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Normal ECG Standards for Infants and Children

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SUMMARY. **Normal ECG values were determined using computer-assisted measurement of the ECGs of 2,141 white children aged 0 to 16 years divided into 12 age groups.**

These values are plotted on graphs containing the second, fifth, 25th, 50th, 75th, 95th, and 98th percentiles for each age group. This provides a convenient, fast, and practical method for comparing the values found in a given ECG with those found in a normal population, taking into account the evolution of ECG patterns with age.

KEY WORDS: **ECG normal standards, children—ECG age evolution—Computer ECG measurements**

The purpose of the study was (1) to facilitate the evaluation of the ECG in children by producing clear, easily understandable graphs and tables and (2) to establish a large data bank of ECGs from normal children that could serve as a development and test library for pediatric computer-ECG programs designed for screening and eventually diagnostic interpretation of ECGs.

A comprehensive review of pediatric ECG standards with an extensive list of references was recently published by Liebman and Plonsey [8]. These authors state: "It is the authors' opinion that no standards available are adequately complete." While ECG standards for normal adults have been firmly established [16], the corresponding standards for normal children have been based on small numbers of subjects from relatively wide age ranges and on a small number of ECG variables. The acquisition of a large data base at all ages if the ECGs are measured by hand would be time-consuming. Automatic ECG measurement procedures such as those possible using tape recorders and computers are therefore attractive.

When the present investigation was initiated in 1972, none of the available computer-ECG programs was completely satisfactory for measurement of the ECGs of small children. Programs usually succeeded in ECG wave recognition, and amplitude and duration measurements then were very accurate. However, wave recognition was sometimes faulty, and gross measurement errors then occurred.

We used a modified version of the Mayo Clinic Computer Program [17] to obtain fast and precise measurements but monitored the results visually and corrected the measurements when wave recognition was seen to be faulty. Thus, a relatively fast analysis of the large ECG data files of the present study became possible, with a satisfactory degree of precision and accuracy.

Methods and Study Population

Selection and Characteristics of the Study Population

The population studied consisted of 2,141 white children aged 0 to 16 years. The source of newborn infants was a large obstetric

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service and of the other age groups either well-child clinics or primary and secondary public schools in Montreal. Schools and clinics were selected to make the population representative of the middle socioeconomic groups. The total population was divided into 12 age groups (Table 1). Seven of the 12 age groups were composed of children in the first year of life because this is when changes in the ECG are greatest. However, in the age groups from 1 week to 6 months the number of subjects is smaller than in the other age groups because mothers were reluctant to bring their child to a well-baby clinic. All children underwent a complete physical examination and were included in the study only if no disease was found.

The anthropometric characteristics of the population, namely, weight, height, and body surface area vs age, are reported in Tables 2, 3, and 4. The body surface area was calculated using the DuBois equation, with the correction factor introduced by Boyd [1]. Data for weight and height at different ages for our sample corresponded reasonably well with those already published for the North American population [18].

Table 1. Age and sex distribution of the study population.

Group	Age[a]	Male	Female	Total
1	0 to 24 hours	85	104	189
2	1 to 3 days	85	94	179
3	3 to 7 days	88	93	181
4	1 to 4 weeks	59	60	119
5	1 to 3 months	51	64	115
6	3 to 6 months	44	65	109
7	6 to 12 months	60	78	138
8	1 to 3 years	94	98	192
9	3 to 5 years	114	98	212
10	5 to 8 years	114	112	226
11	8 to 12 years	110	124	234
12	12 to 16 years	105	142	247
Total		1,009	1,132	2,141

[a] The term "to" specifies the upper limit of each age range in the sense of "less than" logic. For instance, age group 2 (1 to 3 days), includes children from 24 to less than 72 hours.

Recording Techniques

Conventional limb and precordial leads were recorded in all subjects. In agreement with common pediatric practice, lead V3 of the conventional lead system was replaced by V3R.

Five-millimeter-diameter Hewlett Packard electrodes were used. Great care was taken to avoid electrical contact between adjacent electrodes when placing the electrodes and applying the paste. Each tracing was repeated, if necessary, until judged by the technician to be of good quality.

