

Amplification of biosignals by body potential driving. Analysis of the circuit performance

Ch. L. Levkov

Institute of Biomedical Engineering, Medical Academy, 1 G. Sofiiski, Sofia 1431, Bulgaria

Abstract—A method for amplification of biosignals with asymmetrical amplifiers in the presence of mains interference is described. The common mode body potential is reduced by a body potential driver (BPD) circuit. A detailed model of the BPD circuit is analysed. A new quantity, residual impedance Z_r , which estimates the BPD performance is introduced. The influence of the BPD circuit parameters on the stability and Z_r are estimated so that optimal performance can be reached. Practical recommendations for the circuit design are given because controversial conditions must be satisfied to reach both the stability and minimum Z_r . The main advantage of the method is its simplicity, which leads to significant reduction of the number of elements as well as precision requirements in multichannel amplifier design.

Keywords—Biomedical amplifier, Electrocardiography, Electroencephalography, Interference reduction, Multichannel system

Med. & Biol. Eng. & Comput., 1988, 26, 389–396

1 Introduction

AMPLIFICATION of biosignals with a differential amplifier is almost an axiom. In a previous article (LEVKOV, 1982) it was shown that it is possible to amplify biosignals with asymmetrical amplifiers. The common mode 50 Hz potential of the body is cancelled with a two-electrode 'driven-right-leg' circuit (Fig. 1). In the present paper some of the problems connected with the application of the method will be analysed in detail. For shortness and clarity some abbreviations are introduced. Instead of 'driven-right-leg' the proposed two-electrode circuit will be referred to as 'body potential driver', or BPD for short. The asymmetrical amplifier will be referred to as 'amplifier'.

The conclusions presented in the previous paper (LEVKOV, 1982), where two basic assumptions were made, namely an ideal operational amplifier is used in the BPD with infinite gain and bandwidth and the body is an equipotential surface for common mode potentials, are as follows:

- The common mode potential of the body is driven to zero by the BPD.
- The only 50 Hz interference obtained at the amplifier input is due to the difference between voltages across the electrode impedances e_2 and e_3 caused by the capacitive currents flowing through them (eqn. 1, LEVKOV, 1982).
- The biopotential voltage at the amplifier input is equal to the potential differences of the sense electrode e_2 of the BPD and the input electrode of the amplifier e_3 . The location of the driving electrode e_1 of the BPD has no importance.
- The BPD does not create additional noise when there

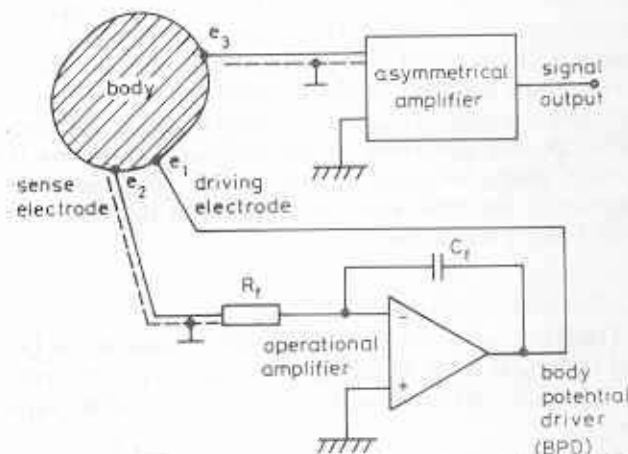


Fig. 1 Amplification of biosignals by body potential driver (BPD) and asymmetrical amplifier. The output voltage is proportional to the biopotential difference between the electrodes e_3 and e_2 . R_f and C_f ensure the BPD stability. Shielded cables are used (for electrodes e_2 and e_3) to reduce the AC interference

is a variation in electrode offset potentials. The voltage at the amplifier input is equal to the difference of the electrode offset potentials of e_2 and e_3 (eqn. 2, *ibid.*).

Good results were obtained with the proposed method but some drawbacks must be mentioned. Reduced rejection for the higher harmonics of the interference was noticed as well as some BPD circuit instability. A small residual common mode potential between the body and the signal earth was always measured. These phenomena will be analysed in detail as they are the main limitations for the improvement of the BPD performance. Also the problems connected with multichannel amplifier design will be discussed.

