CHEST CONDUCTION PROPERTIES AND ECG EQUALIZATION

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INTRODUCTION

The final aim in the detection and recording of any biomedical signal is to obtain a faithful reconstruction of the "original" activity of human organs. It is often implicitly assumed that the signal propagation is frequency and voltage independent and, therefore, possible signal distortions and non linearities are neglected. It should be considered, indeed, that organs such as heart and brain, are immersed in a medium macroscopically inhomogeneous and, somehow, anisotropic (e.g. bones, bloody vessels, air, etc.) The problem of reconstructing the "true" electrical activity is made even more complex by an inaccurate knowledge of dielectric properties at boundaries (e.g. skin-conducting gel-electrodes).

Several papers are devoted to voltage non-linearities; on the other hand, in our opinion, little attention has been paid to the non "flatness" of the frequency response of the global system "organ-electrodes-detecting device": the attenuation of some frequencies will result in signal distortion. We have, therefore, investigated the transmission of electrical signals through the human body at various voltages and frequencies to understand if and to which extent stimulation and recording techniques used in medicine are affected by the global conduction properties even if it may be difficult to separate the effects inherent to the electrodes: it is well known, for instance, that electrode-skin impedance will depend

on skin preparation and on the gel used, if any; furthermore, current density through the electrodes and applied voltage may cause the onset of voltage non-linearities. Once characterized the alterations produced by the electrical properties of chest tissues on the shape of signals passing through them, we have tried to make up an equalizing filter with the aim of emending them.

MATERIALS AND METHODS

Ten adult male subjects were used in this study. The skin was gently rubbed by cotton wet with alcohol before electrodes were placed. The subject was sitting on an insulated chair and was not earthed. Once in place, input electrodes were fed with a sinusoidal signal whose amplitude was increased at fixed steps of 0.1, 0.2, 0.5, 1 and 2 V; output voltages were measured varying frequency in the range 0.5 - 5000 Hz, according to the sequence 1 - 2 - 5. For each subject, measurements were carried out at three different positioning sites, sternomammary, dorsosternal and subascillarysternal, and distances, 5 cm and 20 cm, between electrodes, in order to highlight the effects, if any, of body inhomogeneity and anisotropy. To simplify the comparison among results relative to different subjects, voltage levels and electrode sites, output voltages were normalized to their maximum value rather than to input.

Ecgs have been recorded using the standard leads. The total bandwidth of the signal at the output of the signal conditioning stage is DC-1200 Hz. After the conditioning, the signal is digitized by a 12-bit analogue to digital converter with a sampling frequency of 2.4 kHz. The 1.2 kHz bandwidth is generous by clinical standard (0.1-100 Hz), (1) but necessary to study, in future works, the effect of the equalizing filter on high frequency noise.

An equalization of recorded signals can provide a more faithful reconstruction of electrical activity making the overall frequency response "flat". To this purpose, we have envisaged two possible solutions: 1) the interpositioning of an equalizing two-port passive filter in the recording path; 2) a post processing of recorded data.

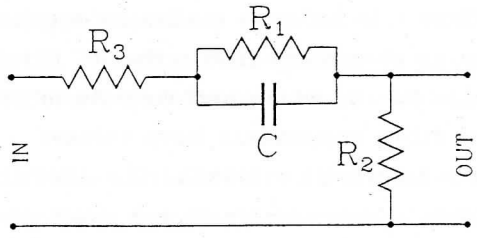

Fig. 1 - High pass filter matching the measured frequency response of fig. 2.

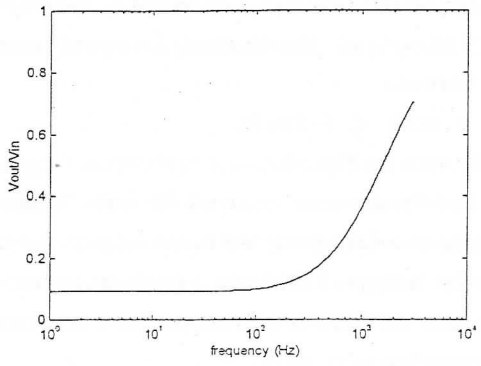

Fig. 2 - Frequency response of chest tissues acting as a high pass filter.

