very different to that of adults and there is a progressive change in T wave axis from birth to early adult life. The rate at which this change occurs varies considerably from one individual to another but some generalisations can be made.

In the first 2–3 days of life upright T waves in the right precordial leads (V1 and V3R) are normal. It is usual for the T wave in these leads to invert in the majority of infants during the first week of life. Because the progression of T wave change in the neonatal period has been studied in only limited numbers of patients it is impossible to indicate the precise age at which an upright T wave would be abnormal; however, in the study of Davignon the T wave amplitude at the 98th centile was positive in the 0–7 day age range and negative in the 7–30 day age range. Persistence of a positive T wave in V1 or V3R beyond the first week of life should therefore raise the suspicion of abnormality. The T wave remains inverted in these leads in the majority of children into the 12–16 year age group.

In the intermediate leads, V2 and V3 the T wave is often inverted in early childhood and there is a progression to the T wave becoming upright in the sequence V3, V2, V1. To illustrate the point, 50% of normal 3–5 year old children will have inverted T waves in V2 but in the 8–12 year age group inverted T waves in V2 will be present in only 5–10% of individuals.

The T wave in V5 and V6 should be upright at all ages, but in a very small number of newborn babies the T wave in these leads may be flat or inverted for 1–3 days.

Variations from sinus rhythm

Ambulatory electrocardiographic monitoring on normal healthy infants and children of all ages^{10–14} has confirmed that regular uninterrupted sinus rhythm may be punctuated from time to time by a variety of rhythm changes which could potentially be regarded as abnormal. The frequency with which these changes occur emphasises the importance of understanding the range of normal variation of heart

Table 1 Q wave amplitude in leads III and V6 taken from the tables of Rijnbeek and the centile charts of Davignon

	Rijnbeek median (98th centile)		Davignon median (98th centile)	
	III	V6	III	V6
0–1 month	0.15 (0.26)	0.11 (0.22)	–	–
1–3 months	0.29 (0.50)	0.16 (0.31)	0.12 (0.55)	0.03 (0.26)
3–6 months	0.31 (0.71)	0.17 (0.35)	0.13 (0.65)	0.04 (0.26)
6–12 months	0.35 (0.79)	0.20 (0.60)	0.17 (0.6)	0.04 (0.3)
1–3 years	0.30 (0.74)	0.20 (0.56)	0.13 (0.52)	0.05 (0.3)
3–5 years	0.19 (0.46)	0.15 (0.42)	0.09 (0.40)	0.07 (0.33)
5–8 years	0.15 (0.36)	0.12 (0.39)	0.09 (0.31)	0.07 (0.45)
8–12 years	0.10 (0.28)	0.12 (0.43)	0.05 (0.28)	0.06 (0.28)
12–16 years	0.10 (0.29)	0.11 (0.43)	0.04 (0.3)	0.04 (0.28)

The values for Rijnbeek are for males only whereas Davignon gives combined data for a group of males and females.

Table 2 R wave amplitude (mV) in leads V1 and V6 taken from the tables of Rijnbeek and the centile charts of Davignon

	Rijnbeek median (98th centile)		Davignon median (98th centile)	
	V1	V6	V1	V6
0–1 month	1.1 (2.05)	1.0 (1.78)	–	–
1–3 months	1.23 (2.07)	1.55 (2.23)	0.9 (1.8)	1.2 (2.15)
3–6 months	1.32 (2.20)	1.65 (2.73)	1.0 (2.0)	1.3 (2.25)
6–12 months	1.12 (2.14)	1.7 (2.79)	0.9 (2.0)	1.25 (2.25)
1–3 years	1.08 (2.11)	1.79 (2.96)	0.85 (1.75)	1.3 (2.25)
3–5 years	0.95 (1.78)	1.98 (3.14)	0.8 (1.75)	1.5 (2.5)
5–8 years	0.63 (1.48)	1.97 (2.98)	0.7 (1.4)	1.65 (2.8)
8–12 years	0.54 (1.14)	2.18 (3.24)	0.5 (1.25)	1.6 (2.5)
12–16 years	0.48 (1.18)	2.02 (3.05)	0.4 (1.0)	1.5 (2.3)

The values for Rijnbeek are for males only whereas Davignon gives combined data for a group of males and females.

rhythm in children and of correlating symptoms with rhythm change when investigating unusual events. Many of these rhythm changes are relatively common, occurring in many individuals, though not necessarily very frequently. The majority of these rhythm changes are therefore very likely to be entirely benign, but at the moment this assumption has not been confirmed by any prospective long term study.

Variation in P-P interval

Phasic changes in the P-P interval are almost universal in children and can be very obvious, leading to unnecessary concerns about the irregular heart rate. The diagnosis of sinus arrhythmia is easily confirmed in most cases by observing the relation of the change to respiration (slowing in expiration, accelerating in inspiration).

