European Heart Journal (2001) **22**, 702–711
doi:10.1053/euhj.2000.2399, available online at http://www.idealibrary.com on IDEAL®

New normal limits for the paediatric electrocardiogram

P. R. Rijnbeek[1], M. Witsenburg[2], E. Schrama[2], J. Hess[3] and J. A. Kors[1]

[1]*Institute of Medical Informatics, Faculty of Medicine and Health Sciences, Erasmus University, Rotterdam, The Netherlands;* [2]*Department of Paediatric Cardiology, Sophia Children's Hospital, Rotterdam, The Netherlands;* [3]*Department of Paediatric Cardiology and Congenital Heart Disease, Deutsches Herzzentrum München, Munich, Germany*

Aims Previous studies that determined the normal limits for the paediatric ECG had their imperfections: ECGs were recorded at a relatively low sampling rate, ECG measurements were conducted manually, or normal limits were presented for only a limited set of parameters. The aim of this study was to establish an up-to-date and complete set of clinically relevant normal limits for the paediatric ECG.

Methods and Results ECGs from 1912 healthy Dutch children (age 11 days to 16 years) were recorded at a sampling rate of 1200 Hz. The digitally stored ECGs were analysed using a well-validated ECG computer program. The normal limits of all clinically relevant ECG measurements were determined for nine age groups. Clinically significant differences were shown to exist, compared with previously established normal limits. Sex differences could be demonstrated for QRS duration and several amplitude measurements.

Conclusions These new normal limits differ substantially from those commonly used and suggest that diagnostic criteria for the paediatric ECG should be adjusted.
(Eur Heart J 2001; 22: 702–711, doi:10.1053/euhj.2000.2399)

Key Words: Electrocardiography, paediatrics, normal limits, computer

Introduction

Several studies have been conducted to determine normal limits for the paediatric electrocardiogram (ECG)[1–9]. However, all these studies have certain imperfections that limit their practical applicability. Firstly, normal limits have often been presented for an incomplete set of clinically relevant parameters and leads. Secondly, in many studies parameters were measured by hand from ECGs recorded on paper. (At present, computer analysis of digitized ECGs allows more accurate measurement.) Thirdly, in some studies the ECG signals may have been recorded less than perfectly owing to low sampling rates or the use of ECG amplifiers with a small bandwidth.

Probably the most comprehensive study to date has been that of Davignon *et al.*[4], in which ECGs of 2141 children aged 0 to 16 years were recorded. The ECGs were digitized at a sampling rate of 333 Hz and normal limits were determined using computer-assisted measurements. Normal limits for a large number of parameters were presented as percentile charts ranging from the 2nd to the 98th percentile. However, in a study of 1780 children, Macfarlane *et al.*[6] recorded ECGs at a sampling rate of 500 Hz and showed that the 98th percentile of normal amplitudes could be up to 46% higher than published by Davignon *et al.*[4]. Unfortunately, in the study of Macfarlane *et al.*[6] normal limits were presented for only a few parameters. Moreover, it is questionable whether even a sampling rate of 500 Hz is high enough to obtain accurate measurements in paediatric ECGs[10–12].

In this study, we wanted to establish an up-to-date and complete set of clinically relevant normal limits for the paediatric ECG, using a high sampling rate of 1200 Hz and an ECG computer program for measurement.

Revision submitted 21 July 2000, and accepted 26 July 2000.

The study was supported by the Netherlands Ministry of Economic Affairs.

Correspondence: Peter R. Rijnbeek, MSc., Institute of Medical Informatics, Faculty of Medicine and Health Sciences, Erasmus University Rotterdam, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands.

Methods

Study population

The study population consisted of 1912 children aged 11 days to 16 years, recruited at three child health centres, three primary schools, and a secondary school

0195-668X/01/080702+10 $35.00/0

Table 1 Age and sex distribution of the study population

Age*	Male	Female	Total
0 to 1 month	16	28	44
1 to 3 months	67	71	138
3 to 6 months	78	104	182
6 to 12 months	130	105	235
1 to 3 years	95	110	205
3 to 5 years	79	79	158
5 to 8 years	142	118	260
8 to 12 years	137	187	324
12 to 16 years	200	166	366
Total	944	968	1912

*The term 'to' specifies the upper limit of the age range in the sense of 'less than' logic.

in Rotterdam. In the Netherlands all children as from about 3 weeks to 4 years old, periodically visit child health centres for a physical examination. Children with previously known cardiovascular abnormalities were excluded from the study. The total population is divided into nine age groups, similar to the grouping used by Davignon *et al.*[4]. All children up to 1 month are combined in one group, because of the relatively small sample size. Table 1 shows the sex distribution for each age group. For each child, weight and height was measured prior to the ECG recordings. Data for weight and height corresponded well with the Dutch growth standard[13]. The study was approved by the local ethics committee. All parents and all children aged 12 or older gave their written informed consent.

ECG measurements

For each child, a 12-lead ECG was recorded using a portable PC-based acquisition system (Cardio Control, Delft, The Netherlands) at a sampling rate of 1200 Hz. The frequency response of this recorder is flat to 320 Hz (−3 db point). The ECGs were recorded by the same technician throughout the study. Following common practice in the department of paediatric cardiology in Rotterdam, V_{3R} was used instead of V_3 and V_7 instead of V_5. All ECGs were processed by the Modular ECG Analysis System (MEANS)[14]. To reduce noise, MEANS computes a representative average beat for each of the 12 leads, from which ECG measurements are derived. MEANS has extensively been evaluated both by its developers[14] and by others[15,16]. In the latter studies, the performance of MEANS was gauged against the measurements obtained from a group of cardiologists, and its good performance shown. Plots of all ECGs showing wave onsets and ends as found by MEANS were visually checked. Because of waveform recognition errors, mainly due to excessive noise, 16 ECGs were removed from the data set. The excluded ECGs were randomly distributed over the age groups.

Estimation of normal limits

The 2nd and 98th percentile of the measurement distribution were taken as the lower limit and the upper limit of normal, respectively. Zero amplitude values indicating absent Q, R, or S waves, were excluded from the statistical analysis of the data. Prior to the estimation of the percentiles, a linear regression analysis on age was performed in each age group. Percentiles were then estimated parametrically on the residuals. Since parametric estimation assumes a sample distribution to be gaussian, possible non-gaussianity of the residuals was removed using a two-stage transformation procedure as recommended by Solberg[17]. In the first stage, asymmetry (skewness) was iteratively eliminated using the exponential function of Manly[18]. In the second stage, peakedness (kurtosis) of the resulting symmetrical distribution was iteratively eliminated with the modulus function of John and Draper[19]. To test the gaussianity of the transformed distribution, the Kolmogorov–Smirnov test was used. Finally, estimated percentiles and their 95% confidence intervals were back-transformed to the original unit of measurement. If a distribution remained non-gaussian after transformation, the non-parametrical ranked-based method, as described by Solberg[17] was applied on the original data. Sex differences were identified by non-overlapping 95% confidence intervals of the percentiles.