First received 2nd September 1987 and in final form 13th January 1988

© IFMBE: 1988

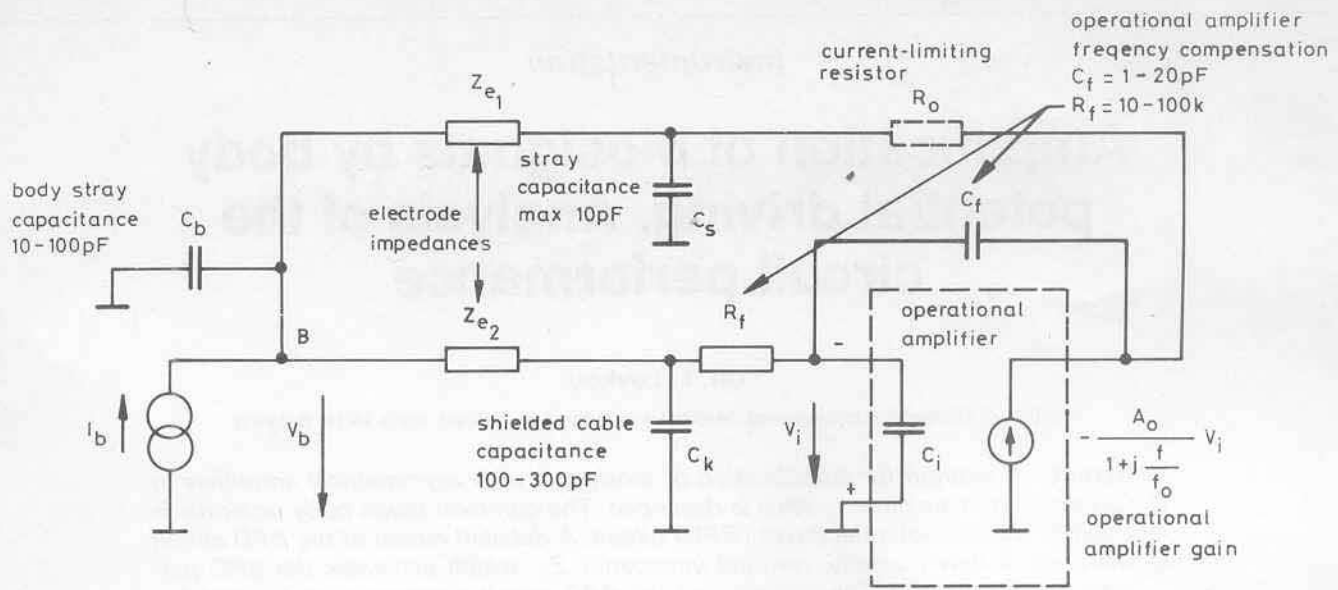


Fig. 2 The BPD equivalent circuit. Some possible values of the elements are shown. Point B represents the body, which is assumed to be an equipotential surface

2 BPD analysis

The BPD performance may be analysed by introducing a more realistic model. Its circuit is shown in Fig. 2. The earth and the signal earth are assumed to be the same. Possible values of the model elements are shown. The body will be considered an equipotential surface (lumped at a point B). Only the displacement current I_b through the body will be of interest. R_f and C_f are essential. They ensure the BPD stability. The operational amplifier is represented by the standard equivalent circuit. All important capacitances and impedances are included in the model. In principle the resistor R_o is not needed and it is included in the model for generality of the analysis. Sometimes it is used for other purposes, as, for example, for defibrillation protection. Later on it will be shown that the value of R_o must be kept to a minimum.

2.1 Residual impedance Z_r

The BPD must cancel the impedance between the body and the signal earth of the amplifier. It is very convenient to introduce a quantity which I will name residual impedance Z_r :

$$Z_r = \frac{V_b}{I_b} \quad (1)$$

This quantity estimates the BPD performance.

The model presented in Fig. 2 is complicated and it is impossible to derive a simple analytical formula for Z_r . A simpler model is presented in Fig. 3. The stray capacitances to the signal ground are ignored because they do not essentially influence the value of Z_r . R_1 and R_2 represent the electrode impedances and the circuit resistors. They will be assumed purely resistive. A standard model of an operational amplifier is used, where

$$A = \frac{A_o}{1 + jf/f_o}$$

f_o corresponds to the first pole of the operational amplifier open loop gain (CLAYTON, 1979). For frequencies up to several kilohertz the following simple equation is obtained:

$$Z_r = \frac{R_1}{A + 1} + j2\pi f C_f \times R_1 \times R_2 \quad (2)$$

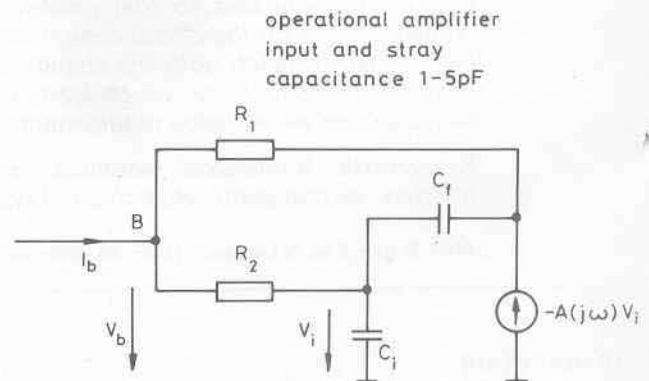


Fig. 3 Simplified equivalent circuit of the BPD. To reduce the residual impedance Z_r between the body (point B) and the earth R_1 , R_2 and C_f must be kept to a minimum

The residual impedance between point B (body) and the signal earth is essentially inductive because the first term in eqn. 2 has a very small value for lower frequencies. Two conclusions can be drawn:

- The value of Z_r is proportional to the frequency f .
- To decrease Z_r the values R_1 , R_2 and C_f must be kept to a minimum. But there are limitations: R_1 and R_2 include the electrode impedances and cannot be reduced arbitrarily; C_f cannot be decreased because the circuit stability will deteriorate.

The overall analysis of the model in Fig. 2 was performed by solving the circuit equations by computer. Standard methods for linear circuit analysis were employed. The main goal was to estimate the boundaries of variation of the residual impedance Z_r when electrode impedances vary from very best to worst contact conditions.

