

Minimum Bandwidth Requirements for Recording of Pediatric Electrocardiograms

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Background—Previous studies that determined the frequency content of the pediatric ECG had their limitations: the study population was small or the sampling frequency used by the recording system was low. Therefore, current bandwidth recommendations for recording pediatric ECGs are not well founded. We wanted to establish minimum bandwidth requirements using a large set of pediatric ECGs recorded at a high sampling rate.

Methods and Results—For 2169 children aged 1 day to 16 years, a 12-lead ECG was recorded at a sampling rate of 1200 Hz. The averaged beats of each ECG were passed through digital filters with different cut off points (50 to 300 Hz in 25-Hz steps). We measured the absolute errors in maximum QRS amplitude for each simulated bandwidth and determined the percentage of records with an error $>25 \mu\text{V}$. We found that in any lead, a bandwidth of 250 Hz yields amplitude errors $<25 \mu\text{V}$ in $>95\%$ of the children <1 year. For older children, a gradual decrease in ECG frequency content was demonstrated.

Conclusions—We recommend a minimum bandwidth of 250 Hz to record pediatric ECGs. This bandwidth is considerably higher than the previous recommendation of 150 Hz from the American Heart Association. (*Circulation*. 2001;104:3087-3090.)

Key Words: electrocardiography ■ pediatrics ■ bandwidth

For accurate recording of ECGs, the bandwidth of the recording system is of major importance. The bandwidth, which is defined as the frequency range between low and high frequency cutoffs (-3 dB), should at least extend to the highest frequency component in the ECG signal. Many studies have been performed to determine the frequency content of the adult ECG,¹⁻⁸ but only few studies addressed the frequency content of the pediatric ECG.^{9,10}

Riggs et al⁹ studied the frequency spectrum of the ECG of only 8 children and concluded that the vast majority of information is confined to frequencies <100 Hz. However, determining the frequency content of an ECG by inspecting its frequency spectrum is difficult. The ECG spectra appear to be monotonically decreasing, and it is hard to tell which frequency components belong to the ECG and which to noise. Moreover, this approach does not show the effect of reduced bandwidth on wave amplitudes, which from a clinical point of view is the more important information.

Berson et al¹⁰ recorded vectorcardiograms from a group of 600 infants. They filtered the waveforms with different low-pass filters and determined the amplitude differences between filtered and unfiltered waves, concluding that a bandwidth of 100 Hz is required to avoid amplitude errors $\geq 10\%$. However, the original signals were recorded at a sampling rate of 500 Hz. It has been questioned whether this

rate is high enough to obtain accurate measurements in pediatric ECGs.^{1,4,11}

The American Heart Association (AHA) recommends 150 Hz as minimum bandwidth and 500 Hz as minimum sampling rate for recording pediatric ECGs, but these recommendations also state that it is unknown how far the bandwidth of systems has to extend due to the limitations of previous studies.¹² In the present study, we wanted to determine the minimum bandwidth requirements for recording pediatric ECGs with the use of a large set of ECGs recorded at a high sampling rate.

Methods

The study population consisted of 2169 children, with and without cardiac abnormalities, who had been referred to the pediatric cardiology department of the Sophia Children's Hospital in Rotterdam, the Netherlands. The Table shows the age distribution of the children. For each child, a 12-lead ECG was recorded at a sampling rate of 1200 Hz using a PC-based acquisition system (Cardio Control). The frequency response of the ECG recorder was flat to 320 Hz (-3 dB point). Following common practice in the Department of Pediatric Cardiology in Rotterdam, V3R was used instead of V3 and V7 instead of V5.

All ECGs were processed by the Modular ECG Analysis System (MEANS), which has been extensively evaluated, both by its developers¹³ and by others.¹⁴ For each of the 12 leads, the program computes a representative averaged beat, from which ECG measure-

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Age Distribution of the Children

Age	Total
0 to 3 months	606
3 to 6 months	226
6 to 12 months	213
1 to 3 years	244
3 to 5 years	240
5 to 8 years	265
8 to 12 years	189
12 to 16 years	186
Total	2169

ments are derived. The averaged beats of the 1200-Hz recordings were passed through digital low-pass filters with different -3 dB points, at 50 to 300 Hz in 25-Hz steps, thus simulating recording systems with reduced bandwidths. The filters were developed with the signal processing toolbox of Matlab. They were designed to have a ripple <0.001 dB in the pass-band and an attenuation <-40 dB within 25 Hz of the cutoff point.

To determine the effect of reduced bandwidth on wave amplitudes, we measured the absolute differences between the maximum QRS deflections in the filtered and unfiltered leads for each of the cutoff points and calculated the 95th percentile of these absolute differences. Because we expected the frequency content of the pediatric ECG to decrease with increasing age, ECGs from children <1 year (n=1045) were taken to determine minimum bandwidth requirements. The total population was used to assess the effect of age on the frequency content of the ECG signals. In addition, we calculated the percentage of recordings in which the absolute differences between the maximum deflections of the filtered and unfiltered leads exceeded 25 μV. The 25-μV threshold was chosen because this was considered an amplitude difference still distinguishable by human interpreters from standard paper ECG recordings.