Apart from a tabular presentation of normal limits in age groups, we determined age-dependent curves that present the normal limits in a continuous form. The two-stage transformation as described above was applied in a window of 200 measurements, moving along the age axis with a step size of one measurement. For each window position the percentiles and their confidence intervals were calculated and related to the median of the age values included in the window. This procedure would imply that the first normal limit corresponds with the median age of the first 200 measurements. To allow for estimates at younger ages, the procedure starts with a small initial window that grows until 200 measurements are included. As a consequence, confidence intervals at the youngest ages are wider. Polynomial curves were then fitted through the 2nd and 98th percentile values to obtain percentiles that smoothly change with age. The order of the polynomials was determined by visual inspection of the fit, selecting the lowest order that yielded curves remaining within the estimated confidence intervals.

Results

Tables 2 to 7 show normal limits for the clinically most relevant parameters. Median values are given together with the 98th percentiles, taken as the upper limits of normal. The 2nd percentiles, taken as the lower limits of normal, are supplemented if clinically relevant. Normal limits are presented separately for boys (upper

Table 2 Lead-independent ECG measurements for boys (upper row) and girls (lower row): median (2nd percentile, 98th percentile)

Lead	0–1 months	1–3 months	3–6 months	6–12 months	1–3 years	3–5 years	5–8 years	8–12 years	12–16 years
Heart rate (beats . min $^{-1}$)	160 (129, 192)	152 (126, 187)	134 (**112**, **165**)	128 (106, 194)	**119** (97, **155**)	98 (73, 123)	88 (62, 113)	78 (55, **101**)	73 (**48, 99**)
	155 (136, 216)	154 (126, 200)	139 (**122, 191**)	134 (106, 187)	**128** (95, **178**)	101 (78, 124)	89 (68, 115)	80 (58, **110**)	76 (**54, 107**)
P axis (°)	56 (13, 99)	52 (10, 73)	49 (− 5, 70)	49 (9, 87)	48 (− 12, 78)	43 (− 13, 69)	41 (− 54, 72)	39 (− 17, 76)	40 (− 24, 76)
	52 (24, 80)	48 (20, 77)	51 (16, 80)	50 (14, 69)	47 (1, 90)	44 (− 6, 90)	42 (− 13, 77)	42 (− 15, 82)	45 (− 18, 77)
P duration (ms)	78 (64, 85)	79 (65, 98)	81 (64, 103)	80 (66, 96)	80 (63, 113)	87 (67, 102)	92 (73, 108)	98 (78, 117)	100 (82, 118)
	79 (69, 106)	78 (62, 105)	78 (63, 106)	80 (64, 07)	83 (62, 104)	84 (66, 101)	89 (71, 107)	94 (75, 114)	98 (78, 122)
PR interval (ms)	99 (77, 120)	98 (85, 120)	106 (87, 134)	114 (82, 141)	118 (86, 151)	121 (98, 152)	129 (99, 160)	134 (105, 174)	139 (107, 178)
	101 (91, 121)	99 (78, 133)	106 (84, 127)	109 (88, 133)	113 (78, 147)	123 (99, 153)	124 (92, 156)	129 (103, 163)	135 (106, 176)
QRS axis (°)	97 (75, 140)	87 (37, 138)	66 (− 6, 107)	68 (14, 122)	64 (− 4, 118)	70 (7, 112)	70 (− 10, 112)	70 (− 21, 114)	65 (− 9, 112)
	110 (63, 155)	80 (39, 121)	70 (17, 108)	67 (1, 102)	69 (2, 121)	69 (3, 106)	74 (27, 117)	66 (5, 117)	66 (5, 101)
QRS duration (ms)	67 (50, 85)	64 (52, 77)	66 (54, **85**)	**69** (52, **86**)	**71** (54, 88)	**75** (58, 92)	**80** (63, 98)	**85** (67, 103)	**91** (**78**, 111)
	67 (54, 79)	63 (48, 77)	64 (50, **78**)	**64** (52, **80**)	**68** (54, 85)	**71** (58, 88)	**77** (59, 95)	**82** (66, 99)	**87** (**72**, 106)
QTc interval (ms)*	413 (378, 448)	419 (**396**, 458)	422 (391, 453)	411 (379, 449)	412 (383, 455)	412 (377, 448)	411 (371, 443)	411 (373, 440)	407 (362, 449)
	420 (379, 462)	424 (**381**, 454)	418 (386, 448)	414 (381, 446)	417 (381, 447)	415 (388, 442)	409 (375, 449)	410 (365, 447)	414 (370, 457)

Bold values indicate that the 95% confidence intervals of the percentile estimates for boys and girls do not overlap.

*Corrected QT interval, according to Bazett's formula: $QTc = QT \cdot \sqrt{\frac{\text{heart rate}}{60}}$.

Table 3 P-wave amplitudes (mV) for boys (upper row) and girls (lower row): median (98th percentile)

Lead	0–1 months	1–3 months	3–6 months	6–12 months	1–3 years	3–5 years	5–8 years	8–12 years	12–16 years
II	0·15 (0·23)	0·16 (0·25)	0·15 (0·22)	0·16 (0·26)	0·15 (0·25)	0·13 (0·23)	0·12 (0·22)	**0·12** (0·22)	**0·13** (0·24)
	0·16 (0·25)	0·16 (0·23)	0·16 (0·23)	0·16 (0·24)	0·16 (0·25)	0·13 (0·23)	0·12 (0·24)	**0·14** (0·24)	**0·15** (0·26)
V_1	0·12 (0·22)	0·10 (0·19)	0·09 (0·17)	0·10 (**0·17**)	0·13 (0·20)	0·12 (0·19)	0·12 (0·20)	0·11 (0·19)	0·11 (0·18)
	0·10 (0·19)	0·10 (0·16)	0·10 (0·16)	0·11 (**0·21**)	0·12 (0·20)	0·12 (0·20)	0·11 (0·18)	0·11 (0·19)	0·10 (0·17)
V_2	0·15 (0·25)	0·13 (0·24)	0·11 (0·20)	0·13 (0·23)	0·13 (0·22)	0·11 (0·20)	0·11 (0·17)	0·11 (0·16)	0·10 (0·17)
	0·16 (0·28)	0·13 (0·23)	0·12 (0·19)	0·13 (0·23)	0·13 (0·23)	0·11 (0·19)	0·11 (0·17)	0·10 (0·18)	0·10 (0·17)

Bold values indicate that the 95% confidence intervals of the percentile estimates for boys and girls do not overlap.