Further on, for simplicity, the electrode impedances Z_{e1} and Z_{e2} are assumed to be equal. Three models of electrode impedances were used (Z'_e , Z''_e , Z'''_e) with the same equivalent circuit as shown in Fig. 4. The electrode impedance parameters are presented in Table 1. Z'_e corresponds

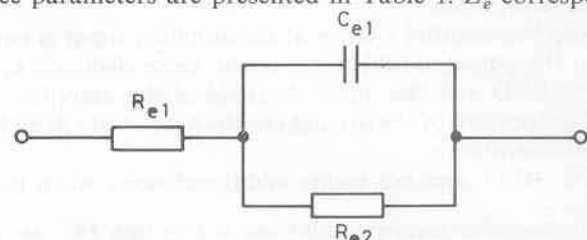


Fig. 4 Equivalent circuit of the electrode impedances used in the BPD computer model

Table 1 Electrode impedance parameters

	R_{e1}, Ω	R_{e2}, Ω	C_{e1}, F
Z_e^I	1×10^3	$6 \times 10^5 \times \omega^{-0.5}$	$2 \times 10^{-6} \times \omega^{-0.5}$
Z_e^{II}	5×10^2	$1.2 \times 10^5 \times \omega^{-0.5}$	$1 \times 10^{-7} \times \omega^{-0.5}$
Z_e^{III}	1×10^3	3×10^5	6×10^{-8}

Note: $\omega = 2\pi f$

to a dry electrode contact. Z_e'' corresponds to a good electrode contact. In both cases $|Z_e|$ decreases with frequency by 10 dB decade⁻¹ and R_{e2} and C_{e1} are frequency dependent (GEDDES *et al.*, 1971). Z_e''' corresponds to dry electrode contact but has a different frequency response. Its modulus decreases by 20 dB decade⁻¹ in the sloping part and R_{e2} and C_{e1} are frequency independent. According to ZIPP (1978) the Z_e''' model represents the upper limit of possible electrode impedances.

Fig. 5 shows the results from the computer modelling. The frequency responses of Z_e^I , Z_e^{II} , Z_e^{III} and the corresponding residual impedances are plotted. The residual impedances are computed for two different sets of circuit parameters. The shaded area gives an idea of the variation of the residual impedance Z_r , following the variation of the electrode impedances from bad to good electrode contacts.

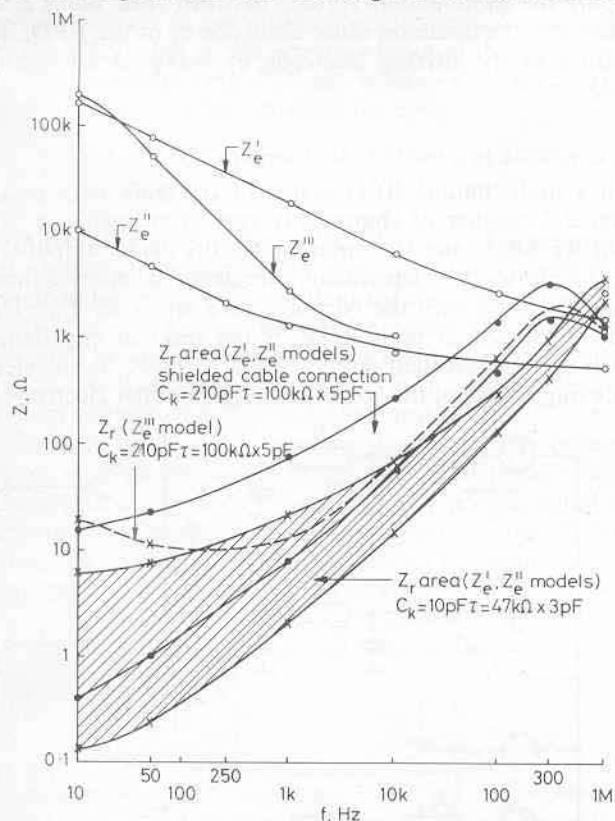


Fig. 5 Results obtained from the BPD computer model. Frequency responses of the electrode impedances and the corresponding residual impedances Z_r are shown. The shaded area shows the possible values of Z_r when the electrode impedance varies between low Z_e^I and high Z_e^{III} values. The model parameters according to Fig. 2 are: $A_0 = 2 \times 10^5$, $f_0 = 17$ Hz, $C_b = 100$ pF, $R_0 = 1$ k Ω , $C_s = 10$ pF, $C_i = 2$ pF. Z_r is computed for two different cases of τ and C_k (where $\tau = C_f R_f$)

2.2 The BPD stability

The BPD stability will be estimated by the classical Bode method. Fig. 6 shows the open loop circuit of the BPD. It is divided into two parts:

- Active part with compensated operational amplifier with a first pole $1/A_0 \tau$, where $\tau = R_f C_f$. This circuit for the frequencies $f > 1/2\pi A_0$ delays the sinusoidal signal maximum to -90° and has a unity gain at the

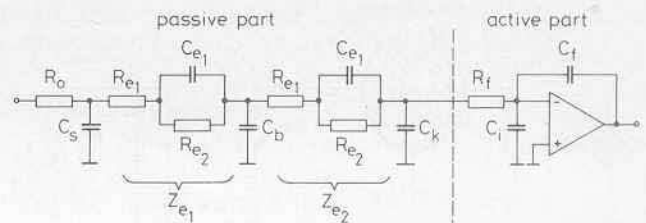


Fig. 6 Open-loop equivalent circuit of the BPD

frequency $1/2\pi\tau$.

- A passive part which includes the body of the patient, the electrodes and the electrode cables. For simplicity the values of the two electrode impedances are assumed to be equal.

