ECG analysis, ST-segment,
international requirements

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ASSESMENT OF LOW-FREQUENCY RESPONSE OF ECG RECORDERS IN RELATION TO INTERNATIONAL REQUIREMENTS

Electrocardiography (ECG) is commonly used non-invasive procedure for recording electrical activity of the heart. It is a powerful clinical non-invasive tool for proper diagnosis and therapy of cardiac abnormalities. Thus, accurate reproduction of the ECG is required especially if diagnosis making process is supported by automatic measurements and their interpretation. The paper presents an assessment of low-frequency response of selected ECG recorders in relation to international requirements. Four recorders have been selected and tested according to IEC draft 62D: 60601-2-51/Ed.1 and the results have been discussed.

1. INTRODUCTION

The electrocardiogram (ECG) is a recording of the electrical changes that occur in the myocardium during a cardiac cycle. These changes result from depolarisation and repolarisation as action potentials occurring in contracting cardiac muscle fibres. The ECG is recorded from the patient's body surface (limbs and chest) by electrodes placed on the skin. Figure 1 presents the electrocardiogram features and various measurements.

The ST-segment is between the end of the QRS complex and the beginning of the T wave. It represents the time when ventricles are depolarised. The ST-segment is normally isoelectric or on the same level as the baseline – the line between the P wave and the QRS complex. The morphology of this segment is very significant in some ECG diagnoses. There are multiple forms of ST-segments changes. This segment can appear as depressed or elevated, descending or ascending, straight or curved and such changes might indicate varies kinds of diseases like: acute myocardial infarction, left bundle branch block, digoxin effect, hypokalemia, ventricular hypertrophy or myocardial ischemia [2]. For correct representation of ECG signal, it is necessary to attenuate DC component of the measured voltage that may be many times larger than amplitude of ECG signal. Thus, the contradictory requirements should be reconciled, i.e. the exact reproduction of ST interval on the one hand and the restriction of electrocardiogram drift in the recording field caused mainly by the change of contact potential at the skin-electrode interface on the other hand.

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The modern electrocardiographs apply various methods of the analogue and digital signal processing to the recorded signals. In further part of the paper, the influence of some filter types on the form of ST-segment is shown.

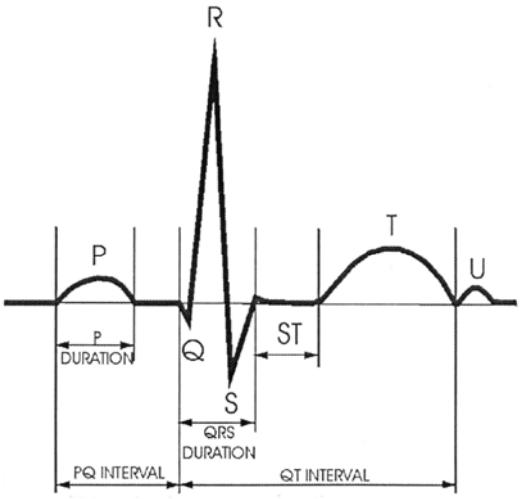

Fig.1. The electrocardiogram features and various measurements.

2. INTERNATIONAL REQUIREMENTS

Accurate reproduction of ECGs requires a sufficient bandwidth. Specifically, good high frequency response is needed to reproduce precisely Q-, R-, S-waves and other details within waves, while good low frequency response is required for accurate reproduction of ST-segment (both level and slope) which influences diagnoses. The low frequency response was previously determined in terms of a cut off low frequency of 0.05 Hz, which was sufficient to achieve accurate ST-segment reproduction even for a first-order filter with unspecified phase response. More sophisticated filters are now commonly used that achieve accurate reproduction of ST-segment level and adequate slope reproduction, even though the filters have a higher cut-off frequency and thus enable faster baseline recovery (antidrift filters – ADF) but causing also a few seconds delay in ECG presentation. Hence, based on the ANSI/AAMI (1991) recommendations [3], low frequency response requirements are now stated in terms of impulse response requirements and are incorporated in draft 62D: 60601-2-51/Ed.1, sub-clause 51.107.1.1.2. These requirements are sufficient to ensure adequate ST-segment reproduction and are also equivalent to the calibration ECG requirements specified in sub-clause 51.107.1.2, as they should be [4].