Table 4 Q-wave amplitudes (mV) for boys (upper row) and girls (lower row): median (98th percentile)

Lead	0–1 months	1–3 months	3–6 months	6–12 months	1–3 years	3–5 years	5–8 years	8–12 years	12–16 years
II	0·14 (0·23)	0·18 (0·32)	0·14 (0·34)	0·18 (0·48)	0·15 (0·44)	0·11 (0·26)	0·10 (0·28)	0·09 (0·24)	0·08 (0·21)
	0·09 (0·26)	0·14 (0·32)	0·15 (0·43)	0·16 (0·44)	0·16 (0·48)	0·13 (0·27)	0·08 (0·26)	0·08 (0·21)	0·09 (0·20)
III	0·15 (0·26)	0·29 (0·50)	0·31 (0·71)	0·35 (0·79)	0·30 (0·74)	0·19 (0·46)	0·15 (0·36)	0·10 (0·28)	0·10 (0·29)
	0·18 (0·35)	0·24 (0·50)	0·28 (0·65)	0·34 (0·79)	0·31 (0·73)	0·18 (0·40)	0·16 (0·38)	0·10 (0·27)	0·10 (0·21)
aVF	0·13 (0·23)	0·20 (0·35)	0·20 (0·40)	0·22 (0·58)	0·20 (0·54)	0·14 (0·34)	0·12 (0·25)	0·09 (0·25)	0·08 (0·23)
	0·10 (0·27)	0·17 (0·35)	0·20 (0·44)	0·23 (0·52)	0·20 (0·54)	0·12 (0·31)	0·11 (0·31)	0·08 (0·21)	0·09 (0·18)
V_6	0·11 (0·22)	0·16 (0·31)	0·17 (0·35)	0·20 (0·60)	0·20 (0·56)	0·15 (0·42)	0·12 (0·39)	0·12 (0·43)	0·11 (**0·43**)
	0·09 (0·17)	0·15 (0·37)	0·15 (0·40)	0·18 (0·39)	0·17 (0·49)	0·15 (0·42)	0·10 (0·41)	0·11 (0·34)	0·09 (**0·23**)
V_7	0·08 (0·13)	0·13 (0·28)	0·14 (0·32)	0·17 (0·52)	0·19 (0·46)	0·13 (0·36)	0·11 (0·30)	0·11 (0·29)	0·11 (**0·32**)
	0·08 (0·15)	0·13 (0·28)	0·13 (0·36)	0·16 (0·34)	0·17 (0·43)	0·15 (0·33)	0·09 (0·36)	0·09 (0·26)	0·09 (**0·24**)

Bold values indicate that the 95% confidence intervals of the percentile estimates for boys and girls do not overlap.

Table 5 R-wave amplitudes (mV) for boys (upper row) and girls (lower row): median (98th percentile)

Lead	0–1 months	1–3 months	3–6 months	6–12 months	1–3 years	3–5 years	5–8 years	8–12 years	12–16 years
I	0·25 (**0·45**)	0·56 (1·12)	0·80 (**1·52**)	0·82 (1·52)	0·77 (1·37)	0·63 (1·09)	**0·62** (**1·16**)	0·59 (1·04)	**0·58** (1·09)
	0·31 (**0·62**)	0·55 (1·09)	0·74 (**1·26**)	0·75 (1·38)	0·68 (1·52)	0·65 (1·20)	**0·49** (**1·00**)	0·54 (1·21)	**0·48** (1·02)
II	0·64 (1·28)	1·08 (1·76)	1·27 (**1·97**)	1·27 (2·09)	1·27 (2·47)	1·36 (2·20)	1·24 (2·42)	1·39 (2·23)	1·31 (2·08)
	0·70 (1·21)	1·15 (2·04)	1·33 (**2·24**)	1·35 (2·21)	1·27 (2·34)	1·38 (2·24)	1·33 (2·27)	1·32 (2·29)	1·32 (2·03)
III	0·79 (1·44)	0·76 (1·60)	0·72 (**1·50**)	0·82 (**1·65**)	0·80 (1·96)	0·94 (1·82)	0·80 (1·92)	0·89 (1·86)	0·85 (1·74)
	0·85 (1·50)	0·91 (1·82)	0·95 (**1·85**)	0·90 (**1·95**)	0·96 (2·00)	0·94 (1·96)	1·03 (2·09)	0·92 (1·88)	0·88 (1·66)
aVR	0·32 (0·52)	**0·36** (**0·63**)	**0·32** (0·58)	**0·30** (**0·62**)	0·21 (0·53)	0·21 (**0·48**)	**0·23** (**0·51**)	**0·24** (**0·49**)	**0·23** (**0·46**)
	0·30 (0·61)	**0·27** (**0·49**)	**0·23** (0·51)	**0·21** (**0·48**)	0·25 (0·48)	0·17 (**0·39**)	**0·18** (**0·40**)	**0·18** (**0·41**)	**0·18** (**0·37**)
aVL	0·16 (0·32)	**0·35** (0·66)	0·40 (1·09)	0·44 (1·04)	0·38 (0·86)	0·26 (0·58)	0·22 (0·70)	0·17 (0·52)	0·19 (0·69)
	0·18 (0·45)	**0·25** (0·69)	0·37 (0·78)	0·40 (0·92)	0·38 (1·02)	0·24 (0·70)	0·18 (0·55)	0·17 (0·69)	0·16 (0·53)
aVF	0·59 (1·36)	0·88 (1·58)	0·93 (1·70)	0·96 (1·81)	1·00 (2·20)	1·13 (1·97)	**1·00** (2·19)	1·16 (2·00)	1·06 (1·88)
	0·72 (1·26)	0·98 (1·91)	1·07 (1·82)	1·11 (2·04)	1·10 (2·08)	1·14 (2·06)	**1·20** (2·17)	1·09 (2·06)	1·10 (1·84)
V_{3R}	0·62 (1·04)	0·58 (**1·24**)	0·57 (1·20)	0·48 (1·24)	0·49 (1·06)	0·41 (**0·81**)	0·23 (0·63)	0·22 (0·51)	0·19 (0·54)
	0·68 (1·26)	0·55 (**0·93**)	0·49 (1·11)	0·42 (0·98)	0·43 (0·92)	0·34 (**0·64**)	0·21 (0·57)	0·19 (0·47)	0·17 (0·49)
V_1	1·10 (2·05)	1·23 (2·07)	1·32 (2·20)	1·12 (2·14)	1·08 (2·11)	0·95 (**1·78**)	0·63 (1·48)	0·54 (1·14)	**0·48** (1·18)
	1·35 (2·22)	1·17 (1·99)	1·14 (2·04)	1·01 (1·92)	1·01 (1·91)	0·77 (**1·38**)	0·55 (1·24)	0·49 (1·14)	**0·35** (1·10)
V_2	1·83 (**2·67**)	1·82 (2·63)	**2·08** (2·54)	1·94 (**2·51**)	1·82 (2·41)	1·58 (2·26)	1·21 (**2·22**)	**1·02** (1·90)	**0·94** (**1·87**)
	1·83 (**2·17**)	1·81 (2·45)	**1·88** (2·60)	1·82 (**2·36**)	1·75 (2·38)	1·41 (2·25)	1·06 (**1·91**)	**0·90** (1·86)	**0·69** (**1·57**)
V_4	1·80 (**2·62**)	2·30 (3·05)	2·32 (3·23)	2·27 (3·32)	2·37 (3·38)	2·42 (3·30)	2·11 (3·11)	1·86 (3·16)	**1·87** (**3·06**)
	1·68 (**2·21**)	2·26 (3·26)	2·26 (3·31)	2·23 (3·09)	2·21 (3·54)	2·24 (3·38)	1·84 (3·04)	1·72 (3·23)	**1·24** (**2·55**)
V_6	1·00 (1·78)	1·55 (**2·23**)	1·65 (2·73)	1·70 (2·79)	1·79 (2·96)	1·94 (3·14)	1·97 (2·98)	**2·18** (3·24)	**2·02** (**3·05**)
	0·93 (1·64)	1·51 (**2·67**)	1·60 (2·80)	1·68 (2·74)	1·68 (2·67)	1·89 (2·91)	2·05 (3·25)	**2·00** (3·04)	**1·65** (**2·52**)
V_7	0·45 (0·93)	0·90 (**1·41**)	1·01 (1·76)	1·04 (1·84)	1·14 (1·99)	1·34 (2·12)	1·26 (2·01)	1·38 (2·24)	1·41 (**2·31**)
	0·52 (0·96)	0·95 (**1·68**)	0·96 (1·80)	1·13 (1·85)	1·15 (1·86)	1·35 (2·12)	1·36 (2·31)	1·35 (2·10)	1·34 (**1·98**)