Recordings were made using a three-channel Marquette console model C-242. The frequency response of this recorder is DC to 250 Hz (−3 db point), with an input impedance of 50 megohms. The console was coupled with an Ampex model C-602 FM recorder. This configuration permitted the technician to check the quality of the record on paper at the same time it was recorded on magnetic tape. Each subject was assigned an identification code that included age, weight, height, and sex. The FM recordings of the ECGs were intermittently transmitted through a telephone line for signal preprocessing using an IBM 1800 computer.

Analog-to-digital conversion was performed at a sampling rate of 1,000/sec, ie, 333/sec/channel. The computer program used for data acquisition and measurement of the 12-lead ECG was a modified version of the Mayo Clinic Program [17]. This program was originally designed for analysis of the orthogonal Frank-lead ECGs, and changes were necessary to adapt it to the conventional 12-lead ECG of children. Amplitude measurements were made using the PR segment as reference for the baseline. The measurements are made from a single P-QRS-T cycle representative of the majority-type (normal) complex.

Verification of Amplitude and Duration Measurements

After ECG wave amplitude and duration were determined by the aforementioned program, the values were stored on punched cards and analyzed using a CDC 7400 computer. Visual verification using a magnifier was systematically performed on all data in the upper and lower decile in each age group from which graphs and tables were later constructed. In instances of poor quality records, the measurement was discarded. When the wave was easily measurable by visual inspection and there was a com-

Table 2. Weight (kilograms) by age-group

Age	Number of subjects	Mean	Stand. deviat.	Percentile						
				2%	5%	25%	50%	75%	95%	98%
0 to 24 hours	189	3.3	0.4	2.4	2.6	2.9	3.3	3.6	4.0	4.1
1 to 3 days	179	3.3	0.4	2.5	2.7	3.0	3.2	3.5	3.9	4.0
3 to 7 days	181	3.2	0.5	2.3	2.4	2.9	3.2	3.5	4.0	4.3
1 to 4 weeks	119	3.5	0.5	2.3	2.6	3.1	3.6	3.9	4.4	4.6
1 to 3 months	115	4.8	0.9	2.6	3.5	4.0	4.8	5.5	6.0	6.7
3 to 6 months	109	6.6	1.3	4.5	4.9	5.7	6.8	7.2	8.6	10.0
6 to 12 months	138	8.7	1.3	5.9	6.4	7.8	8.8	9.5	11.1	11.6
1 to 3 years	192	12.4	2.0	7.7	8.0	10.0	12.5	15.0	17.0	17.3
3 to 5 years	212	16.1	2.4	11.0	12.6	14.0	15.8	17.8	22.0	23.9
5 to 8 years	226	20.9	3.7	13.0	13.9	18.2	20.5	23.2	27.3	31.4
8 to 12 years	234	31.1	7.7	18.8	20.9	25.5	29.9	35.8	47.7	53.8
12 to 16 years	247	47.8	10.2	32.1	34.4	40.0	46.2	54.6	65.3	73.6

puter wave-recognition error, the visually determined value was substituted in the data file. This visual inspection was carried out separately by two observers, and a more experienced observer adjudicated whenever there were differences between the two initial independent measurements.

Because amplitude distortions produced by a direct-writing electrocardiograph can be large, depending on the writing characteristics of the recorder and the ECG wave form, no substitution for amplitudes measured by the computer were made when the differences between visual and computer measurements were less than approximately 10% for large waves or 50 µV for small waves. With improved standards of ECG recording equipment, the fidelity of ECG records has in general improved. However, in actual operating conditions most instruments in use in hospitals can produce fairly large distortions. As a result, when the baseline or tracing width is too large, the visually measured ECG wave durations may seem to be less than they really are. This error is particularly pronounced with certain types of round, pressurized-ink stylus recorders [14]. Substantial hysteresis errors can produce a considerable bias toward reduced ECG amplitudes even with the most modern direct-writing electrocardiographs. For this reason, amplitude measurements in a given medical center may be lower than ours, which are based on more accurate and precise computer measurements. The differences between visual and computer measurements may become less, with a general improvement in the fidelity of ECG machines.