2.1. LOW-FREQUENCY IMPULSE RESPONSE

According to sub-clause 51.107.1.1.2, an electrocardiograph shall exhibit a frequency response conforming to the specifications of the following test at normal sensitivity. A 300 $\mu V \cdot s$ impulse shall not produce an offset on the ECG trace from the isoelectric line greater than 100 μV,

and shall not produce a slope greater than 250 μV/s in a 200 ms region following the impulse and a slope of 100 μV/s anywhere outside this region [4].

For the electrocardiograph with digital input, it is permissible to use the 500 $\mu V \cdot s$ test impulse. The displacement and slope allowed are the same as previously.

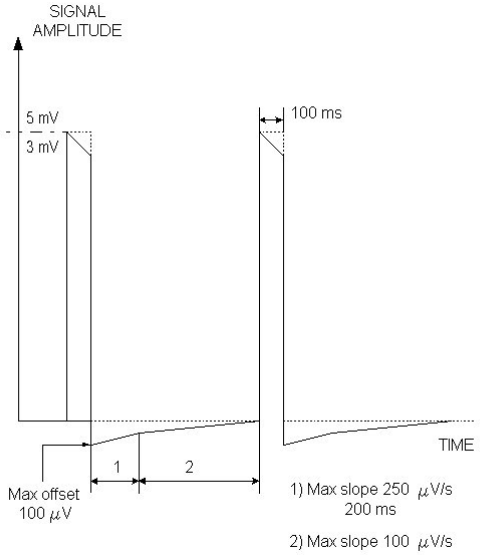

Fig.2. The input impulse signal (doted) and the worst expected electrocardiograph response (continuous).

In equipment which changes the ac coupling upon detection of a pacemaker pulse, the pacemaker pulse detection shall be disabled. Figure 2 presents the input impulse signal and the worst expected electrocardiograph response.

2.2. TESTS WITH CALIBRATION TRACES

According to sub-clause 51.107.1.2, the specified calibration traces from CTS Database shall be fed into the electrocardiograph under test [4].

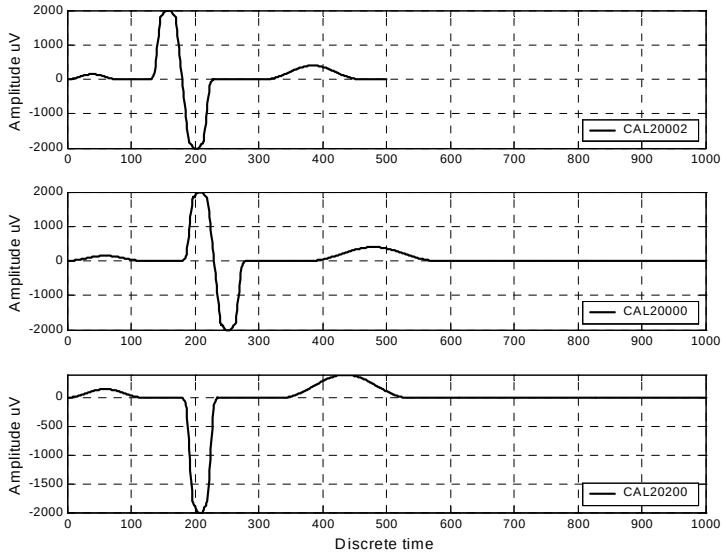

Fig.3. Calibration traces from CTS Database: CAL20002, CAL20000, CAL20200.