Bold values indicate that the 95% confidence intervals of the percentile estimates for boys and girls do not overlap.

row) and girls (lower row). To indicate sex differences, non-overlapping 95% confidence intervals are visualized by bold percentiles. Because of space limitations, continuous age-dependent percentile curves are only shown for heart rate (Fig. 1) and QRS duration (Fig. 2).

Table 6 S-wave amplitudes (mV) for boys (upper row) and girls (lower row): median (98th percentile)

Lead	0–1 months	1–3 months	3–6 months	6–12 months	1–3 years	3–5 years	5–8 years	8–12 years	12–16 years
I	0·42 (0·71)	**0·46 (0·94)**	**0·41** (0·77)	**0·40 (0·81)**	0·27 (0·82)	0·21 (0·69)	0·22 (0·56)	**0·22** (0·50)	**0·19** (0·48)
	0·51 (1·01)	**0·35 (0·71)**	**0·32** (0·73)	**0·33 (0·73)**	0·35 (0·70)	0·20 (0·52)	0·22 (0·54)	**0·16** (0·47)	**0·13** (0·40)
II	0·24 (0·46)	0·29 (0·55)	0·29 (**0·61**)	**0·30** (0·62)	0·25 (0·55)	**0·28 (0·58)**	**0·27 (0·64)**	**0·30 (0·63)**	0·27 (**0·63**)
	0·26 (0·53)	0·22 (0·53)	0·24 (**0·46**)	**0·23** (0·54)	0·26 (0·56)	**0·20 (0·46)**	**0·19 (0·46)**	**0·20 (0·52)**	0·22 (**0·54**)
III	0·16 (**0·28**)	0·27 (0·54)	0·30 (**0·87**)	0·34 (0·86)	0·30 (0·72)	0·22 (0·51)	0·21 (**0·65**)	0·19 (0·56)	0·20 (0·57)
	0·19 (**0·34**)	0·24 (0·50)	0·28 (**0·63**)	0·33 (0·77)	0·32 (0·86)	0·19 (0·54)	0·18 (**0·41**)	0·16 (0·48)	0·17 (0·61)
aVR	0·41 (0·68)	0·76 (1·30)	0·98 (1·47)	0·98 (1·47)	0·95 (1·63)	0·93 (1·40)	0·90 (1·51)	0·96 (1·45)	0·91 (1·39)
	0·44 (0·64)	0·81 (1·31)	0·96 (1·49)	0·97 (1·48)	0·92 (1·61)	0·95 (1·49)	0·90 (1·40)	0·91 (1·51)	0·89 (1·35)
aVL	0·47 (**0·77**)	0·51 (1·02)	0·44 (**0·83**)	0·47 (0·98)	0·40 (1·00)	0·34 (0·87)	0·33 (**0·84**)	0·28 (0·88)	0·28 (0·94)
	0·63 (**1·17**)	0·53 (1·04)	0·46 (**0·98**)	0·52 (1·03)	0·44 (1·06)	0·33 (1·12)	0·43 (**1·02**)	0·30 (0·88)	0·28 (0·84)
aVF	0·18 (**0·27**)	0·22 (0·39)	0·23 (0·57)	0·23 (0·59)	0·23 (0·53)	**0·22** (0·52)	0·21 (**0·57**)	0·21 (**0·56**)	0·22 (0·54)
	0·18 (**0·38**)	0·20 (0·35)	0·20 (0·44)	0·24 (0·51)	0·24 (0·60)	**0·16** (0·40)	0·16 (**0·37**)	0·17 (**0·45**)	0·18 (0·55)
V_{3R}	0·12 (0·22)	**0·24** (0·86)	0·31 (0·90)	0·34 (1·04)	0·45 (1·21)	0·53 (0·99)	0·53 (1·06)	0·60 (1·17)	0·57 (1·14)
	0·25 (0·62)	**0·35** (0·76)	0·31 (0·98)	0·34 (0·95)	0·42 (1·08)	0·50 (1·16)	0·52 (1·07)	0·55 (1·20)	0·50 (1·04)
V_1	0·74 (1·41)	0·63 (1·57)	0·69 (2·02)	0·69 (1·88)	0·95 (2·27)	1·09 (2·11)	1·15 (2·29)	1·30 (2·46)	1·30 (**2·44**)
	0·72 (1·48)	0·82 (1·59)	0·74 (1·64)	0·76 (1·86)	0·86 (2·13)	1·03 (2·11)	1·23 (2·49)	1·32 (2·58)	1·15 (**2·05**)
V_2	1·53 (2·40)	1·26 (2·54)	1·49 (2·48)	1·50 (2·78)	1·77 (2·95)	2·01 (3·08)	2·17 (3·25)	2·28 (3·44)	**2·39 (3·58)**
	1·47 (2·47)	1·55 (2·61)	1·47 (2·48)	1·56 (2·52)	1·70 (2·91)	1·96 (2·93)	2·17 (3·49)	2·29 (3·46)	**1·87 (3·14)**
V_4	1·17 (1·71)	1·11 (2·25)	1·22 (2·42)	**1·25** (2·35)	**1·16** (2·16)	**1·25 (2·51)**	**1·28 (2·68)**	**1·31** (2·44)	**1·16 (2·23)**
	1·04 (1·87)	1·18 (1·87)	1·19 (2·18)	**0·98** (2·04)	**0·91** (2·00)	**0·97 (1·75)**	**1·05 (2·33)**	**1·00** (2·28)	**0·73 (1·60)**
V_6	0·49 (0·77)	0·51 (**1·12**)	0·46 (1·25)	**0·46 (1·21)**	0·37 (0·91)	0·34 (**0·86**)	**0·34** (0·89)	**0·34** (0·79)	**0·37 (0·85)**
	0·44 (1·07)	0·39 (**0·77**)	0·41 (0·97)	**0·31 (0·70)**	0·33 (0·88)	0·30 (**0·61**)	**0·29** (0·77)	**0·27** (0·75)	**0·30 (0·67)**
V_7	0·18 (0·31)	**0·24** (0·46)	0·22 (0·50)	**0·26 (0·58)**	0·22 (0·53)	0·21 (0·41)	0·17 (0·39)	**0·16** (0·39)	**0·20 (0·38)**
	0·16 (0·37)	**0·18** (0·39)	0·19 (0·43)	**0·20 (0·37)**	0·21 (0·48)	0·17 (0·36)	0·13 (0·40)	**0·12** (0·33)	**0·16 (0·34)**

