Noise of surface bio-potential electrodes based on NASICON ceramic and Ag-AgCl

C. Gondran[1]   E. Siebert[1]   S. Yacoub[2]   E. Novakov[2]

[1] Laboratoire d'Ionique et d'Electrochimie du Solide de Grenoble, ENSEEG, BP 75, 38402 Saint Martin d'Hères Cedex, France
[2] Laboratoire d'Instrumentation Micro-informatique et Electronique, Université Joseph Fourier, BP 53X, 38041 Grenoble Cedex, France.

Abstract—*The electrochemical noise from dry NASICON-based surface electrodes and pregelled Ag-AgCl electrodes is evaluated in saline solutions and on the skin. The electrochemical noise from the electrode/electrolyte interface is found to be negligible (less than 1 μV peak to peak). On the skin, the noise level is highly dependent on the patient. At high frequencies, the skin/electrode interface noise is equal to 'thermal noise' and can be related to the real part of the skin/electrode impedance. At low frequencies (f < 100 Hz), excess noise is observed that varies as f^{-2}. It is tentatively ascribed to a non-stationary process or noise of electrochemical origin due to the ionic nature of the skin. The contribution of residual EMG signal of low amplitude (5 μV peak to peak) is suggested for electrodes with large surface area.*

1 Introduction

NOISE RESULTING from electrodes and the electrode/skin interface can contribute to signal distortion in recordings of low-amplitude bio-electric signals (FLASTERSTEIN, 1966a; b; FERRIS and STEWART 1974). Theoretically, the voltage noise generated by an electrode (i.e. an electrochemical system) that is in equilibrium with its surroundings is equal to the 'thermal noise' given by the Nyquist equation (NYQUIST, 1928; CALLEN and WELTON, 1951; BARKER, 1969; FLEISCHMAN and OLDFIELD, 1970)

$$\Phi_{Re}(f) = 4kT\mathrm{Re}(f) \tag{1}$$

where $\Phi_{Re}(f)$ is the frequency-dependent noise power spectral density (PSD), k is the Boltzmann constant, T is the absolute temperature, and Re (f) is the real part of the impedance of the system, which is frequency-dependent. Clearly, any noise that is to be measured must be detectable above the thermal noise of the system.

As early as 1958, Nightingale developed a low-noise amplifier to measure the electrical fluctuations generated at the electrode/skin interface (NIGHTINGALE, 1958; 1959). The observed voltage fluctuations were found to be greater than the expected thermal noise associated with the impedance.

According to Nightingale, they could not be due to incomplete relaxation. Later, De Vries *et al.* proposed that these observed electrical fluctuations could originate from muscle action potentials (DE VRIES *et al.*, 1976).

More recently, Godin *et al.* reported that stainless-steel surface electrodes tested in saline solution have no noise above amplifier noise (GODIN *et al.*, 1991). On the skin, the electrode voltage noise was the amplifier current-generated noise. Fernandez *et al.* measured the noise PSD of pairs of Ag-AgCl electrodes placed face to face and found a low frequency $1/f$ noise (FERNANDEZ *et al.*, 1991; FERNANDEZ and PALLAS-ARENY, 1992). They also measured a noise greater than the thermal noise for electrodes placed on the skin. In previous experiments on pairs of dry NASICON-based electrodes, a low-frequency excess noise was also found (GONDRAN *et al.*, 1995b).

Accurate measurements of electrode noise levels are difficult to achieve because of the low amplitude of the signal and contamination by the noise of the amplifiers. Special attention must be paid to the measuring conditions and techniques to obtain reliable data.

This paper reports on the voltage noise levels of pregelled Ag-AgCl and dry surface bio-electrodes based on NASICON. NASICON is a fast Na^+ ionic conductor (ceramic) that has been proposed (GONDRAN *et al.*, 1992) as a sensitive membrane for the recording of bio-electric signals. The electrode noise levels were evaluated in saline solutions (noise from the electrochemical process) and on the skin (electrode/skin interface noise). The dependence on the electrode surface area was investigated. The voltage noise was analysed with

---

respect to the thermal noise generated by the impedance of the electrodes.

2 Electrode noise measurements

2.1 Auto-spectrum

The principle of measurements with a one-channel system is schematically depicted in Fig. 1. The voltage fluctuations between a pair of electrodes are amplified. Such a measurement system is subject to undesired noise from the amplifier. The amplifier noise can be modelled as shown in Fig. 1b (FITCH 1973). e_0 and i_0 are uncorrelated voltage and current noise generators and e is the signal source. The noise of the amplifier output results from these three uncorrelated noise sources. The PSD of the output signal $\Phi_s(f)$ can therefore be expressed as

$$\Phi_s(f) = |G(f)|^2[\Phi_{e_0}(f) + |Z_e(f)|^2\Phi_{i_0}(f) + \Phi_e(f)] \tag{2}$$

where $\Phi_{i_0}(f)$ is the amplifier current noise PSD ($A^2\ Hz^{-1}$); $\Phi_{e_0}(f)$ is the amplifier voltage noise PSD ($V^2\ Hz^{-1}$); $\Phi_e(f)$ is the PSD of the signal source (pair of electrodes); $|Z_e(f)|$ is the modulus of the impedance of the pair of electrodes; and $G(f)$ is the voltage gain of the amplifier.

The electrode noise is composed of the thermal noise and an excess noise. It can be expressed as

$$\Phi_e(f) = \Phi_{Re}(f) + \Phi_{exs}(f) \tag{3}$$

where $\Phi_{Re}(f)$ is the PSD of the thermal noise generated by the real part of the impedance of the pair of electrodes, calculated according to eqn. 1; $\Phi_{exs}(f)$ is the PSD of the excess noise.