At normal sensitivity, the output peak amplitudes for R- and S-waves of recorded calibration ECGs shall not deviate by more than 5% from the original values. ST amplitude measurements taken on the ECG record between 20 ms and 80 ms after QRS-offset shall not deviate more than $\pm$ 25 μV from reference amplitude of the calibration signal (in CTS Test Atlas). Ringing noise on the ECG record before and after the main deflection (QS, R, RS) shall be smaller than 25 μV peak. The slope of the ST-segment on the ECG record shall not exceed 50 μV/s.

Figures 3 and 4 present calibration traces mentioned above [5].

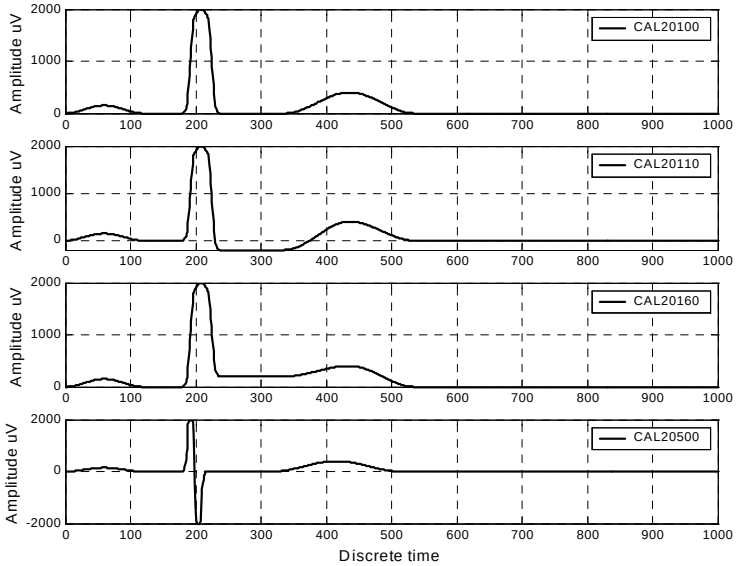

Fig.4. Calibration traces from CTS Database: CAL20100, CAL20110, CAL20160, CAL20500.

3. RESULTS

Four ECG recorders have been chosen. For all the four recorders low frequency impulse responses in various bandwidths have been measured. Figures 5÷14 present obtained results. The features of acquired 300 $\mu V \cdot s$ impulse responses are specified in Table 1.

The 500 $\mu V \cdot s$ impulse response for one of the low frequency cut off has been additionally measured in recorder number 4. The results are also presented in Table 1.

The following notations have been assumed:

Offset – offset from the isoelectric line,

Slope1 – slope in a 200 ms region following the impulse,

Slope2 – slope beyond 200 ms,

ADF – anti-drift filter.

All recorders had active notch filter during measurements.

3.1. IMPULSE RESPONSE

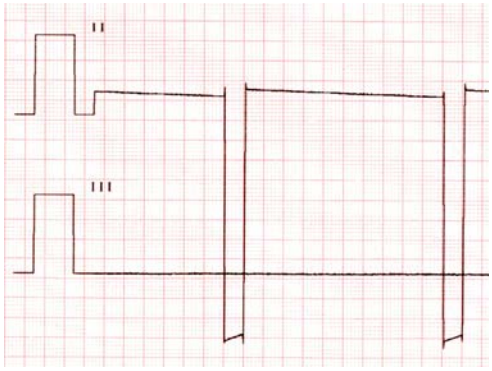

Fig.5. The 300 μV response of recorder no. 1, lead II, 20 mm/mV, good fulfillment of requirements (without overshoot).

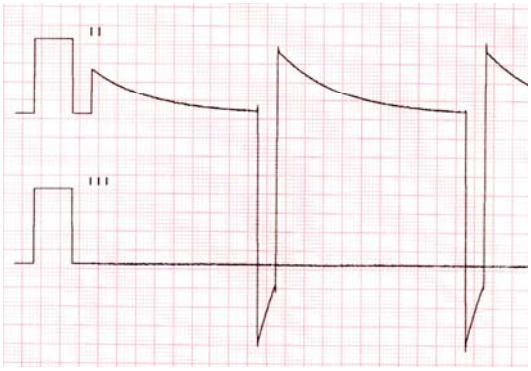

Fig.6. The 300 μV response of recorder no. 1, lead II, 20 mm/mV, bad settings for ST measurements.