Bold values indicate that the 95% confidence intervals of the percentile estimates for boys and girls do not overlap

Table 2 summarizes the normal limits for the lead-independent ECG measurements. Heart rate substantially decreases with age as also illustrated in Fig. 1. The upper limit of normal of the heart rate is slightly higher for girls than for boys from the age of 8 years onward. The decrease in heart rate during growth is accompanied by an increase in the duration of the P wave, PR interval, and QRS complex. The median QRS duration is greater for boys than for girls in most age groups, but the differences in upper limits of normals are small, ranging from 2 to 7 ms. The median QRS axis is directed to the right in the first months of life, reflecting the still increased right ventricular mass in that period. From the age of 3–6 months no further changes in QRS-axis direction are observed. The QTc interval, calculated according to Bazett's formula[20], remains relatively constant over the years with an upper limit of normal of approximately 450 ms.

In Table 3, the P-wave amplitude is given for leads II, V_1, and V_2. The P-wave amplitudes in II and V_1 do not change during growth, while in V_2 a gradual decrease with age is apparent. The highest upper limits of normal of the P-wave amplitude, approximately 0·25 mV, were found in lead II.

The Q-wave amplitude is presented for clinically important leads in Table 4. The upper limit of normal of the Q-wave amplitude in the first month of life increases at least twofold to a maximum between 1 and 3 years, after which a decrease is seen towards the initial value. In the 12–16 year group, girls have significantly lower upper limits of normal of the Q-wave amplitude in V_6 and V_7 than boys.

The normal limits of the amplitude of the R and S wave are shown in Tables 5 and 6, respectively. R-wave amplitudes decrease with age in the right precordial leads, with a concomitant increase in the left precordial leads. S-wave amplitudes show a similar but inverse pattern. In the early adolescent years, girls have substantially lower precordial R-wave amplitudes than boys. However, the S waves in V_4, V_6, and V_7 are lower for girls than for boys from the first month of age onward.

In Table 7, the R/S ratio is presented for the precordial leads. Although a steady decrease is observed, the median R/S ratio in V_1 remains greater than 1 up to 3 years of age. In some age groups the upper limit of normal could not be calculated because S waves were absent in more than two percent of the ECGs.

Discussion

ECGs of healthy children change markedly from birth to young adulthood. Knowledge of the normal variation of ECG measurements with age is essential for proper interpretation of the paediatric ECG. Previous studies that determined normal limits for the paediatric ECG had their imperfections: ECGs were recorded at a relatively low sampling rate, ECG measurements were taken manually, or normal limits were presented for only a limited set of parameters. In this study, normal limits of ECG parameters were based on computerized analysis of a large set of ECGs recorded at a high sampling rate, thus obviating some of the limitations of previous studies. These new normal limits differ substantially

Table 7 R/S ratio in precordial leads for boys (upper row) and girls (lower row): median (2nd percentile, 98th percentile)

Lead	0–1 months	1–3 months	3–6 months	6–12 months	1–3 years	3–5 years	5–8 years	8–12 years	12–16 years
V_{3R}	2·4 (1·2, S=0)*	2·4 (0·5, S=0)	1·8 (0·4, S=0)	1·5 (0·4, S=0)	1·2 (0·4, S=0)	0·7 (0·1, S=0)	0·4 (0·0, 1·6)	0·4 (0·1, 1·2)	0·3 (0·1, 1·1)
	3·5 (0·0, S=0)	1·7 (0·5, S=0)	1·7 (0·2, S=0)	1·2 (0·2, S=0)	1·2 (0·2, S=0)	0·6 (0·1, S=0)	0·4 (0·1, 1·7)	0·3 (0·0, 1·2)	0·3 (0·0, 1·5)
V_1	1·6 (0·8, 3·7)	1·9 (0·5, 5·0)	1·8 (0·4, 4·9)	1·6 (0·7, 4·2)	1·2 (0·5, 2·9)	0·8 (0·3, 1·9)	0·6 (0·1, 1·7)	0·4 (0·1, 1·2)	0·4 (0·1, 1·1)
	1·8 (1·0, 4·9)	1·5 (0·6, 4·4)	1·6 (0·4, 4·1)	1·4 (0·4, 3·4)	1·2 (0·5, 2·8)	0·7 (0·2, 1·8)	0·5 (0·1, 1·4)	0·4 (0·1, 1·1)	0·3 (0·1, 1·0)
V_2	1·1 (0·7, 2·3)	1·4 (0·6, 2·8)	1·3 (0·8, 2·2)	1·3 (0·7, 2·5)	1·0 (0·5, 2·4)	0·8 (0·3, 1·5)	0·5 (0·1, 1·3)	0·5 (0·1, 1·1)	0·4 (0·1, 1·1)
	1·3 (0·7, 2·5)	1·1 (0·7, 2·8)	1·3 (0·6, 2·9)	1·2 (0·5, 2·2)	1·1 (0·4, 1·7)	0·7 (0·3, 1·5)	0·5 (0·1, 1·2)	0·4 (0·1, 1·2)	0·4 (0·1, 1·0)
V_6	1·9 (1·0, 3·7)	3·0 (0·8, 8·3)	3·6 (0·4, S=0)	3·7 (1·1, S=0)	5·0 (0·8, S=0)	6·1 (1·9, S=0)	5·9 (1·8, S=0)	6·2 (1·7, S=0)	5·5 (2·0, S=0)
	2·0 (1·0, 3·7)	3·6 (1·7, 8·7)	4·0 (1·1, S=0)	4·9 (1·8, S=0)	5·6 (0·5, S=0)	7·2 (2·7, S=0)	6·8 (1·7, S=0)	7·2 (2·0, S=0)	5·4 (1·3, S=0)
V_7	2·9 (1·2, S=0)	3·6 (1·4, S=0)	4·4 (1·1, S=0)	4·8 (1·4, S=0)	6·8 (2·0, S=0)	8·1 (2·0, S=0)	8·2 (2·2, S=0)	8·4 (1·6, S=0)	7·4 (3·1, S=0)
	2·8 (0·7, S=0)	4·9 (1·6, S=0)	5·3 (2·2, S=0)	6·3 (2·1, S=0)	6·3 (0·6, S=0)	8·1 (1·8, S=0)	8·3 (2·3, S=0)	10·0 (3·0, S=0)	7·6 (2·7, S=0)