Differences Between Computer and Visual Measurements of Selected ECG Amplitudes and Intervals

Table 5 shows a comparison between visual reading of tracings obtained with the Marquette console from 24 children, two from each age group, and computer measurements of selected waves from the same children. There is a reasonable agreement for PR, QRS, and QT intervals, computer measurements being 4 to 6 msec greater than visual measurements. The greatest difference is for P wave duration where the computer measurement is on the average 16 msec longer. For amplitudes, visual measurements are consistently less than computer measurements. The relative error for R and T mean amplitude is of the order of 10% and somewhat greater for P waves. Table 5 shows that the mean

Table 3. Height (centimeters) by age-group

Age	Number of subjects	Mean	Stand. deviat.	Percentile						
				2%	5%	25%	50%	75%	95%	98%
0 to 24 hours	189	51	2.2	46	47	49	51	52	54	56
1 to 3 days	179	51	2.0	46	47	49	51	52	54	54
3 to 7 days	181	50	2.0	47	48	49	50	52	54	56
1 to 4 weeks	119	51	3.0	45	43	49	51	53	56	58
1 to 3 months	115	56	4.7	45	48	53	56	59	63	68
3 to 6 months	109	63	5.9	55	56	60	63	66	71	75
6 to 12 months	138	71	5.0	60	61	67	72	77	81	87
1 to 3 years	192	85	7.3	70	72	81	86	92	99	100
3 to 5 years	212	101	6.0	86	90	95	101	106	112	117
5 to 8 years	226	115	7.6	101	102	110	115	120	129	133
8 to 12 years	234	135	9.6	113	117	127	134	141	153	158
12 to 16 years	247	154	8.7	137	140	148	154	160	169	173

Table 4. Body surface area (square metres) by age-group

Age	Number of subjects	Mean	Stand. deviat.	Percentile						
				2%	5%	25%	50%	75%	95%	98%
0 to 24 hours	189	0.20	0.02	0.17	0.18	0.19	0.20	0.21	0.23	0.24
1 to 3 days	179	0.20	0.02	0.17	0.18	0.19	0.20	0.21	0.23	0.23
3 to 7 days	181	0.20	0.02	0.17	0.17	0.19	0.20	0.21	0.23	0.24
1 to 4 weeks	119	0.21	0.02	0.16	0.18	0.19	0.21	0.23	0.25	0.25
1 to 3 months	115	0.26	0.03	0.17	0.21	0.23	0.26	0.28	0.31	0.32
3 to 6 months	109	0.32	0.04	0.26	0.27	0.29	0.32	0.35	0.38	0.42
6 to 12 months	138	0.44	0.04	0.30	0.31	0.36	0.42	0.50	0.58	0.59
1 to 3 years	192	0.57	0.07	0.35	0.43	0.49	0.55	0.62	0.72	0.74
3 to 5 years	212	0.69	0.07	0.50	0.56	0.64	0.69	0.73	0.86	0.89
5 to 8 years	226	0.83	0.10	0.61	0.63	0.76	0.82	0.89	1.02	1.04
8 to 12 years	234	1.09	0.17	0.77	0.81	0.95	1.06	1.19	1.43	1.53
12 to 16 years	247	1.43	0.17	1.14	1.18	1.30	1.41	1.57	1.73	1.84

difference for the R wave amplitude in V5 can be expected to exceed 20% of its absolute value in 5% of records. This suggests that channel saturation or clipping of tall R waves can take place in paper tracings.

Reproducibility of ECG Measurements

To evaluate total variability of all components of the system, including electrode placement as well as other biological and technical sources of variation, the ECG was repeated after a short interval in 50 children, 25 from the age group 3 to 7 days and 25 from the age group 12 to 16 years. At first, the electrode replacement procedure may not have been entirely blind, although our initial procedure called for a several-hour interval between the two recordings; the slight red circle from the adhesive tape of the electrodes was still visible after several hours in some cases. On the other hand, if the excess paste was removed immediately after taking off the electrodes, marks made by the electrodes were not distinguishable because the whole area was slightly hyperemic. Consequently, the electrodes were replaced within a few minutes after the first recording. The results in Table 6 obtained using the latter procedure indicate that biological and technical short-range variations constitute the greatest source of error, exceeding the differences observed between visual and computer measurements. Electrode placement variation is probably the greatest source of short-range, age-independent ECG variation in clinical applications.