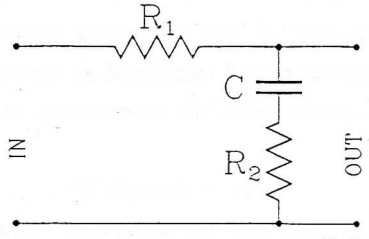

Fig. 3 - Frequency response of low pass equalizing filter of fig. 4.

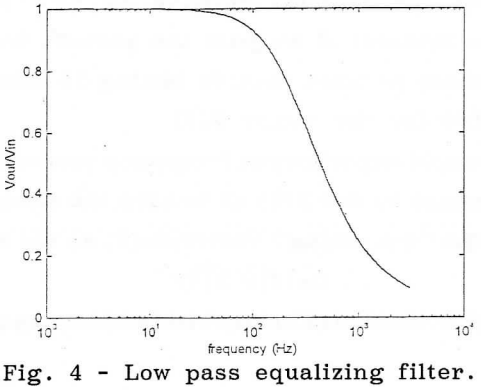

Fig. 4 - Low pass equalizing filter.

Equalization by filter - In order to realize an equalizing filter, we have taken into account an elementary first order RC filter: the limited high-pass filter drawn in fig. 1, which well reproduces the behaviour of the chest tissues; the filter components have values:

R1 = 35.5kΩ, R2 = 3.6kΩ, R3 = 500kΩ, C = 19nF;

its response matches rather closely to our experimental curves and is plotted in fig. 2.

The required equalization can be, therefore, achieved by means of a complementary RC filter, as the limited low-pass one of fig. 3, whose components have values:

R1 = 50kΩ, R2 = 2.5kΩ, C = 12nF;

its response is plotted in fig. 4.

Considering that the frequency content of most biomedical signals does not exceed 300 Hz, in the following we have limited the frequency analysis of the filters to the range 1-300 Hz. Higher order filters have been examined too, but the difficulties involved are not balanced by a closer matching to the experimental data.

Equalization by numerical treatment - We have also developed an "off-line" procedure consisting of the following steps:

1) Signals are first recorded and digitized as previously described (1,2).

2) By means of FFT a spectrum in the frequency domain of sampled signals is obtained; the vector

$$S(f) = Abs(FFT)$$

is constructed; its elements are the absolute values of FFT components. In order to avoid inaccuracies relative to FFT of pseudoperiodic phenomena, a time interval of at least ten periods has been examined. In our work, we chose to treat records lasting 10 seconds, resulting in a dimension of 10000 for the vector S(f)

3) The table of averaged experimental frequency response was interpolated to construct a response vector R(f) as to have the same dimension of S(f)

4) We define next the "equalizing" vector Ge(f) as the reciprocal of R(f):

$$Ge(f) = R(f)^{-1}$$

5) The equalized (i.e. flattened) signal in the frequency domain E(f) will

be expressed by the product:

$$E(f) = S(f) \cdot Ge(f)$$

6) A final inverse FFT antitransforms the equalized signal back in time domain.

As a practical application of the method, we have treated normal ECG recordings digitized with a sampling frequency of 1 kHz.

Statistical methods have been used in order to evaluate if equalization produces significant signal distortion; spectral analysis and coherence have been applied as frequency shape descriptors of ecg.

RESULTS

In fig. 5, an "average" normalized response for different input voltages is shown. In this case, the electrodes were placed at the sternodorsal position. The input electrode were fed with three voltages at 200 mV, 500 mV and 1 V. It is clear that there is no substantial difference among the relative curves.