*S waves were absent in more than two percent of the ECGs (S=0).

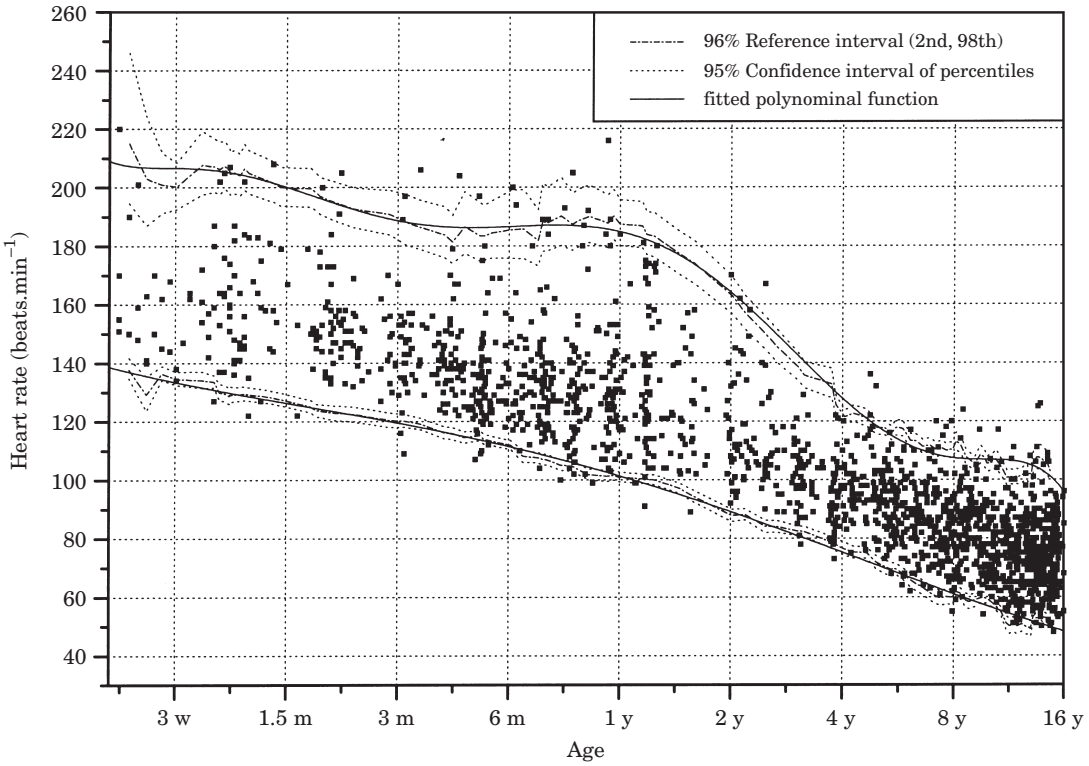

Figure 1 **Continuous age-dependent percentile curves of the heart rate for the total population.**

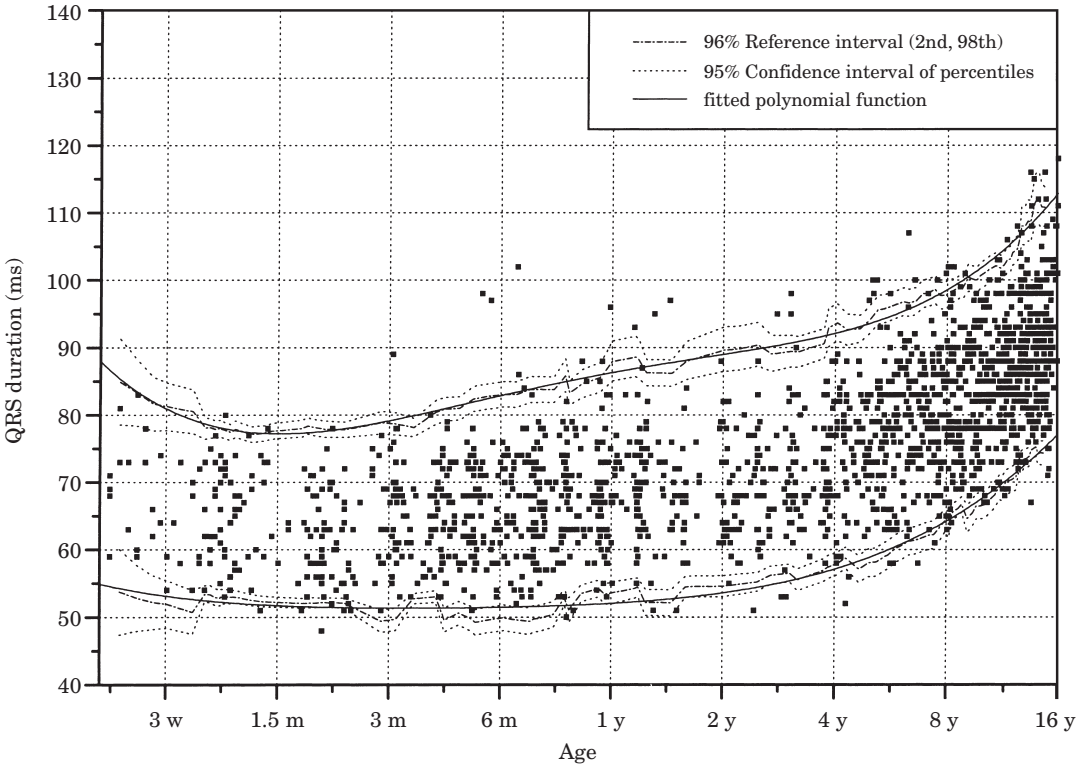

Figure 2 **Continuous age-dependent percentile curves of the QRS duration for the total population.**

from the limits presented by Davignon *et al.*[4], which are commonly used in paediatric electrocardiography, and may call for changes in diagnostic ECG criteria. We will discuss some implications for the assessment of prolonged QRS and QTc interval duration, and for the diagnosis of right atrial hypertrophy and ventricular hypertrophy.