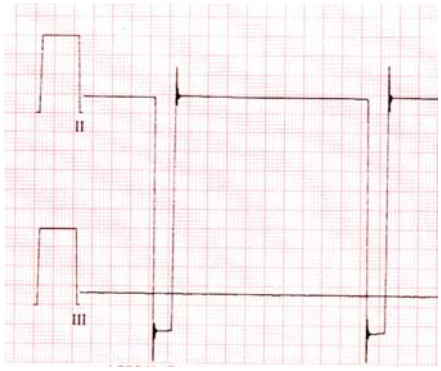

Fig.7. The 300 μV response of recorder no. 2, lead II, 20 mm/mV, good fulfillment of requirements (without ringing noise).

Fig.8. The 300 μV response of recorder no. 2, lead II, 20 mm/mV, bad settings for ST measurements.

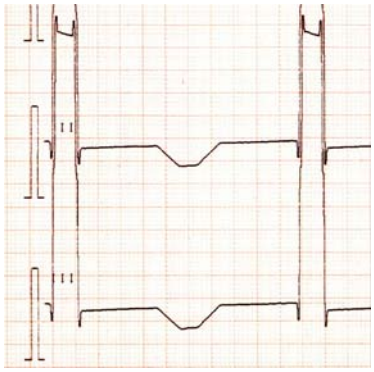

Fig.9. The 300 μV response of recorder no. 3, lead II, 20 mm/mV, bad fulfillment of requirements, abnormal distortion.

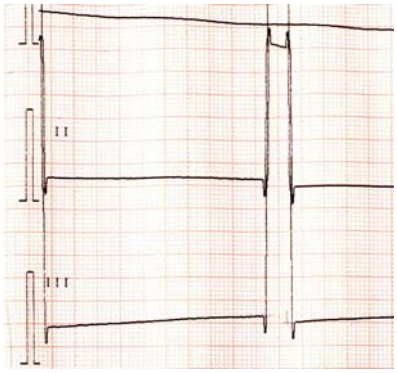

Fig.10. The 300 μV response of recorder no. 3, lead II, 20 mm/mV, good fulfillment of requirements (without overshoot).

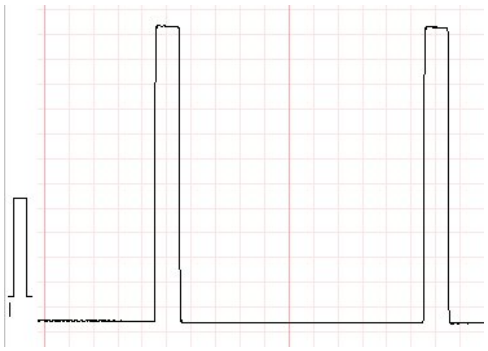

Fig.11. The 300 μV response of recorder no. 4, lead I, 20 mm/mV, good fulfillment of requirements.

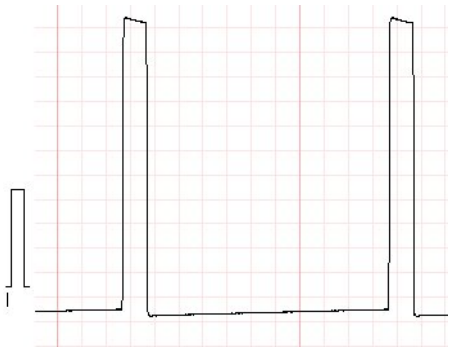

Fig.12. The 300 μV response of recorder no. 4, lead I, 20 mm/mV, good fulfillment of requirements.