Table 5. Differences between computer and visual measurements of selected ECG amplitudes and intervals in a group of 24 children.

Measurement	Lead	Mean difference[a]	S.D.[b]
P amplitude	II	0.04	0.05
R amplitude	V_5	0.21	0.18
S amplitude	V_2	0.21	0.24
T amplitude	V_4	0.05	0.06
P duration	II	16	15.7
PR interval	II	4	12.5
QRS duration	V_5	5	5.9
QT interval	V_5	6	23.4

[a] A positive value for the mean difference indicates that computer measurement was larger than visual measurement.
[b] S.D.: Standard deviation of the differences. The amplitudes are given in millivolts and the intervals in milliseconds.

Table 6. Variability of selected ECG amplitudes and intervals in a group of 50 children.

Measurement	Lead	Percentile difference[a]	
		50%	90%
P amplitude	II	0.06	0.12
Q amplitude	V_6	0.03	0.07
R amplitude	V_6	0.10	0.17
S amplitude	V_2	0.12	0.24
T amplitude	V_4	0.19	0.24
P duration	II	25	60
PR duration	*	21	43
QRS duration	V_6	6	18
QT duration	V_6	36	72

* Second longest PR interval in frontal plane leads.
[a] The recording, including electrode placement, was repeated within a few minutes. The absolute differences between paired measurements were determined and are expressed by their median (50th percentile) and 90th percentile values. The amplitude differences are given in millivolts and the duration differences in milliseconds.

Sample Size Considerations

The number of subjects in each group is an important determinant of the confidence limits for various distributions of ECG measurements. Table 7 lists standard deviations of the mean and 95th and 98th percentiles as a function of sample size, assuming a normal distribution, for selected ECG measurements. The values suggest that it is desirable to have more than 100 subjects to secure 98th percentile limits for the most important ECG variable, especially since their frequency distribution often is not normal.

Data Analysis

The relation between ECG wave amplitudes and durations as well as some other ECG indices commonly used in pediatric cardiology and heart rate, age, height, weight, body surface area, and sex were studied. A total of 461 tables and graphs were produced. Figure 18 is a representative graph. On the horizontal axis are the different age ranges and on the vertical axis the scale for the variable studied; in this example, the amplitude of the R wave is expressed in millivolts. Each continuous line indicates a given percentile limit interpolated from age group to age group, ranging from the second to the 98th percentile values. The mean value for each age group is indicated by an •. At the top of the graph, the first row indicates the total number of subjects studied in each group for that particular variable. Below this are figures giving the minimum and maximum values observed.

We believe this is a good way to concentrate a large amount of information in an easily understandable form. These graphs also facilitate serial ECG comparisons, permitting the physician to decide whether observed ECG changes can be attributed to the normal evolution with age. This is also a simple way to present an asymmetric distribution, which many ECG variables have. However, the time scale provided is neither linear nor continuous. The percentiles given in each age range are for all the children in that range combined, the most reliable values probably being those at the median age for the group. The exact ages at which a given ECG value first falls below or rises above, say, the second or 98th percentiles cannot be determined from these graphs. Where a percentile line is "smooth," it seems reasonable to place more reliance on it than where it is "unsmooth," ie, where there are inconsistent differences between adjacent age ranges.

In addition to the percentile charts, an equal number of tables were made showing the distributions of data in more detail. These tables are not reproduced here but are available from the authors on request.

Table 7. The dependence of the confidence limits on the sample size[a]