Normal limits for the QRS duration are substantially higher than those reported by Davignon *et al.*[4]. For instance, children aged 12–16 years had a median QRS duration of 90 ms compared to 65 ms in the Davignon study. However, Davignon *et al.* only calculated the QRS duration in V_5, whereas MEANS determines the QRS duration over all leads, which yields longer QRS durations. Our findings corroborate with the study of Macfarlane *et al.*[6], who reported a mean QRS duration of 86 ms for children aged 13–14 years.

QTc interval prolongation is a valuable tool for detecting and quantifying the risk of arrhythmia due to drugs[21,22]. Moreover, QTc interval prolongation has been associated with sudden infant death syndrome or apparently life threatening incidents in infants[23]. Valid normal values are a prerequisite for proper interpretation in these studies. We found an upper limit of normal for the QTc interval of approximately 450 ms, which is higher than the commonly used criterion of 440 ms[24].

For the diagnosis of right atrial hypertrophy, the P-wave amplitude should be greater than 0·25 mV[24] or 0·30 mV[2,5] in any lead. This criterion is based on the upper limit of the normal P-wave amplitude. In our study the upper limit of normal of the P-wave amplitude is 0·25 mV in lead II, while in V_1 and V_2 substantially lower upper limits of normal are found (Table 3). These results suggest that the amplitude criterion in the diagnosis of right atrial hypertrophy should be made lead dependent.

In diagnosing ventricular hypertrophy, amplitude criteria for different ECG parameters are employed. Deep Q waves in V_6 are suggestive of left ventricular hypertrophy[5]. The upper limit of normal of the Q-wave amplitude in our study is substantially higher than presented by Davignon *et al.*[4]. For example, for children aged 3–5 years we found an upper limit of normal of the Q-wave amplitude of 0·54 mV against 0·30 mV in the Davignon study. Macfarlane *et al.*[6] obtained similar results for Q-wave amplitudes in neonates. Considering that narrow deep Q waves contain relatively high frequencies, our findings may demonstrate the effect of using a higher sampling rate. Another reason that may partly explain the differences is that we only included non-zero values in computing the percentiles. It is not clear whether this was also done in the Davignon study. When we recomputed the upper limit of normal of the Q-wave amplitude with zero values included, the upper limit of normal decreased to 0·47 mV. However, because a Q wave is defined as a negative deflection, we believe the exclusion of zero values is the preferred approach.

R- and S-wave amplitudes in the precordial leads are important parameters in the diagnosis of both right and left ventricular hypertrophy. We found considerable differences in R- and S-wave amplitudes compared to Davignon *et al.*[4], especially in V_6. For example, in our study the median of the R-wave amplitude in V_6 for children aged 8–12 years is 2·09 mV as compared to 1·68 mV in the study of Davignon *et al.* Higher R-wave amplitudes in V_6 were also presented by Macfarlane *et al.*[6], who found a mean R-wave amplitude in V_6 of 1·9 mV for children aged 5–12 years. For all age groups, the upper limits of normal of the R-wave amplitude in V_6 are substantially higher in our study, e.g., 3·14 mV for children aged 5–8 years compared to 2·65 mV in the study of Davignon *et al.*[4]. Notably, the upper limit of normal of the R-wave amplitude in V_{3R}, V_2 and especially V_4 is lower in almost all age groups. For instance, Davignon *et al.* report an upper limit of normal of 4·5 mV in V_4 for children aged 3–5 years, compared to 3·27 mV in our study. R-wave amplitudes in V_4 larger than 3·5 mV are exceptional in our material. S-wave amplitudes are considerably larger than reported by Davignon *et al.* in V_6 for all age groups, and in V_4 after 3 years of age. In the other precordial leads the S-wave amplitude is comparable in most age groups. These findings suggest that the amplitude criteria for ventricular hypertrophy should be adjusted.

Influence of sex differences on the paediatric ECG has been reported in a number of studies[3,7,8,25–27]. However, to our knowledge this is the first major study that examined sex differences in amplitude measurements for children in all age groups. In our study, amplitudes of the Q, R and S waves are higher for boys than for girls during adolescence in most precordial leads. For example, the upper limit of normal of the R wave in V_6 is 3·05 mV for boys and 2·55 mV for girls in the age group of 12 to 16 years. Little change in voltages is seen in boys during adolescence, while in girls a progressive decline is observed. In a study of 114 adolescents, Strong *et al.*[3] stated that the sex differences were primarily a reflection of the boys being greater than girls of reproductive age. Another reason for the amplitude differences during adolescence could be the development of breast tissue[28]. Moreover, we found clinically significant differences at younger ages, especially in the S waves in the left precordial leads. At this point we are none the wiser about the sex differences at these young ages. Overall, the amplitude differences are substantial and indicate that sex-dependent criteria could improve the sensitivity and specificity for left ventricular hypertrophy in children. For adolescents, this was already noted by Walker *et al.*[25] in the early 1970s but to our knowledge it is not used in daily practice. Furthermore, effects of sex on ECG interval measurements were seen for QRS duration, which is consistently longer for boys in all age groups. This was also previously shown by Macfarlane *et al.*[7]. No substantial sex differences for the QTc interval could be demonstrated. However, in the group aged 12–16 years, the confidence intervals of the upper limit of normal of the QTc interval only marginally overlapped, possibly indicating longer QTc intervals for girls. In a recent study, Eberle *et al.*[27] also

suggested that, in the group aged 13 to 16 years, gender influences the QT interval. Pearl *et al.*[8] demonstrated significantly longer QTc intervals for girls from the age of 14 years. The difference appears to be due to QT shortening in boys rather than QT prolongation in girls[26].

A minimal sampling rate of 500 Hz has been recommended for the adult ECG[29], but for paediatric ECGs higher sampling rates have been suggested[11,12]. We used a sampling rate of 1200 Hz, which was deemed sufficiently high to accurately record paediatric ECGs. When we downsampled the signals to 500 Hz and repeated our analyses, normal limits remained essentially the same. However, when we downsampled to 333 Hz, as used by Davignon *et al.*[4], lower amplitudes were found, e.g. R-wave amplitudes in V_6 decreased by up to 0·15 mV. However, we consider it unlikely that amplitude differences between our study and that of Davignon *et al.* can solely be attributed to differences in sampling rate, since we found lower QRS amplitudes in some leads. Other factors may also play a role, such as population differences and physiological changes in children, e.g. height, in the 20 years that passed between both studies.