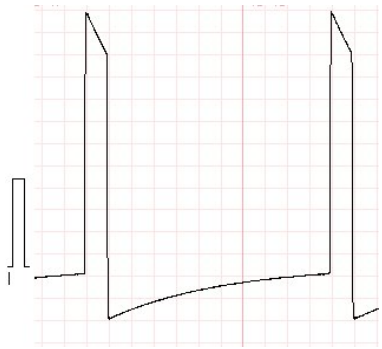

Fig.13. The 300 μV response of recorder no. 4, lead I, 20 mm/mV, bad settings for ST measurements.

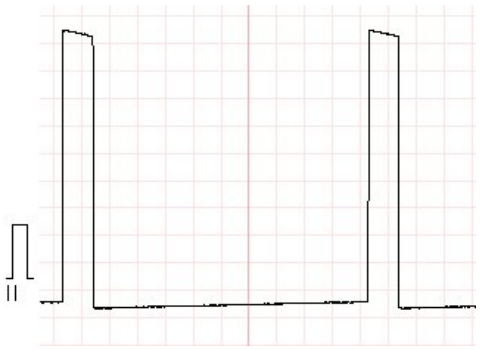

Fig.14. The 500 μV response of recorder no. 4, lead II, 10 mm/mV, good fulfillment of requirements.

Recorder	Impulse response	Bandwidth	Offset	Slope1	Slope2
			μV	μV/s	μV/s
I 300 μV	Figure 5	0.05÷150 Hz	95*	75	75
	Figure 6	0.50÷150 Hz	825*	about 2700	about 1500
II 300 μV	Figure 7	0.01÷150 Hz	20#	50	50
	Figure 8	0.32÷150 Hz	510#	about 1000	about 900
III 300 μV	Figure 9	0.05÷150 Hz, with ADF	75*	15	abnormal distortion
	Figure 10	0.05÷150 Hz, without ADF	75*	25	15
IV 300 μV	Figure 11	less than 0.01÷150 Hz, with ADF	0	0	0
	Figure 12	0.05÷150 Hz, with ADF	60	75	50
	Figure 13	0.32÷150 Hz, with ADF	520	about 1100	about 1000
IV 500 μV	Figure 14	0.05÷150 Hz, with ADF	100	130	100

* without overshoot, # without ringing noise.

Tab.1. Features of the impulse responses for all recorders.

3.2. CALIBRATION TRACES

All measurements have been made on paper printouts with a scaled magnifier (10× magnification) and reading accuracy better than of 0.1 mm. Thus, measurement absolute error (for 20 mm/mV scale) is less than 5 μV. Tables below present obtained results for all the four recorders. Bold numbers denote measurements which do not fulfil the requirements. Gray cells denote measurements with non-zero error that is allowed by the requirements.

Calibration traces	ST20	ST40	ST60	ST80
20000, 20002, 20100	0	0	0	0
20110	-200	-200	-200	-200
20160	200	200	200	200
20200, 20500	0	0	0	0

Tab.2. ST segment reference amplitudes (leads I÷III) in μV for calibration traces from CTS Database.

Bandwidth	0.05 Hz ÷ 150 Hz + *notch filter*				0.50 Hz ÷ 150 Hz + *notch filter*			
ECG	ST20	ST40	ST60	ST80	ST20	ST40	ST60	ST80
CAL20000	0	0	0	0	**+35**	**+35**	**+35**	**+35**
CAL20002	0	0	0	0	**+50**	**+50**	**+50**	**+50**
CAL20100	0	0	0	0	**-170**	**-160**	**-145**	**-130**
CAL20110	-215	-215	-215	-215	**-350**	**-325**	**-305**	**-280**
CAL2016	+185	+185	+185	+185	**+25**	**+25**	**+25**	**+25**

0								
CAL20200	+20	+20	+20	+20	**+185**	**+180**	**+170**	**+160**
CAL20500	0	0	0	0	0	0	0	0

Tab.3. ST segment amplitudes in μV for recorder 1.