Fig. 7 shows the frequency response of the passive part loaded with the input impedance of the active part. Three curves are plotted for the three cases of the electrode impedances Z_e^I , Z_e^{II} , Z_e^{III} . The point where the passive circuit delays the signal by 45° is denoted as $f(45)$. The closed-loop stability will be guaranteed if the compensated operational amplifier has a gain below unity at this frequency (45° phase margin). This condition is satisfied when

$$\tau > \frac{1}{2\pi f(45)} \quad (3)$$

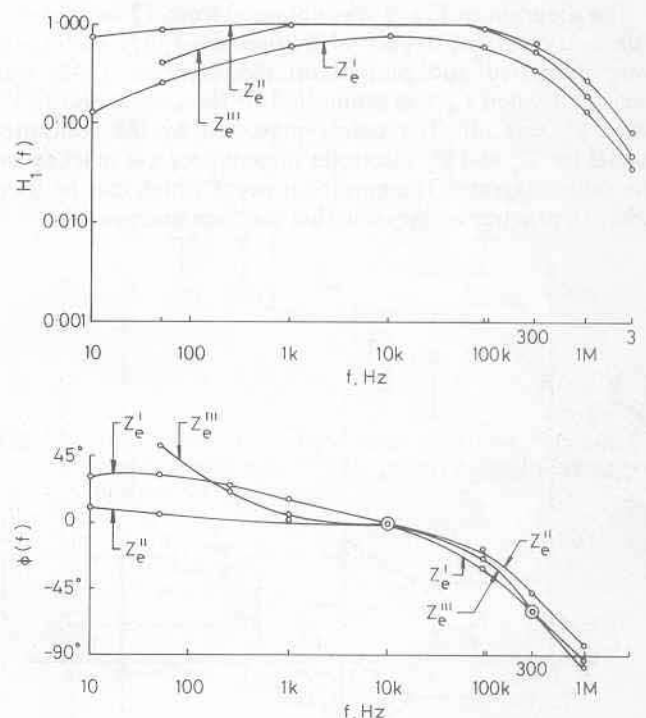


Fig. 7 Frequency response of the passive part of the open-loop BPD circuit loaded with the active part input impedance. The model parameters according to Fig. 6 are: $A_0 = 2 \times 10^5$, $f_0 = 17$ Hz, $C_b = 100$ pF, $R_0 = 1$ k Ω , $C_s = 10$ pF, $C_i = 2$ pF, $R_f = 47$ k Ω , $C_f = 10$ pF, $C_k = 210$ pF

2.3 Experimental investigation of the passive part of the BPD

It is impossible to model exactly the real electrode impedances so the analysis we made is only qualitative. An experiment has been carried out to determine the real frequency $f(45)$ of the passive part in the worst case conditions. According to Fig. 7 the worst case condition is when the electrode impedance is high (Z_e^{III} model). The experimental circuit is shown in Fig. 8. Dry stainless-steel electrodes were placed on the dorsal side of the limbs. Their area was 10 cm². The 45° phase difference between V_1 and V_2 is measured by an oscilloscope. A switch is included in

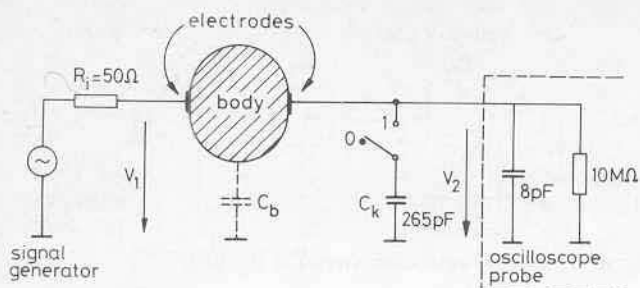


Fig. 8 The experimental circuit to obtain the frequency $f(45)$ where the phase angle between V_1 and V_2 is 45° . C_k simulates the shielded cable capacitance

the circuit to connect C_k . This capacitor simulates the shielded cable capacitance. Two measurements were made with C_k connected and disconnected to the circuit. The stray capacitance of the body to the signal earth was increased artificially by the patient having in his hand a metal tube insulated by polyethylene film and electrically connected to a water tap. The signal earth of the experimental circuit was also connected there and the passive pole of the mains plug was not connected to any point of the circuit. All the measurements were made within a maximum of 2 min after electrode placement to avoid liquid layer appearance in the electrode/skin contact, which substantially reduces the electrode impedances.

The diagram in Fig. 9 was obtained from 12 individuals. For every patient a pair of frequencies $f_1(45)$ and $f_2(45)$ were measured and plotted on the diagram. $f_1(45)$ was measured when C_k was connected to the circuit and $f_2(45)$ when C_k was off. The points predicted by the computer model for Z_e' and Z_e'' electrode impedances are marked on the same diagram. The empirical point which can be used safely in practice is shown with a star (see discussion).

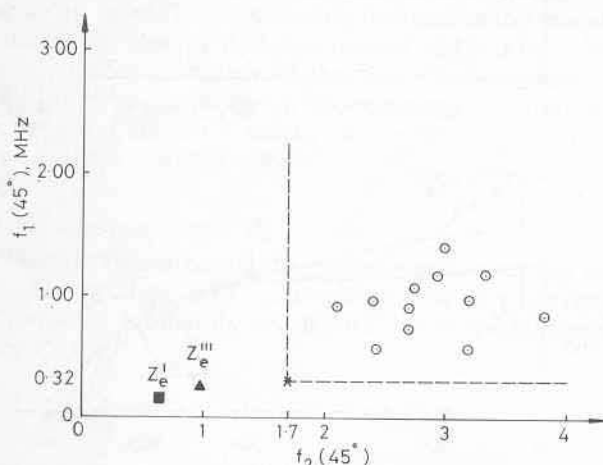


Fig. 9 Diagram of the experimentally obtained frequency pairs $f(45)$ for 12 individuals. $f_1(45)$ corresponds to a case where a shielded cable for the BPD sense electrode is used. $f_2(45)$ refers to a case of active electrode BPD design. The black square and triangle are the points obtained by the computer model. The star is an empirical point that can be recommended safely for practical purposes

2.4 BPD noise performance

Fig. 10 shows the equivalent circuit when the internal noise of the BPD operational amplifier is considered. This noise can be represented by equivalent voltage source E_N (CLAYTON, 1979). Bearing in mind ideal operational amplifier, the analysis shows that the noise voltage at the input of the amplifier $V_N = E_N$. The conclusion is that the noise performance of the operational amplifier used in BPD must fulfil the same noise requirements needed for the amplifiers in the signal channels.