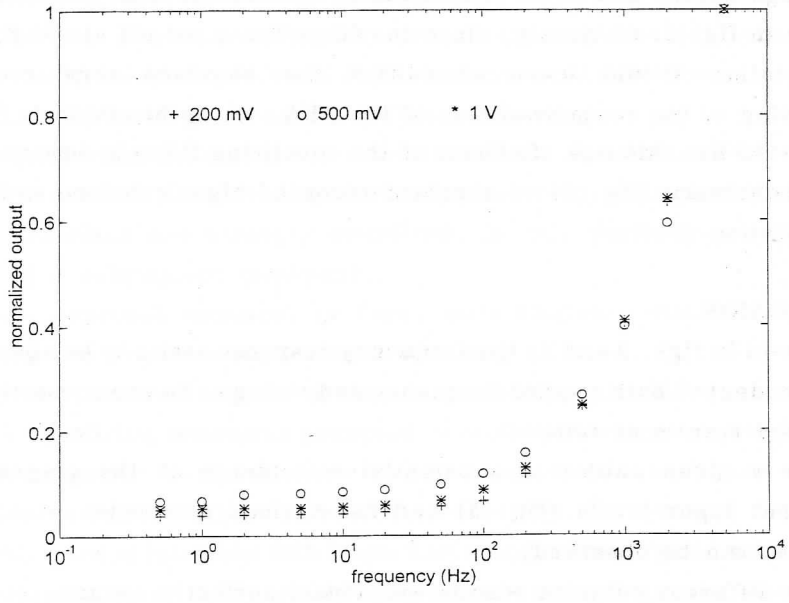

Fig. 5 - Average normalized response for different input voltage.

Similarly, in fig. 6 the responses for different electrode positioning at constant input voltage of 1 V demonstrate no significant effect of electrode position on transfer function.

In both the figures, however, the frequency response show a quite regular behaviour exponentially increasing for frequencies beyond 250 Hz: these responses would indicate that the chest tissues act as a high pass filter on the electrical signal flowing through them, well matching with filter model of fig. 1 and its frequency response shown in fig. 2. On these results, we have then made up the equalizing filter shown in fig. 3, having the frequency response exhibited in fig. 4.

The upper graph of fig. 7 shows an ECG obtained from D1 lead while, below, there is the correspondent equalized versions: an improvement in the signal-to-noise ratio, a more accurate measurability of the QT interval as well as a better overall readability are evident.

The size of the equalized signal is significantly decreased, but the overall shape is well preserved and evident also from the simple comparison of the ecgs before and after equalization. Attenuation and phase-lag are shown in fig. 8. Obviously, since the filter has a cut off at 250 Hz, the equalization should leave unmodified the standard ecgs recorded according to the recommendation of the AHA, whose bandwith is limited to DC-100 Hz: this lack of effects of the equalizing filter is demonstrated from coherence (fig. 9) of standard-recorded signals before and after equalization.

DISCUSSION

As shown in figs. 2 and 4, the frequency response seems to be absolutely independent of both applied frequency and voltage. We can summarize the obtained results as follows:

1) for a given subject a substantial coincidence of the response to different input levels (fig. 5) and for various electrodes positioning (fig. 6) can be observed;

2) for different subjects results are almost perfectly congruent;

3) attenuation and phase lag versus frequency show a quite regular

behaviour of the transmission system, which can be, therefore, considered a sort of high-pass filter (3) (fig. 8).
A first conclusion can be drawn about electric behaviour of human body: inhomogeneity and anisotropy play a negligible role, if any, in the examined range of voltages and frequencies: distortions are to be referred mainly to electrode-gel-skin boundaries.
Equalization allows an improvement in the signal-to-noise ratio, a more accurate measurability of the QT interval as well as a better overall readability. A neat ECG graph allows to get more precise and reliable evaluations and avoids discarding relevant details. This should be important especially when automated methods of clinically significant parameter detection are used. The proposed treatment reduces scattering errors due to subjective evaluations. Recourse to a filter appears to be the simpler solution in the common clinical practice: morphological and structural diversities among subjects can be compensated by scaling the values of all the filter components: uniquely the global attenuation factor will be affected.
Furthermore, recovery of voltage drop caused by filter insertion can be performed by a low-noise, high CMRR voltage amplifier (4): the input circuit could be arranged as in fig. 10 where switch T allows to bypass the whole input stage to obtain a direct recording.
This equalization process has a main drawback: signals are recorded in a form irreversibly modified by the filter; recovery of original shape, to which clinicians are strongly committed, is only partially possible by means of a subsequent treatment.
Software approach appears, in turn, more flexible, with the further advantage to preserve recording in the original form.
Richer the harmonic content of signals, more evident will be the results of both equalizing processes proposed. Even if presently we have limited our investigation to equalization of ECG signals, the procedure can be easily extended to other biomedical recordings. At present it seems certainly hard to interfere with biomedical standard coding and recording: the actual utility of this method, as improvement in diagnostic accuracy, is left to the judgement of clinicians.