Parameter	Mean	SE sample size				SD 95th% sample size				SD 98th% sample size			
		20	50	100	200	20	50	100	200	20	50	100	200
P II amplitude	.15	.011	.0075	.0050	.0035	.023	.015	.010	.0073	.031	.022	.014	.010
Q III amplitude	.12	.029	.018	.013	.0092	.060	.037	.021	.019	.083	.051	.037	.026
R V_5 amplitude	1.9	.13	.082	.058	.041	.21	.17	.12	.09	.37	.24	.17	.12
S aVR amplitude	.35	.11	.066	.047	.033	.23	.14	.10	.07	.31	.19	.13	.09
T V_4 amplitude	.40	.049	.031	.022	.015	.10	.065	.046	.032	.14	.088	.063	.043
PR II interval	114	4.0	2.5	1.7	1.2	8.4	5.3	3.6	2.5	11.5	7.2	4.9	3.4
QT V_5 interval	299	4.9	3.1	2.2	1.5	10.2	6.5	4.6	3.1	14.1	8.9	6.3	4.3
QRS V_5 duration	56	1.9	1.2	.86	.61	4.0	2.5	1.8	1.3	5.5	3.4	2.5	1.8
Q III duration	10.3	1.7	1.0	.74	.52	3.6	2.1	1.6	1.1	4.9	2.9	2.1	1.5

[a] Expressed as standard deviation of the mean (standard error, SE) and the standard deviation (SD) of the 95th and 98th percentiles for selected ECG measurements.

$SE = \frac{\delta}{\sqrt{n}}$ and $SD = \frac{P(1-p)}{f(p)} \frac{\delta}{\sqrt{n}}$, where δ = SD of the parameter, p = percentile and f = probability density of normal distribution.

Results

"Within normal limits" refers to values between the second and 98th percentiles in each age range.

Heart Rate (Fig. 1)

The mean heart rate increases between the first day of life and about 1 month of age and slowly decreases from about 3 months onward. There is wide variability of heart rate in all age groups. The highest mean heart rates occur between 1 and 3 months of age, with a mean value in that age range of nearly 150/min.

Frontal Plane QRS Angle (Fig. 2)

The frontal plane angle is the conventional mean electrical axis, with 0° to the left, 90° vertical down, and 180° to the right.

The mean value of the QRS frontal plane angle between 0 to 7 days is about 135°, progressively decreasing to about 60° in the age range 3 to 6 months and remaining relatively unchanged thereafter.

PR interval (Fig. 3 and 4)

The mean PR interval changes little until about the age of 3 months and then gradually increases (Fig. 3). Similarly mean PR interval increases as heart rate decreases (Fig. 4). However, the scatter of PR intervals around the mean at different ages and different heart rates is very large.

Table 8. Sex differences in R wave amplitudes in age group 12 to 16 years.

Lead	Sex[a]	Mean[b]	SD	Percentile limit				
				02%	05%	50%	95%	98%
aVR	girls	0.11	0.11	0.00	0.01	0.09	0.35	0.40
	boys	0.13	0.12	0.00	0.01	0.12	0.37	0.42
	D	0.02 NS						
aVL	girls	0.23	0.18	0.01	0.03	0.18	0.62	0.70
	boys	0.23	0,20	0.01	0.02	0.19	0.60	0.86
	D	0.00 NS						
aVF	girls	0.96	0.33	0.27	0.35	0.95	1.53	1.66
	boys	1.05	0.41	0.17	0.33	1.06	1.73	2.04
	D	0.09 NS						
V_1	girls	0.37	0.23	0.01	0.04	0.35	0.85	0.96
	boys	0.44	0.25	0.02	0.05	0.42	0.94	1.03
	D	0.07*						
V_2	girls	0.92	0.36	0.28	0.36	0.87	1.63	1.72
	boys	1.11	0.40	0.23	0.44	1.11	1.79	1.94
	D	0.19***						
V_4	girls	1.76	0.57	0.61	0.76	1.74	2.79	3.32
	boys	2.58	0.72	1.11	1.36	2.55	3.81	3.94
	D	0.82***						
V_5	girls	1.66	0.50	0.63	0.83	1.63	2.73	2.99
	boys	2.40	0.60	1.09	1.29	2.41	3.39	3.47
	D	0.74***						
V_6	girls	1.23	0.30	0.59	0.72	1.22	1.78	1.91
	boys	1.58	0.40	0.80	1.01	1.59	2.23	2.41
	D	0.35***						

[a] Mean values (millivolts), standard deviations (SD) and percentile limits are listed separately for 105 boys and 142 girls. D = amplitude difference (boys − girls)

[b] *** = p value < 0.0001, * = p < 0.05, NS = non-significant difference.