Results

Figures 1 and 2 show the 95th percentiles of the absolute differences between filtered and unfiltered leads for the maximum positive and maximum negative QRS deflections, respectively. The largest absolute differences in both positive and negative deflections are found in lead V4, whereas the smallest differences are seen in lead aVR for positive deflections and in lead I for negative deflections. The clinically important leads V2 and V6 also show large absolute differ-

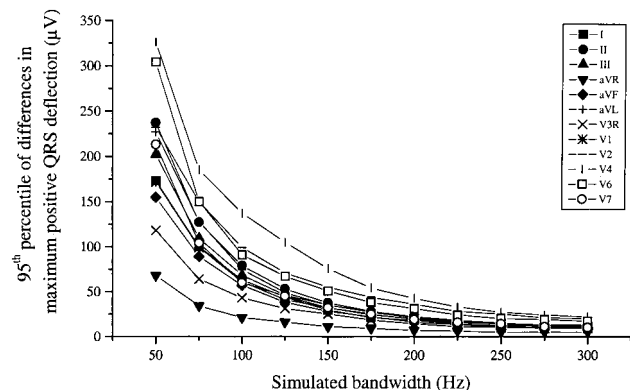


Figure 1. The 95th percentile of the absolute differences between the maximum positive QRS deflection in filtered and unfiltered leads for different bandwidths.

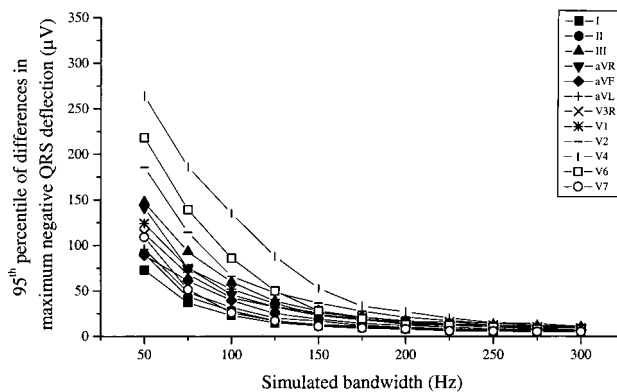


Figure 2. The 95th percentile of the absolute differences between the maximum negative QRS deflection in filtered and unfiltered leads for different bandwidths.

ences in both positive and negative deflections. Figure 3 presents, for each lead, the percentage of recordings and the differences between the maximum positive QRS deflections in the filtered and unfiltered leads exceeding 25 μV. Figure 4 gives these results for maximum negative deflections. The errors in the positive deflections are higher than in the negative deflections, and amplitude errors increase considerably with decreasing bandwidth. In any lead, a bandwidth of 250 Hz yields amplitude errors <25 μV in >95% of the cases (Figures 1 and 3).

Figure 5 shows the relationship between age and the 95th percentile of the difference in maximum positive QRS deflections in lead V1 for different bandwidths, illustrating that ECGs have a higher frequency content at younger ages. For example, for children from 0 to 3 months, the effect of a low-pass filter at 100 Hz triples compared with the oldest children in our study population. In V4, the lead that showed the largest amplitude differences, there is a small initial increase of the difference with increasing age up to ≈1 year, with a gradual decrease onward (Figure 6). The other leads show comparable patterns of decreasing frequency content with increasing age.

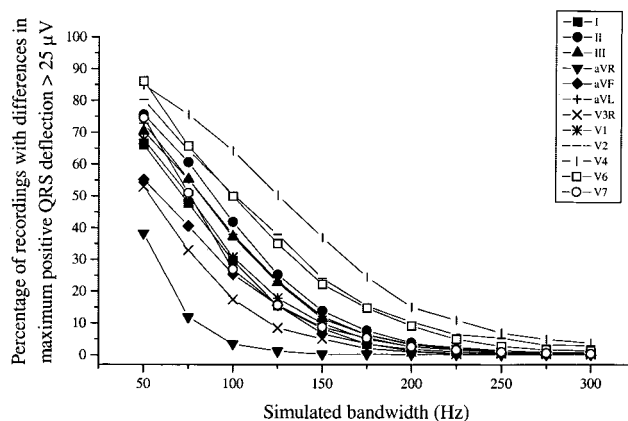


Figure 3. Percentage of recordings with differences in the maximum positive QRS deflection in filtered and unfiltered leads exceeding 25 μV for different bandwidths.

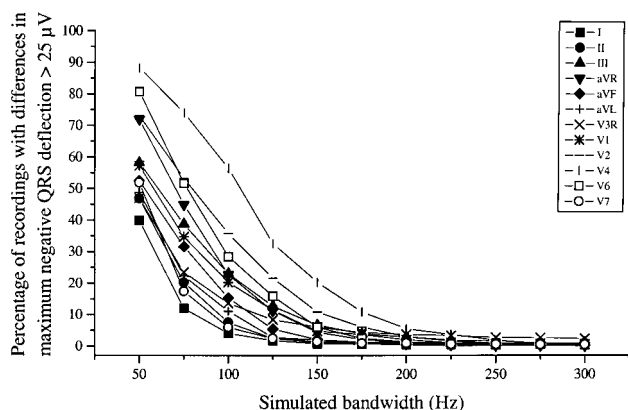


Figure 4. Percentage of recordings with differences in the maximum negative QRS deflection in filtered and unfiltered leads exceeding 25 μV for different bandwidths.