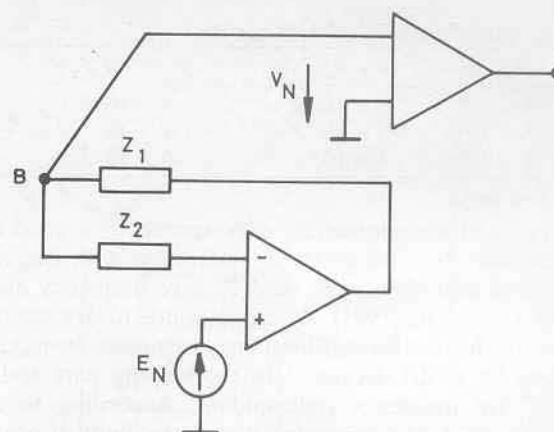


Fig. 10 Noise voltage of the BPD operational amplifier is applied to the input of the signal channels. The noise performance of this amplifier must fulfil the same requirements needed for the other amplifiers in the signal channels

3 Multichannel amplifiers

The operating conditions of the BPD are not changed when more asymmetrical amplifiers are included. They will amplify the biopotential voltage between their input electrodes and the common sense electrode e_2 of the BPD, the location of the driving electrode e_1 being of no significance.

3.1 Crosstalk in a multichannel amplifier

In a multichannel BPD system a crosstalk may occur when the number of channels is very large owing to the input RF filters and the input capacitors of the amplifiers. Fig. 11 shows the equivalent circuit of a multichannel amplifier along with the biopotential sources E_1-E_N . The body is lumped at point B. Z_r is the residual impedance which is the equivalent circuit of the BPD. Z_{ei} is the electrode impedance of the corresponding amplifier electrode i .

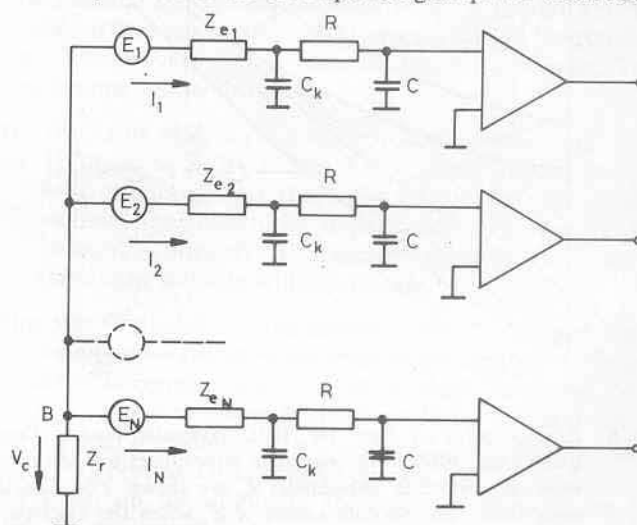


Fig. 11 In a multichannel version a crosstalk can occur due to the currents flowing through the input circuit of the amplifiers. The crosstalk voltage V_c is proportional to the residual impedance Z_r

C_k is the shielded cable capacitance. R and C form a low-pass filter to eliminate RF interference at the amplifier input. Its cutoff frequency is usually above 1 kHz. The input impedance of the amplifiers will be assumed to be very high ($>10\text{ M}\Omega$). The crosstalk path is clear: every biopotential source will cause a current I_i to flow through the capacitors C_k and C and through the residual impedance Z_r . The voltage drop on Z_r will be fed to all inputs of the amplifiers. Considering only one biopotential source E_i

$$V_{c_i} = \frac{E_i}{Z_{e_i} + Z_r + Z_f} Z_r \quad (4)$$
$$Z_f = \frac{sRC + 1}{sC_k(1 + C/C_k + sRC)}$$

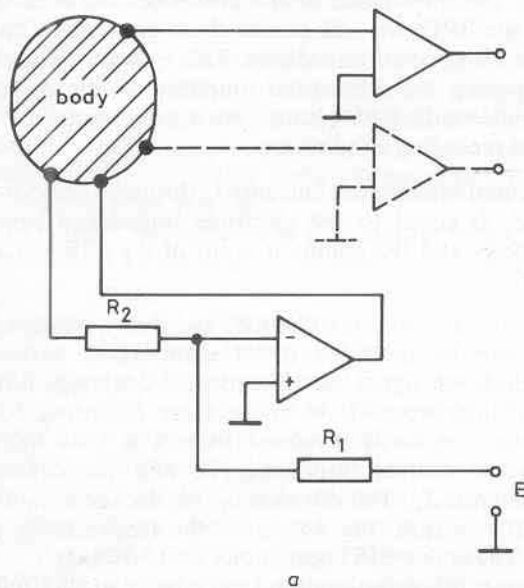
If $Z_{ei} \gg Z_r$ (which is almost always true) and then summing eqn. 4 for all channels the following equation will be obtained:

$$V_c = \sum_{i=1}^N \frac{E_i}{Z_{e_i} + Z_f} Z_r \quad (5)$$

3.2 Electrode-to-skin contact monitoring

$$V = E \frac{Z_{e2} + R_2}{R_1} \quad (6)$$

Some difficulties arise because the output test voltage is mixed with biopotential voltages and interference voltages. These problems can be solved easily by proper signal processing. The amplitude of the input test voltage V can be increased so that it becomes much higher than the other voltages. If $E = 0.1 \text{ V}$, $|Z_{e2}| = 10 \text{ k}\Omega$, $R_2 = 100 \text{ k}\Omega$, $R_1 =$