QRS Duration (Fig. 5)

QRS duration was measured in lead V5 (Fig. 5) because, in our series, V5 is one of the leads where the beginning of QRS seems more sharply defined and thus easier to identify. The values for QRS durations measured by the computer from V2 were about 10 to 15 msec longer. The QRS duration measured by computer using multiple, simultaneously recorded leads can be expected to be wider than that measured using a single lead because the beginning or end of the QRS may deviate from the baseline only slightly or not at all, in some leads.

QT Duration (Fig. 6, and 7)

The mean QT duration decreases steadily with increasing heart rate (Fig. 6). The nonlinear relationship between QT duration and age (Fig. 7) roughly corresponds to the relationship expected from the variation of heart rate with age; the scatter of QT duration is particularly large in the younger age groups, probably reflecting the wide variation in heart rate. The corrected QT (QT/$\sqrt{RR}$) was also calculated. It was found that the mean value of the corrected QT interval remains at about 0.40 throughout all age groups studied. In 95% of the subjects, the corrected QT interval is less than 0.45 and in 98% less than 0.48, with the exception of the first day of life where the values are slightly higher.

P Wave Amplitude (Fig. 8)

Mean P amplitude in lead II remains remarkably unchanged from birth until at least 16 years of age. After 6 to 12 months, the 98th percentile is 0.25 mV, whereas slightly higher extreme values (up to 0.3 mV) can be seen in younger subjects. In several age groups, negative P waves were occasionally found. These may represent ectopic atrial rhythms but were not excluded from the group of normal subjects because it was assumed that they would not significantly influence the percentile distribution curves because of their rarity.

Q Wave Amplitude (Fig. 9 to 12)

Q amplitude distributions according to age are shown in Fig. 9 to 12 for leads III, AVF, V5, and V6. In contrast to adult ECGs, fairly large amplitude Q waves are seen in children. For instance, in lead III the 98th percentile exceeds 0.45 mV until the age range 1 to 3 years. In lead V5 and V6 prominent Q waves can be present at least up to the age range 12 to 16 years. Twenty-five percent of normal newborns have no Q wave in lead V6 (Fig. 12). A Q wave was found in V1 only once; V1 showed a QS wave in a one 3-day-old child, but at 3 months the EGC pattern was normal.

R Wave Amplitude (Fig. 13 to 19)

Amplitude distributions of the R wave according to age in a VR, V3R, V1, V2, V4, V5, and V6 are shown in Fig. 13 to 19. The scatter for extreme values is larger in the younger age groups. There is a sharp reduction in the upper normal limits with age. Minimal values indicated as 0 in this table mean that any R wave is not greater than 20 μV.

The amplitude of the mean R wave decreases progressively in V3R, with concomitant decrease in the normal range. The upper normal limits for R in V3R are very high, with maximum values about 2 mV in the first two age ranges. As can be expected, the mean amplitude of R wave in the right chest leads (Fig. 14 and 15) decreases with age, whereas in the left leads (Fig. 18 and 19) there is a gradual increase in this amplitude. In all age groups extreme values for the R wave were seen, especially in V5; the highest value, 4.6 mV, occurred in the 8- to 12-year age group.

R wave amplitude distributions were studied separately in all age groups stratified by sex. Some highly significant differences were observed within the age group 12 to 16 years. Table 8 summarizes the mean differences between R wave amplitudes. The normal percentile limits are listed for boys and girls separately. No significant R wave amplitude differences were found in the limb leads, whereas the R wave amplitudes in the anterior and especially the left chest leads were significantly larger in boys than in girls. The amplitudes in girls are mainly responsible for the decline in R wave amplitudes observed in the oldest age group in Fig. 18 and 19, probably reflecting changes in extracardiac factors (eg, breast development and greater amount of subcutaneous fat) associated with the puberty.

S Wave Amplitude (Fig. 20 to 25)

Amplitude distributions for the S wave in leads V4 through V6 show, as expected, a progressive amplitude reduction in the left chest leads as age increases. In leads V3R through V2 there is an initial reduction of the mean S wave amplitude followed by an increase after 1 to 3 months.