Discussion

To establish minimum bandwidth requirements for the accurate recording of pediatric ECGs, we used a large set of pediatric ECGs recorded at a high sampling frequency of 1200 Hz, thus obviating some of the limitations of previous studies.^{9,10} To our knowledge, this is the first study that demonstrates the effect of bandwidth limitations for all 12 leads of the ECG and that illustrates the influence of age on frequency content. On the basis of our results, we recommend a minimum bandwidth of 250 Hz for recording pediatric ECGs. This bandwidth requirement of 250 Hz is considerably higher than the 150 Hz previously recommended by the AHA.¹² With a bandwidth of 150 Hz, 38% of the cases in our study had an error $>25 \mu\text{V}$ in the maximum positive deflection in lead V4. For leads V2 and V6, these percentages are 25% and 23%, respectively. In vectorcardiographic leads, Berson et al¹⁰ found amplitude errors $>50 \mu\text{V}$ in 8% of the R-wave amplitudes and 5% of the S-wave amplitudes when using a 150 Hz filter. In our study, 15% of the positive deflections and 7% of the negative deflections in V4 have amplitude errors $>50 \mu\text{V}$ when a 150 Hz filter is used. These differences between

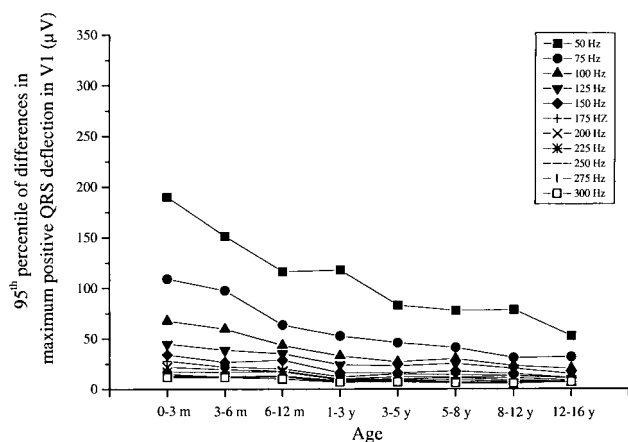


Figure 5. The 95th percentile of the differences of the maximum positive QRS deflection in the filtered and unfiltered lead V1 for different age groups.

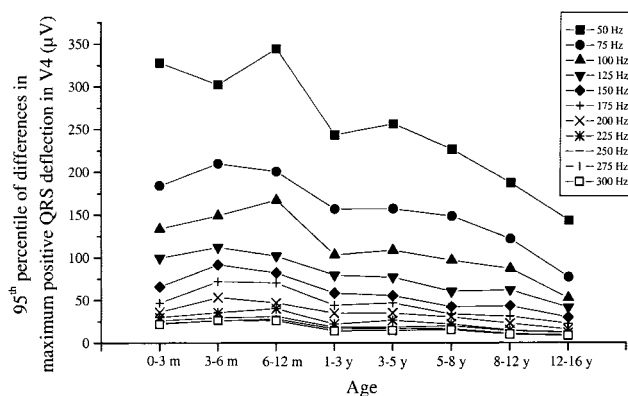


Figure 6. The 95th percentile of the differences of the maximum positive QRS deflection in the filtered and unfiltered lead V4 for different age groups.

the 2 studies may, in part, be explained by the difference in sampling rate (500 versus 1200 Hz) and by the use of different lead systems. Furthermore, the analyses by Berson et al¹⁰ were not done on separate leads but on leads X, Y, and Z combined, which is likely to underestimate the effect of filtering for individual leads. More importantly, however, we found a threshold of 25 μV instead of 50 μV is preferable for measuring the effect of reduced bandwidth on signal amplitudes.

We also studied the effect of age on the frequency content of the ECG signals. As shown in Figures 5 and 6, the frequency content gradually decreases from infancy to adulthood. Strictly speaking, for older children, a lower bandwidth would suffice. Our data for children aged 12 to 16 years indicate that the system bandwidth should be $\approx 150 \text{ Hz}$ to yield amplitude errors $< 25 \mu\text{V}$ in $>95\%$ of the cases in this age group. This is close to the 125 Hz recommendation of the AHA for the adult ECG.¹² Nevertheless, we recommend using the minimum bandwidth of 250 Hz for the entire pediatric population, because the age range of the patients will often not be known in advance.

An increase in bandwidth will also affect the sampling rate. Shannon's theorem prescribes a minimum sampling rate that is twice the highest frequency in a signal, which in our case gives a rate of 500 Hz. However, this theorem is valid only for an infinite sampling period and would require a sophisticated but impractical interpolation technique. Therefore, the AHA recommends a sampling rates of 2 or 3 times the theoretical minimum.¹² On the basis of this rule of thumb, a sampling frequency of at least 1000 Hz would seem desirable.

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