In common practice of detecting and recording biomedical signals, it is often implicitly assumed that the propagation, through the whole circuit human body-electrodes recording devices, is frequency and voltage independent. As a consequence, clinicians are not aware that recorded signals do not correspond faithfully to the original electrical activity of organs under investigation. We have studied the transmission of electrical signals in human body at various voltages and frequencies to understand if and to which extent the most diffused stimulating and recording techniques used in medicine are affected by global body conduction properties.

Our results show that, in order to obtain a more faithful detection of electrical activity produced or evoked by human organs (e.g. EGG, electromyography, etc.), it is convenient to 'equalize'' recorded signals. To this purpose, two equalization techniques are proposed, based, respectively, on a simple hardware filtering during acquisition, or FFT post-processing of the acquired signals.

As an application, we have studied the transmission of electrical signal in human chest and have compared equalized high frequency ECG signals with raw (original) recordings.

1) PIZZUTI G.P. et al., J. Biomed. Eng., 1985, 7, 247-250.
2) HILTON BROWN B. et al., IEEE Trans. on Biomed. Eng., 1994, 41, 729-733.
3) MENZ M.D., J. Clin. Eng., 1994, 19, 386-394.
4) PALLAS-ARENY R., WEBSTER J., IEEE Trans. on Biomed. Eng., 1993, 40, 830-833.

KEY WORDS: body conduction, signal distortion, faithful recording, equalization.

Lectured at the meeting held in Naples June 30, 2000.
Received: June 30, 2000; accepted: July 14, 2000.

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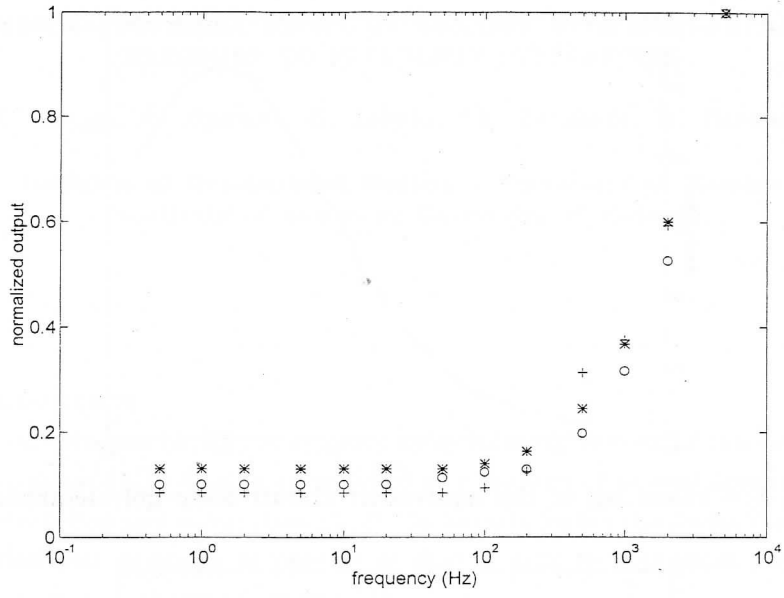

Fig. 6 - Average normalized response for different electrode positioning sites: dorsosternal (*), sternomammary (o), and subascillary (+). Voltage = 1V.