Occasional episodes characterised by sudden prolongation of the P-P interval are also relatively common and were found in 50% of the newborn infants studied by Southall and colleagues.¹⁰ In older children the frequency of such episodes appears to fall, occurring in only 16% of teenage boys. Although these sinus pauses are seen in many individuals they are infrequent, almost invariably occurring in isolated cardiac cycles and with no more than two or three in a 24 hour period. In both neonates and older children the longest pauses recorded were no more than 1.8–1.9 seconds in duration. As sinus arrhythmia makes it difficult to measure the resting sinus cycle length in many children, the precise mechanism responsible for these pauses is uncertain in most cases. Some may conform to patterns consistent with either sino-atrial block or sinus arrest, but without direct measurement of sinus node potentials a conclusive diagnosis is probably not possible. Whatever the precise mechanism it is clear that such pauses are common at all ages. Although sinus node disease does occur in young children and can result in syncope, in the vast majority of children sinus pauses are benign.

Common variations in rhythm which may be normal

- ▶ Pronounced sinus arrhythmia
- ▶ Short sinus pauses <1.8 seconds
- ▶ First degree atrioventricular block
- ▶ Mobitz type 1 second degree atrioventricular block
- ▶ Junctional rhythm
- ▶ Ventricular or supraventricular extrasystole

Variation in P wave morphology and PR interval

Changes in P wave morphology associated with slowing of the heart rate and a shortening on the PR interval occur in 20–30% of infants and children. These episodes of junctional rhythm usually follow a gradual slowing of the sinus rate during sleep, but may also occur during waking hours. In most individuals the episodes are short, lasting no more than a few seconds to about one minute, but occasionally more prolonged episodes lasting several hours have been reported. A common pattern is for many short self limiting episodes to occur over several hours during sleep.

The PR interval on resting 12 lead ECGs in children varies mainly in relation to heart rate and is therefore usually shorter in younger children. In infants with heart rates in the range 100–150 beats/min one would expect the PR interval to be within the range 80–110 ms extending in occasional individuals to 150 ms. In teenagers with slower heart rates the upper limit of normal would be around 180 ms. Ambulatory ECG monitoring shows that at all ages some individuals with a normal resting PR interval will from time to time have periods when the PR interval becomes prolonged to >200 ms. In the studies reported from Leeds this occurred in between 8–12% of children in the 10–16 year age group. Episodes of first degree heart block were more common during sleep and varied in duration from a few seconds to several hours. Occasional individuals may have first degree heart block as their normal resting heart rhythm.

Around 10% of normal children will have episodes of Mobitz type 1 second degree atrioventricular block (Wenckebach). Some, but not all, of these individuals will have episodes of first degree atrioventricular block. Episodes may vary in number from single isolated events to many hundreds in a 24 hour period. In some individuals the atrioventricular block will persist as 2:1 block for a few seconds after the initial Wenckebach sequence. There are very occasional reports of progression of Mobitz type 1 atrioventricular block to complete atrioventricular block but such progression must be very unusual given the relatively frequent occurrence of Mobitz type 1 block in healthy asymptomatic children.

In teenagers involved in intensive physical training, changes in the PR interval occur with even greater frequency with first degree and type 1 second degree atrioventricular block and were noted intermittently in 20% of those studied.

Extrasystoles

Isolated ventricular premature beats may be identified on a routine resting ECG in 0.2–2.2% of normal children.¹⁵ On

ambulatory monitoring these extrasystoles are common, occurring in 20–30% of younger children and up to 40% of teenage boys. Typically the extrasystoles are isolated, of uniform morphology, and are associated with periods of slower heart rates. Multifocal extrasystoles are seen and in a small number of individuals couplets of ectopic activity occasionally occur. The frequency of extrasystoles is usually no more than 1–5 per hour, but occasional individuals will be seen with much more frequent ectopic activity or long periods of ventricular bigeminy. Extrasystoles which conform to this pattern and suppress on exercise are almost certainly benign. This view is supported by very limited longer term follow up data,¹⁵ but recently a cautionary note has been sounded by the observation that children with benign ventricular ectopy do have greater corrected QT interval dispersion than randomly selected controls.¹⁶ Abnormal QT dispersion is a feature of patients with long QT syndrome and its significance in the context of children with benign ventricular ectopy merits further investigation.

In older teenagers taking part in athletic training ectopic activity is seen in around 50%, similar to the observed prevalence reported in normal adults.¹⁴ In these individuals the ectopic activity did not seem to be related to slower heart rates, with ectopics occurring less frequently during sleep and at higher heart rates than in normal age matched controls.

Isolated supraventricular premature beats are fairly common at all ages. Southall and colleagues¹⁰ felt that all the premature beats found in 14% of the newborn infants they studied were supraventricular. In older children supraventricular premature beats have been reported in between 15–40% of individuals studied. The usual pattern is for isolated ectopics to occur at a frequency of less than one per hour but occasional individuals (often in the newborn period) will be encountered with more frequent ectopic activity of up to 10 per hour. Couplets are occasionally seen but sustained supraventricular tachycardia, even of short duration, was not identified in these studies of normal children.