1 M Ω , then V will be approximately 10 mV and the test current through the body will be less than 10^{-7} A.

3.3 Practical design

The diagram shows a two-stage differential amplifier. The first stage consists of two input transistors with emitters connected to a common emitter resistor Z_{e2} . The base of one transistor is connected to a bias voltage B . The collector of this transistor is connected to a load resistor Z_{e1} . The output of the first stage is taken from the collector of the other transistor, which is connected to a load resistor R_2 . The second stage is a differential amplifier with two input transistors. The base of one transistor is connected to ground. The collector of this transistor is connected to a load resistor R_1 . The output of the second stage is taken from the collector of the other transistor, which is connected to a load resistor R_1 . The feedback path is connected from the output of the second stage back to the input of the first stage through a resistor Z_e . A voltage V is indicated across the feedback resistor Z_e .

this resistor is not needed for patient safety because the eventual shock current path passes only through the input resistors of the amplifiers and the BPD. Overall patient safety can be achieved by the standard methods (floating module etc.).

When the multichannel system is used as an ECG amplifier the sense and the driving electrodes can be placed on the left and right leg, respectively; thus all ECG voltages will be referred to the left leg.

4 Discussion

4.1 Stability against low residual impedance Z_r

Controversial conditions must be satisfied to reach both stability of the BPD and minimum residual impedance Z_r . A higher value for τ must be used for compensation if $f(45)$ of the passive part is low (Fig. 7). According to eqn. 2 the residual impedance will increase. The actions which can be carried out more or less easily to reach an optimum are as follows:

- (i) to omit R_0 or to use the minimum possible value if R_0 is needed for some other reason (defibrillation protection etc.)
- (ii) to decrease the shielded cable capacitance C_k
- (iii) to decrease τ to a reasonable minimum as a consequence of (i) and (ii).

In the previous article (LEVKOV, 1982) it was shown that it is necessary to use shielded cable for the sense electrode of the BPD. The shielded cable can be omitted if the BPD circuit is placed closely to the electrodes—the so-called active electrode design and thus τ can be reduced.

As can be seen from Fig. 9 the computer model predicts rather low $f(45)$ frequencies compared with the experimental results. Possibly very high values for the electrode impedances are used in the model or the real body-earth capacitance is less than 100 pF in the experiment. PALLAS-ARENY (1986) considers capacitances between 50 pF and 1 nF taking 200 pF as the most usual value. It is not clear from his paper whether these values were obtained experimentally or if this is just a rough estimation.

The electrode impedance values above 100 kHz are of particular interest if the BPD stability is considered. At these frequencies the R_{e1} value in the electrode model (Fig. 4) is essential. In the majority of papers related to electrode impedance measurements these frequencies are neglected and very few experimental data are available. For this reason the values for R_{e1} used in the model are to some extent arbitrary.

In the paper of WINTER and WEBSTER (1983b) some quantitative results are obtained for the frequency compensation needed to ensure the stability of the driven-right-leg circuit. Pure resistive electrode impedances between 50 k Ω and 100 k Ω are used in their equivalent circuit. This leads to an increased value of τ for the lag RC compensation. Thus the driven-right-leg circuit will be overcompensated, not reaching the desired optimum.

Empirically, two values can be suggested for which the BPD stability will be ensured in the region marked with broken lines in the $f(45)$ diagram (Fig. 9). For the BPD with shielded cable $\tau = 100 \text{ k}\Omega \times 5 \text{ pF}$ and for active electrode design $\tau = 47 \text{ k}\Omega \times 3 \text{ pF}$. In both cases R_0 must not exceed 1–5 k Ω . It is more advantageous to use minimum practical values for C_f in the compensation circuit as that will ensure smaller values for Z_r when the electrode impedances are high (see eqn. 2).

When designing BPD as a floating module the signal common point is not equivalent to the earth (Fig. 14). In

this case the conditions for the BPD stability are more favourable because the equivalent capacitance C_{eq} between the body and the signal common point is reduced:

$$C_{eq} = \frac{C_B C_g}{C_B + C_g}$$

Consequently τ can be decreased but additional experiments must be carried out to obtain the lower safe limit for the particular floating module design.

Almost any modern operational amplifier can be used in BPD design if its first open-loop pole is $> 1/A_0 \tau$.

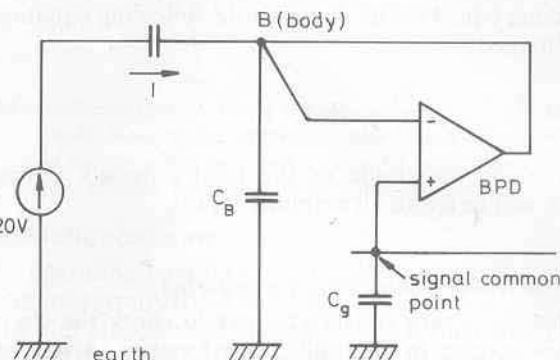


Fig. 14 The equivalent circuit of BPD and body capacitances when a floating module is used

4.2 Comparison with differential amplifier

When comparing the two methods of biosignal amplification we will consider only the interferences which are due to the common mode potential of the body. As was shown (LEVKOV, 1982) the interferences which are due to the capacitive currents through the electrodes are identical for both cases and will not be discussed. WINTER and WEBSTER (1983a) defined the so-called effective common mode rejection ratio ($CMRR_e$). $CMRR_e$ determines the real rejection of the common mode interference by the differential amplifier.