T Wave Amplitude (Fig. 26 to 30)

In V3R and V1 the mean value for the T wave is positive at birth but becomes negative within the first three days of life. In the 3- to 7-day range the T amplitude at the 98th percentile is positive, but in the 7- to 30-day range it is negative. Although our charts do not indicate the exact age at which this 98th percentile first becomes negative, it is generally agreed that this occurs by the age of 7 days and that it remains negative until about the age of 5 years (3 to 8 years in our charts). Our maximum values were negative between 1 month and 3 years but were positive before and after this range. In V2, the T wave can be negative at least until the age of 12 years. Over the left chest leads (Fig. 26 and 29), the mean T wave amplitude increases progressively with age until 8 to 12 years and then shows a small decrease. In a small proportion of cases the T wave in V6 can be negative at birth but becomes positive between 1 and 3 days of age.

R/S Amplitude Ratio (Fig. 31 to 34)

In V3R the mean R/S ratio is greater than 1/1 until after 1 to 3 months of age; its mean value then becomes less than 1/1. Up to the age of about 3 years, there is substantial scatter of normal values for this ratio. After that, a ratio exceeding 1/1 is abnormal. In V1, R/S ratio can exceed 1/1 at least until the age of 16 years, and a ratio up to 2/1 is within normal limits until the age of 5 to 8 years. As expected, R/S ratio increases progressively with age in V5 and V6 with increasing normal range. Minimal and maximal values have been omitted from these tables because the ratio loses its practical meaning when either R or S wave are extremely small.

Sum of R and S Amplitudes (Fig. 35 to 38)

The mean value of the sum of R and S wave amplitudes in anterior chest leads changes little with age. The 98th percentile for lead V2 decreases from about 6.3 mV to about 4.8 mV with increasing age. In V4 it stays stable at a level of approximately 5 mV except for a peak between 3 and 6 months where values up to 5.8 mV are observed.

The mean value of the sum of R wave amplitude in left precordial leads plus the S wave amplitude in right precordial leads remains relatively unchanged until 1 week–1 month, progressively increases to reach a peak value in the group from 8 to 12 years, then declines (Fig. 37 and 38).

QR Interval (Ventricular Activation Time) (Fig. 39)

The QR interval measured from the beginning of the Q wave to the peak of the R wave in V5 increases progressively from a mean value of 18 msec at birth to 32 msec in the age group 12 to 16 years. The range of normal value is fairly narrow in all age groups. A deviation from the mean exceeding roughly 10 msec is outside the normal range.

QRS Transition Zone

The location of the QRS transition zone was also investigated. It was found that the location of the transition zone is extremely variable, and graphic presentation was not considered useful.

Discussion

The evolution and progression of the ECG and vectorcardiogram from birth to adolescence in normal children have been discussed by many authors, notably Liebman [7], Ziegler [20], Liebman and Plonsey [8], McCammon [9], and Rautaharju et al [13].

In the interpretation of children's ECGs, one practical need preponderates: In what proportion of normal children of the same age is the observed value for a given measurement expected to occur? The charts provided here should enable that need to be fulfilled if high-fidelity records are used.

ECG patterns and the normal limits for ECG measurements determined for clinically healthy children change markedly with age. An example of the striking differences between children and adult ECGs is seen in Fig. 37, representing the sum of R wave amplitude in V5 and S in V2. The sum of these waves exceed 3.5 mV in more than 80% of the children of the 5- to-8-year group. This value is much less frequent in adults and in them is a criterion of left ventricular hypertrophy.

It is of interest to examine some diagnostic criteria used by pediatric cardiologists in ECG interpretation. The pathological significance of a Q wave in V3R or V1 at any age [19] or a positive T wave in these leads after the first few days of life in younger children [21] is reemphasized by our findings. A positive T wave in V1 is above the 98th percentile between the first week of life and the range 3 to 5 years (Fig. 27). Its occurrence at 1 month of age, as reported by Rosen and Gardberg [15], is certainly exceptional. By the age of 5 years, positive T waves in V1 are becoming more and more common.

The R/S amplitude ratio in V1 is considered useful in the diagnosis of right ventricular hypertrophy in children. Our data suggest that a criterion of normality currently used [5] may need revision. An R/S ratio of 2/1 is still within normal limits in the age group 5 to 8 years, as is a ratio of 1.6/1 in the groups from 8 to 16 years (Fig. 32).