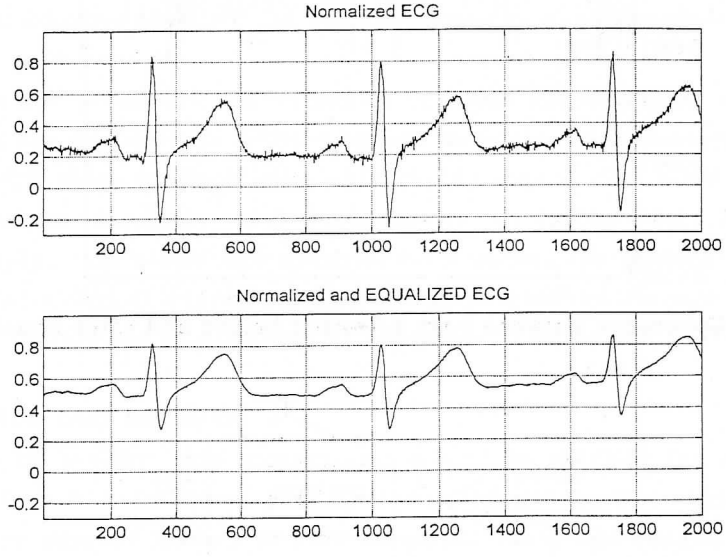

Fig. 7 - Ecg signal compared below with its equalized version.

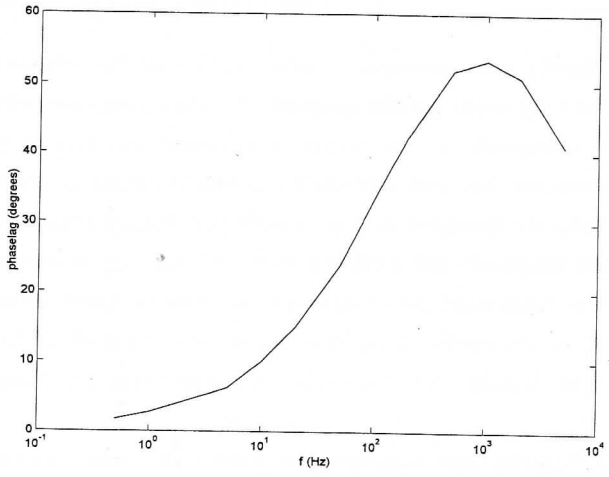

Fig. 8 - Phase lag of the equivalent circuit body-gel-electrodes.

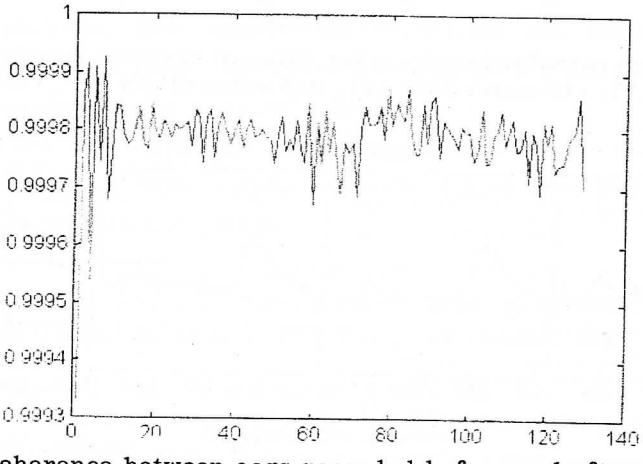

Fig. 9 - Coherence between ecgs recorded before and after equalization.

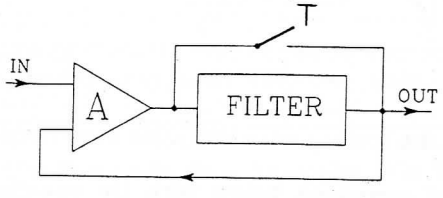

Fig. 10 - Basic circuit for compensating voltage drop due to equalizing filter.