A new quantity can be introduced—the equivalent rejection of the BPD:

$$ER = 20 \log \frac{Z_e}{Z_r} \quad (7)$$

Z_e is the impedance of the electrodes between the body and the BPD (we will assume them to be equal to Z_e) and Z_r is the residual impedance. This quantity is useful when comparing the differential amplifier to the asymmetrical amplifier with BPD. Both systems are supposed to be in equal recording conditions:

- (i) equal interference currents I_b through the body
- (ii) Z_e is equal to the electrode impedance between the body and the common point of the differential amplifier.

The effective rejection $CMRR_e$ and the equivalent rejection ER can be used for direct comparison between both methods of signal amplification. Equal rejections mean equal interference level in the same recording conditions. ER can be easily obtained from Fig. 5 as the distance between residual impedance Z_r and the corresponding impedance Z_e . The distance of one decade is equivalent to 20 dB rejection. Fig. 15 shows the frequency response of ER . The active BPD design has 12–15 dB better rejection.

Some rough estimations may be made as follows. At 50 Hz the equivalent rejection is between 70 and 85 dB, for 1 kHz it is 45–60 dB. It must be noted that the $CMRR_e$ of the differential amplifier also decreases for higher frequencies. For frequencies around 1 kHz it can be as low as

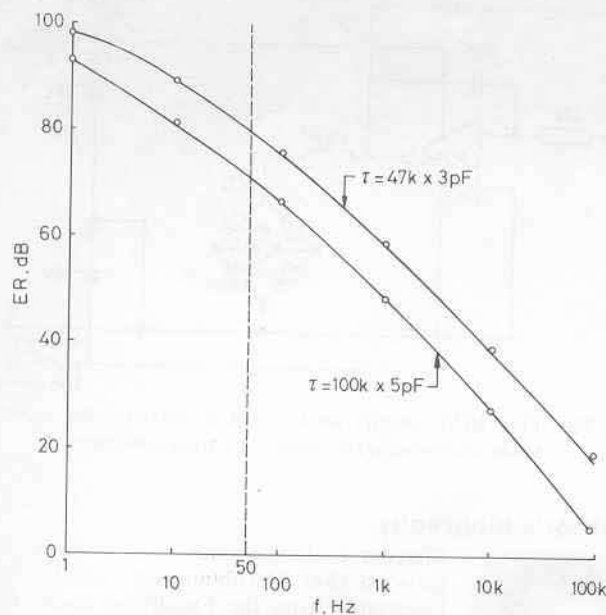


Fig. 15 Frequency response of the equivalent rejection ER. Lower curve: BPD design with shielded cable. Upper curve: active electrode design of the BPD. The curves are computed for the case of a bad electrode contact (Z_e model)

30 dB regardless of the high CMRR of the differential amplifier itself. The impairment is due to the input stray capacitance and the RF filters in the differential amplifier inputs.

It is interesting to know the absolute level of the residual common mode potential of the body. From the drawing in Fig. 5 approximate values for the residual impedance Z_r can be obtained. For a medium level of interference ($I_b = 100$ nA at 50 Hz) the residual potential will be 0.02–2 μ V. The maximum interference level is for the case of dry electrodes. Usually the BPD electrodes are placed on the limbs, their area is large and electrode jelly is used and consequently lower residual impedances can be expected.

For higher frequencies Z_r increases. The third and fifth harmonics of the mains must be considered, for they have relatively higher amplitudes. By the experiments it was found that their energies in the residual voltage spectrum are lower than the energy of the first harmonic. Additional rejection is reached in real cases, bearing in mind that usually the ECG and EEG amplifiers are low-pass filtered with cutoff frequencies between 100 and 200 Hz.

Recently, WINTER and WEBSTER (1983b) have shown that high-frequency interference from fluorescent lamps can occur with maximal spectral density around 1 kHz with amplitudes between 10 per cent and 50 per cent of the 50 Hz harmonic. 50 nA, 1 kHz body current will produce 0.2–4 μ V residual body voltage.

The BPD circuit can be used in conjunction with differential amplifiers if an extremely high common mode rejection is needed, especially for higher frequencies. The usual practice of obtaining the common mode potential from the outputs of the front end stages (HUHTA and WEBSTER, 1973) is not optimal because additional delay is introduced in the BPD closed loop (WINTER and WEBSTER, 1983b) and higher value for τ must be used, thus reducing the circuit efficiency. The price for the better performance is one additional electrode (for the BPD sense electrode).

Some observations have been made in a real environment to check whether the BPD with differential amplifier will have a better performance than the proposed circuit by simply measuring the interference voltage (50 Hz harmonic) between the outputs of two amplifiers. Any two amplifiers can be considered as a differential pair. The differential interference voltage at their outputs must be

lower than the interference voltage at the outputs referred to the signal common point provided a residual common mode potential exists.