QRS duration

The normal limits for QRS duration given by Davignon were calculated only from measurements made in lead V5. Later studies have determined the maximum QRS duration from measurement of all leads and this fact may be responsible for the considerable differences in ranges between earlier and later studies. There is a progressive change in QRS duration with age, with a normal range from about 70–85 ms in neonates and from 90–110 ms in adolescents according to the tables of Rijnbeek. Relatively little change is apparent during

Common indications for paediatric electrocardiography

- ▶ Diagnosis and management of congenital heart disease
- ▶ Diagnosis and management of arrhythmia
- ▶ Diagnosis and management of rheumatic fever, Kawasaki's disease, pericarditis, myocarditis
- ▶ Syncope, seizures, and "funny turns"
- ▶ Cyanotic episodes
- ▶ Chest pain or other symptoms related to exertion
- ▶ Family history of sudden death or life threatening event
- ▶ Electrolyte abnormalities
- ▶ Drug ingestion

1629

the first three years of life but thereafter QRS duration increases in a linear manner into adolescence.

QT interval

Detecting prolongation of the QT interval is important in the identification of individuals at risk of life threatening arrhythmia. Because of the relation between QT interval and heart rate and the considerable variability of heart rate in the paediatric age group it is difficult to judge whether a measured QT interval is normal or not. The principle of correction for heart rate is generally accepted, but there is debate about how this should be achieved.¹⁷ The question as to whether other factors such as age and sex ought to be taken into account also continues to be a subject for discussion. For practical purposes Bazett's formula (measured QT interval divided by the square root of the R-R interval) remains the most commonly used method for determining the rate corrected QT interval (QTc) and was used in the studies of both Davignon and Rijnbeek. In both studies the mean QTc was around 410 ms throughout childhood with an upper limit of normal of 450 ms.

INFLUENCE OF SEX

The influence of sex on some electrocardiographic variables has been noted in a small number of reports^{18 19} and recently has been investigated more systematically by Rijnbeek and colleagues. Some differences in Q, R, and S wave amplitude measurements between boys and girls are apparent at all ages. These differences are greatest in adolescents when the amplitudes of Q, R, and S waves are fairly consistently higher in males in most precordial leads. In the 12–16 year age group many of these differences are significant (table 3). Although these differences were noted many years ago,¹⁸ the information is still not often used in daily practice. It seems very

Table 3 R wave amplitude (mV) for males and females in leads V1 and V6 taken from the tables of Rijnbeek

	Males median (98th centile)		Females median (98th centile)	
	V1	V6	V1	V6
0–1 month	1.1 (2.05)	1.0 (1.78)	1.35 (2.2)	0.93 (1.64)
1–3 months	1.23 (2.07)	1.55 (2.23)	1.17 (1.99)	1.51 (2.67)
3–6 months	1.32 (2.20)	1.65 (2.73)	1.14 (2.04)	1.6 (2.8)
6–12 months	1.12 (2.14)	1.7 (2.79)	1.01 (1.92)	1.68 (2.74)
1–3 years	1.08 (2.11)	1.79 (2.96)	1.01 (1.91)	1.68 (2.67)
3–5 years	0.95 (1.78)	1.98 (3.14)	0.77 (1.38)	1.89 (2.91)
5–8 years	0.63 (1.48)	1.97 (2.98)	0.55 (1.24)	2.05 (3.25)
8–12 years	0.54 (1.14)	2.18 (3.24)	0.49 (1.14)	2.0 (3.04)
12–16 years	0.48 (1.18)	2.02 (3.05)	0.35 (1.10)	1.65 (2.52)

In the 12–16 year age group the 95% confidence intervals of the centiles for boys and girls do not overlap.

likely that the use of sex specific data would improve the sensitivity and specificity of diagnostic criteria for ventricular hypertrophy in adolescents.

In childhood sex does not have a major influence on electrocardiographic interval measurements although some small differences can be seen. Rijnbeek's tables show that the QRS duration is consistently longer in boys in all age groups. However, in absolute terms the differences are small—of the order of a 2–5 ms difference in median QRS duration—and probably not therefore important in day to day practice.

In prepubertal children sex does not appear to be of significance in determining the QT interval. Even in the adolescent group the differences are small but probably significant. In Rijnbeek's study the upper limits of normal of the QTc overlapped only marginally in boys and girls. Pearl and colleagues²⁰ showed that the QTc was significantly longer in girls from the age of 14 years, probably due to shortening of the QTc in boys rather than prolongation in girls. In girls in this age group a QTc of 460 ms would probably be regarded as the upper limit of normal.

CONCLUSIONS

Standards of normal values to help in the interpretation of the ECG of children have been available for many years. Recent research suggests that some of these standards should be reviewed and perhaps revised to take account of changes in electrocardiographic instrumentation and possible physiological changes in children which might have taken place since the original standards were established. The rhythm changes seen in apparently normal children during random 24 hour periods of observation are well described, but the longer term implications of these changes (if any) have not been systematically investigated.

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