We chose to present most of our results in tables rather than plots because of space limitations. However, one should be aware that the tabulated normal values are estimates for the median age in the age groups and that an age-effect within age groups may still be present. For children with ages close to the boundary of an age group, it is prudent to interpolate normal values between adjacent age groups. This is well illustrated by the continuous age-dependent percentile curves of the heart rate in Fig. 1, which shows a strong age-dependency within the age group of 1 to 3 years. Moreover, continuous age-dependent curves are preferred for computerized interpretation of paediatric ECGs, since they help to avoid abrupt changes in diagnosis with small differences in age.

Study limitations

The normal limits of the group of 0–1 month should be used with caution, because the sample size of this group is relatively small and our database does not contain ECGs recorded during the first 10 days after birth. The collection of the huge number of ECGs, necessary to obtain reliable estimates of normal limits for the youngest ages, would require a further study.

Conclusions

Normal limits have been estimated for paediatric ECGs recorded at a high sampling rate of 1200 Hz and analysed with the use of a computer program, thus obviating some of the limitations of previous studies. Normal limits of many ECG measurements were shown to differ from those reported earlier. Significant sex differences could be demonstrated for amplitude measurements and QRS duration. These findings are clinically significant and suggest that diagnostic criteria for the paediatric ECG should be adjusted.

The authors wish to thank Joke van Woerkom for recording all ECGs, and the children for their participation in our study. This study was supported by the Netherlands Ministry of Economic Affairs (Senter grant ITU94035).

References

[1] Maroney M, Rantz L. Electrocardiograms in 679 healthy infants and children. Pediatrics 1950; 5: 396.
[2] Ziegler R. Electrocardiographic studies in normal infants and children. Springfield: Charles C. Thomas, 1951.
[3] Strong WB, Downs TD, Liebman J, Liebowitz R. The normal adolescent electrocardiogram. Am Heart J 1972; 83: 115–28.
[4] Davignon A, Rautaharju P, Boisselle E, Soumis F, Megelas M, Choguette A. Normal ECG standards for infants and children. Pediatr Cardiol 1979/80; 1: 123–31.
[5] Liebman J, Plonsey R, Gillette P. Pediatric cardiology. Baltimore: Williams & Wilkins, 1982.
[6] Macfarlane PW, Coleman EN, Pomphrey EO, McLaughlin S, Houston A, Aitchison T. Normal limits of the high-fidelity pediatric ECG. Preliminary observations. J Electrocardiol 1989; 22: 162–8.
[7] Macfarlane PW, McLaughlin SC, Devine B, Yang TF. Effects of age, sex, and race on ECG interval measurements. J Electrocardiol 1994; 27: 14–9.
[8] Pearl W. Effects of gender, age, and heart rate on QT intervals in children. Pediatr Cardiol 1996; 17: 135–6.
[9] Tutar HE, Ocal B, Imamoglu A, Atalay S. Dispersion of QT and QTc interval in healthy children, and effects of sinus arrhythmia on QT dispersion. Heart 1998; 80: 77–9.
[10] Golden DP, Wolthuis RA, Hoffler GW. A spectral analysis of the normal resting electrocardiogram. IEEE Trans Biomed Eng 1973; 20: 366–72.
[11] Barr R, Spach M. Sampling rates required for digital recording of intracellular and extracellular cardiac potentials. Circulation 1977; 55: 40–8.
[12] Garson A, Jr. Clinically significant differences between the "old" analog and the "new" digital electrocardiograms. Am Heart J 1987; 114: 194–7.
[13] Van Wieringen JC, Roede MJ, Wit JM. Groeidiagrammen voor patientenzorg [Growth diagrams for patient care]. Tijdschrift Kindergeneeskunde 1985; 53: 147–52.
[14] Van Bemmel JH, Kors JA, Van Herpen G. Methodology of the modular ECG analysis system MEANS. Methods Inf Med 1990; 29: 346–53.
[15] Willems JL, Zywietz C, Arnaud P, van Bemmel JH, Degani R, Macfarlane PW. Influence of noise on wave boundary recognition by ECG measurement programs. Recommendations for preprocessing. Comput Biomed Res 1987; 20: 543–62.
[16] Willems JL, Arnaud P, Van Bemmel JH *et al.* A reference data base for multilead electrocardiographic computer measurement programs. J Am Coll Cardiol 1987; 10: 1313–21.
[17] Solberg HE. Approved recommendation (1986) on the theory of reference values. Part 1. The concept of reference values. J Clin Chem Clin Biochem 1987; 25: 337–42.
[18] Manly BFJ. Exponential data transformations. The Statistician 1976; 25: 37–42.
[19] John JA, Draper NR. An alternative family of transformations. Applied Statistics 1980; 29: 190–7.
[20] Bazett HC. An analysis of the time-relations of electrocardiograms. Heart 1918; 7: 353–70.
[21] Moss AJ. Measurement of the QT interval and the risk associated with QTc interval prolongation: a review. Am J Cardiol 1993; 72: 23B–25B.

[22] Hill SL, Evangelista JK. Proarrhythmia associated with casapride in children. Pediatrics 1998; 101: 1053–6.
[23] Schwartz PJ, Stramba-Badiale M. Prolongation of the QT interval and the sudden infant death syndrome. N Engl J Med 1998; 338: 1709–14.
[24] Park MK, Guntheroth G. How to read pediatric ECGs. St Louis: Mosby-Year Book Inc., 1992.
[25] Walker CHM, Rose RL. Importance of age, sex and body habitus in the diagnosis of left ventricular hypertrophy from the precordial electrocardiogram in childhood and adolescence. Pediatrics 1961; 28: 705.
[26] Rautaharju PM, Zhou SH, Wong S *et al*. Sex differences in the evolution of the electrocardiographic QT interval with age. Can J Cardiol 1992; 8: 690–5.
[27] Eberle T, Hessling G, Ulmer HE, Brockmeier K. Prediction of normal QT intervals in children. J Electrocardiol 1998; 31 (Suppl): 121–5.
[28] LaMonte CS, Freiman AH. The electrocardiogram after mastectomy. Circulation 1965; 32: 746–54.
[29] Pipberger H, Arzbaecher R, Berson A *et al*. Recommendations for standardization of leads and specifications for instruments in electrocardiography and vectorcardiography. Report of the Committee on Electrocardiography, American Heart Association. Circulation 1975; 52: 11–31.