An ECG database (created for other purposes) was used. It comprises records of the ECG standard leads referred to the left leg electrode made with an 8-channel asymmetrical floating amplifier with BPD. The difference between any two channels was estimated by subtracting the sampled signals. Only the periodic mains interference was measured by a digital procedure in the differential and unipolar signals. More than 100 recordings were analysed. The comparison clearly shows that there are no statistically significant differences in the interference levels between the two modes of operation. The obvious conclusion is that in standard recording conditions (stainless-steel electrodes with jelly) the common mode potential of the body is effectively removed by the BPD and the interference created by unequal electrode impedances become much more important.

4.3 Multichannel amplifier

The design of a multichannel amplifier with BPD is trivial. Connecting N amplifiers to the body does not impair the BPD performance. The system is much cheaper and simpler compared to the standard differential multichannel amplifier design. Precise resistor values for achieving differential symmetry are not needed any more.

The possibility of a crosstalk between the channels is more theoretical than practical. This can be illustrated with an example: the worst case is when all biopotentials E_i (Fig. 11) are correlated and let us consider them to be equal to E . For simplicity all impedances Z_{ei} will be assumed equal. For a 20 Hz frequency of E (ECG maximal spectral density) Z_r is around 3 Ω (Fig. 5). According to eqn. 5 for $N < 300$ channels the crosstalk voltage will be more than 80 dB below the level of the biopotential E .

The simple way to check the electrode-to-skin contact of all channels simultaneously and to locate the faulty channel is one additional advantage of the proposed system. OBERG (1982) has used a similar technique for contact monitoring for the case of a single differential amplifier but it is much more difficult to use his method when more differential amplifiers are involved to locate the faulty channel.

5 Conclusion

This paper has reported an analysis of an equivalent circuit for estimating the effect of BPD on biopotential amplifiers. This leads naturally to practical recommendations for circuit design and a simple method for monitoring electrode-to-skin contact has been outlined.

References

- CLAYTON, G. B. (1979) *Operational amplifiers*, 2nd edn. Butterworth, (Bulgarian translation, 1982).
- GEDDES, L. A., COSTA, C. P. and WISE, G. (1971) The impedance of stainless steel electrodes. *Med. & Biol. Eng.*, **9**, 511–521.
- HUHTA, J. C. and WEBSTER, J. G. (1973) 60-Hz interference in ECG. *IEEE Trans.*, **BME-20**, 91–101.
- LEVKOV, C. L. (1982) Amplification of biosignals by body potential driving. *Med. & Biol. Eng. & Comput.*, **20**, 248–250.
- OBERG, T. (1982) A circuit for contact monitoring in electrocardiography. *IEEE Trans.*, **BME-29**, 361–364.
- PALLAS-ARENY, R. (1986) On the reduction of interference due to common mode voltage in two-electrode biopotential amplifiers. *Ibid.*, **BME-33**, 1043–1046.

- WINTER, B. B. and WEBSTER, J. G. (1983a) A reduction of interference due to common mode voltage in biopotential amplifiers. *Ibid.*, **BME-30**, 58-62.
- WINTER, B. B. and WEBSTER, J. G. (1983b) Driven-right-leg circuit design. *Ibid.*, **BME-30**, 62-66.
- ZIPP, P. (1978) Die Bemessung der Elektroden-Haut-Kontakt-Fläche und der Verstärkereingangsimpedanz bei der quantitativen Oberflächenelektrographie (EKG und EMG). *Biomed. Techn.*, **23**, 130-140.

Appendix

Increasing common mode rejection of a ready-made equipment with BPD

Fig. 16 shows the schematic diagram of BPD as an active electrode system. The LED at the output is an indicator of the level of the driving voltage. The amplitude of this voltage is proportional to the interference current I_h and the recording environment can be checked. The power supply consists of two small 9 V batteries. The BPD circuit is mounted in a small plastic box. The BPD can be connected to the signal earth of any ready-made equipment which has a biopotential amplifier (electrocardiograph, electroencephalograph etc.) and the circuit will effectively remove the common mode potentials between the body and the signal earth. The BPD circuit can be used to renew older equipment without modifying the input amplifiers. In the case of an electrocardiograph the point O of the BPD must be connected to the right leg cable N and the two BPD electrodes can be placed at any convenient location of the body.

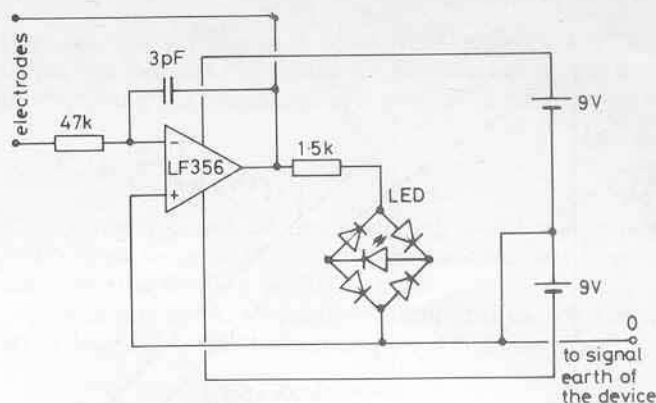
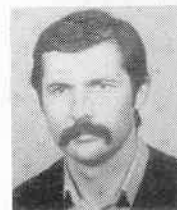


Fig. 16 This BPD circuit can be used to increase the common mode interference rejection of existing equipment

Author's biography



Chavdar L. Levkov was born in Sofia, Bulgaria, in 1949. He obtained his BS degree in Electronics from the Faculty of Radio Electronics, Sofia, in 1973. He has been a research engineer at the Institute of Medical Engineering of the Medical Academy since 1975, working on analogue preprocessing and computing circuits for ECG analysis. His current interests include hardware and software problems of modern electrocardiography.