The presence of large R and S waves in the midprecordial leads is generally considered a sign of biventricular hypertrophy [4]. However, the value of 5 mV for the sum of R and S amplitudes suggested as a criterion for biventricular hypertrophy by Elliot et al [2] is below our 98th percentile at least up to about 8 years in V2 (Fig. 35) and at most ages in V4 (Fig. 36). The value of 6 mV proposed by Namin [11] is more plausible, being above our 98th percentile after 3 to 7 days of age, although we had some maximum values greater than this in V2 and even more in V4.

In the age group from 8 to 16 years, 5 mV is above our 98th percentile in both V2 and V4.

Q waves in V5 or V6 greater than 0.4 mV, alone or in association with tall symmetrical T waves, are generally accepted as a sign of left ventricular hypertrophy [5, 6, 10]. In our study (Fig. 12) 0.3 millivolts for Q wave amplitude in V6 is above the 98th percentile up to 1 to 3 years and after 8 to 12 years. In V5, a Q wave up to 0.4 mV is within normal limits in the age groups from about 1 to about 8 years (Fig. 11).

Left ventricular hypertrophy is also believed to be likely when the sum of R in V6 and S in V1 exceeds 5 mV at any age [6, 10, 12]. Our data are consistent with that belief in that 5 mV was above the 98th percentile in all age ranges and very few maximum values exceed 5 mV. Perhaps an even lower voltage should be used, even in the age range 5 to 8 years in which the highest values are found. High-amplitude R waves in the left precordial leads are relatively common, especially between about 5 to 12 years when the mean values exceed 2.5 mV. Therefore, the charts for these leads should be checked before an R wave is declared above normal limits and left ventricular hypertrophy invoked. The aforementioned comments regarding amplitude criteria for ventricular hypertrophy relate only to the specificity of these criteria. No conclusions regarding their sensitivity can be drawn from our study.

We would also like to caution users of our charts not to place too much emphasis on the extreme minimal and maximal values given for each measurement. These values depend heavily on the sample size, and with a large number of observations occasional anomalous or even erroneous values cannot be easily eliminated in this type of study. On the other hand, with a large sample these occasional deviant values will not significantly influence the confidence limits for percentile values.

A potential technical limitation of our study is the relatively low sampling rate used in the analog-to-digital conversion. The sampling rate of 333 per channel corresponds to the Nyquist frequency of about 166 Hz. It is conceivable that there are higher-frequency components in the ECGs of young children. It is not known whether such higher-frequency components contain significant energy or significant medical information. In future ECG studies in children, therefore, it may be desirable to use a higher sampling rate. Despite this possible limitation, the present study represents an improvement in signal fidelity and measurement precision in comparison with analyses performed from direct-writing electrocardiograph tracings, as is evident from Table 5.

Of special concern is the limited reproducibility of ECG measurements observed in our test group of 50 children (Table 6). The variability in records repeated at short intervals is substantial. To a large extent, this variability is caused by variations in electrode placement. It is likely that the normal limits would be narrower if the magnitude of this error source could be reduced. This is an important technical problem that seems to warrant further studies.

As indicated in Table 7, the sample size of the different age groups in the present study seems adequate for reliable determination of normal percentiles, including the second and 98th percentile values. These sample size calculations assume a normal distribution; greater or smaller sample sizes may be needed for the extreme percentiles where the distributions are grossly nonnormal, eg, R/S ratio in V1. To our knowledge, this is the first time that limits for 96% normal range for infants and children have been determined using such large homogenous samples in all age groups. Previous reports have presented 90% normal range because of insufficient sample size for reliably determining 96% ranges. The utility of 90% limits is less because one tenth of normal children would be outside these limits for each variable used. While stratification of the different age groups according to anthropometric variables such as height, weight, and body surface area would presumably narrow normal ranges, it was believed that this would be too complicated for general application. In the oldest age group the stratification according to sex seems important because of significant sex-related differences in R wave amplitudes. Also sample size needs to be larger if different age groups are stratified as indicated previously, and since all of these anthropometric variables are strongly correlated with age, the additional data would include much redundant information. It is conceivable, however, that in the future multiple correlation techniques will further improve the computer analysis of pediatric ECGs.

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