Bandwidth	0.01 Hz ÷ 150 Hz + *notch filter*				0.32 Hz ÷ 150 Hz + *notch filter*			
ECG	ST20	ST40	ST60	ST80	ST20	ST40	ST60	ST80
CAL20000	0	0	0	0	+10	+20	+20	+20
CAL20002	0	0	0	0	+10	+15	+15	+15
CAL20100	0	0	0	0	**-115**	**-105**	**-95**	**-85**
CAL20110	-200	-200	-200	-200	**-320**	**-290**	**-280**	**-270**
CAL20160	+200	+200	+200	+200	**+80**	**+80**	**+80**	**+80**
CAL20200	0	0	0	0	**+115**	**+115**	**+115**	**+115**
CAL20500	0	0	0	0	0	0	0	0

Tab.4. ST segment amplitudes in μV for recorder 2.

Bandwidth	0.05 Hz ÷ 150 Hz + *notch filter + ADF*				0.05 Hz ÷ 150 Hz + *notch filter*			
ECG	ST20	ST40	ST60	ST80	ST20	ST40	ST60	ST80
CAL20000	0	0	0	0	0	0	0	0
CAL20002	-10	-20	-10	+20	0	0	0	0
CAL20100	-15	-15	-15	-15	-20	-20	-20	-20
CAL20110	-210	-210	-210	-210	-220	-220	-215	-215
CAL20160	+190	+185	+185	+185	+190	+190	+190	+190
CAL20200	+25	+25	+25	+25	+15	+15	+15	+15
CAL20500	0	0	0	0	0	0	0	0

Tab.5. ST segment amplitudes in μV for recorder 3.

Bandwidth	0.01 Hz ÷ 150 Hz + *notch filter + ADF*				0.05 Hz ÷ 150 Hz + *notch filter + ADF*				0.32 Hz ÷ 150 Hz + *notch filter + ADF*			
ECG	ST20	ST40	ST60	ST80	ST20	ST40	ST60	ST80	ST20	ST40	ST60	ST80
CAL20000	0	0	0	0	0	0	0	0	+20	+20	+20	+20
CAL2000	0	0	0	0	0	0	0	0	**+40**	**+40**	**+40**	**+40**

2												
CAL20100	0	0	0	0	0	0	0	0	**-100**	**-95**	**-85**	**-80**
CAL20110	-200	-200	-200	-200	-210	-210	-210	-200	**-310**	**-290**	**-270**	**-250**
CAL20160	+200	+200	+200	+200	+180	+180	+180	+180	**+80**	**+80**	**+80**	**+80**
CAL20200	0	0	0	0	+20	+20	+20	+20	**+130**	**+120**	**+110**	**+105**
CAL20500	0	0	0	0	0	0	0	0	0	0	0	0

Tab.6. ST segment amplitudes in μV for recorder 4.

4. CONCLUSIONS

The paper presents an assessment of low-frequency response of selected ECG recorders in relation to international requirements.

As it can be seen impulse responses in various electrocardiographs differ only in size and type of overshoot. Despite these differences, frequency responses still conform to the specifications of the standard. The only exception is recorder number 3. The excessive distortion in a 200 ms region following the test impulse occurs with active anti-drift filter (ADF).

Testing with calibration ECGs shows how the value of measurement error of ST-segment varies in different types of QRS complexes, depending on a low frequency cut off. Application of the 0.01 Hz bandwidth is obvious considering the minimizing measurement error of ST-segment, although in practice the application of ADF filter is necessary. Bad response of recorder number 3 for rectangular impulse with active ADF filter occurs only in test with calibration ECG CAL2002, with rate 120, as an error with different sign of value depending on measurement site.

The low frequency cut off higher than 0.05 Hz produces measurement error of ST-segment which exceeds permissible value of 25 μV. So the results of measurements show how these errors size depends on a type of QRS complex, measurement site and features of device. Overshoot omission in assessment of impulse response for ST-segment measurement correctness is fully allowable, though as it can be seen in record for electrocardiograph number 3, existence of such great overshoot produces excessive errors in amplitude measurements of waves.

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