With this experimental set-up, the electrode noise levels must be greater than the amplifier current and voltage noise contributions to be measured with good accuracy.

2.2 Cross-spectrum

As proposed for the measurement of low-level electrochemical noises (BLANC et al., 1975), a two independent channel measuring mode can be used to eliminate the amplifier voltage noise contribution. The principle of the measuring system and
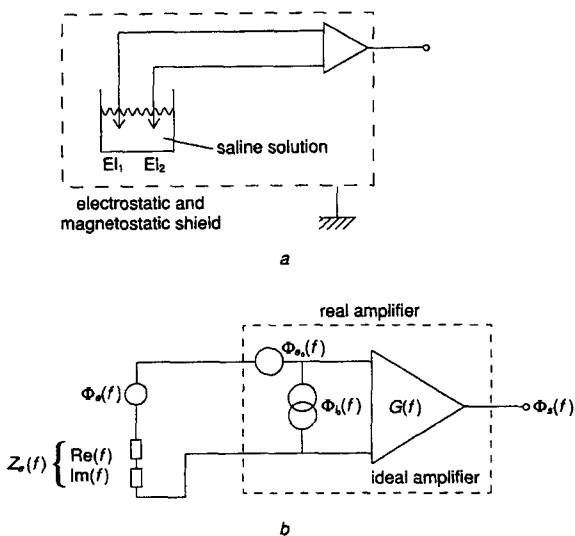
Fig. 1 *Principle of noise measurement with a one-channel system: (a) principle of measuring system; (b) equivalent noise model*
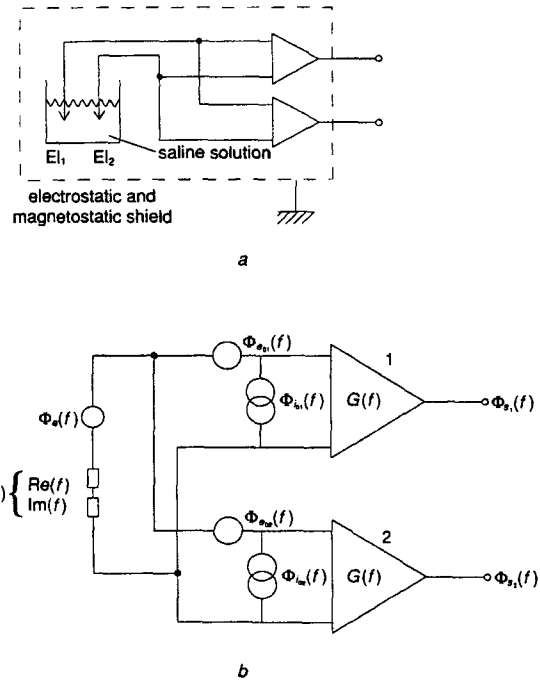
Fig. 2 *Principle of noise measurements with two-channel system: (a) principle of measuring system; (b) equivalent noise model*

the equivalent noise model are depicted in Figs. 2a and b. Two amplifiers with identical gain are used.

The noise at the output of the amplifiers, denoted $\Phi_{s_i}(f)$, can be calculated according to eqn. 2. It can be expressed as

$$\Phi_{s_i}(f) = |G(f)|^2[\Phi_{e_{0i}}(f) + \Phi_e(f) + |Z_e(f)|^2[\Phi_{i_{01}}(f) + \Phi_{i_{02}}(f)]] \tag{4}$$

It results from the amplifier voltage noise signal, denoted $n_i(t)$, and the signal source $B(t)$, which is composed of the electrode noise and the noise related to the current noise of both amplifiers.

The cross-correlation function of these two signals $R_{12}(\tau)$ is equal to

$$R_{12}(\tau) = E[(n_1(t) + B(t))(n_2(t + \tau) + B(t + \tau))] \tag{5}$$

where $E(x)$ is the expected value of x.

As $n_1(t), n_2(t)$ and $B(t)$ are uncorrelated, eqn. 5 becomes

$$R_{12}(\tau) = R_B(\tau) \tag{6}$$

where $R_B(\tau)$ is the auto-correlation function of the signal $B(t)$.

According to the Wiener–Khintchine theorem, the PSD is obtained through a Fourier transformation of its auto-correlation function. It gives

$$\Phi_{S_1S_2}(f) = F[R_{12}(\tau)] = F[R_B(\tau)] = \Phi_B(f) \tag{7}$$

The power interspectral density of the two output signals is equal to the PSD of the noise generated by the electrodes and the noise resulting from the amplifier current. It can be expressed as

$$\Phi_{S_1S_2}(f) = |G(f)|^2[|Z_e(f)|^2(\Phi_{i_{01}}(f) + \Phi_{i_{02}}(f)) + \Phi_e(f)] \tag{8}$$

If $Z_e(f)$ is low, or $\Phi_{i_{01}}(f)$ and $\Phi_{i_{02}}(f)$ are low, eqn. 8 is simplified and $\Phi_{S_1S_2}(f)$ is simply the PSD of the signal source.

2.3 Estimation of peak-to-peak voltage value

The noise power P_S in the bandwidth $[f_1, f_2]$ is expressed as

$$P_s = \int_{f_1}^{f_2} \Phi_s(f)\, df = \sigma_s^2 \ (V^2) \tag{9}$$

where σ_s^2 is the variance of the signal.

If the noise is assumed to have a Gaussian distribution, the peak-to-peak voltage value can be calculated according to

$$e_{pp} = 6\sigma_s \ (V) \tag{10}$$

This definition results in a peak-to-peak value that will not be exceeded 99·7% of the time.

3 Experiment

3.1 Instrumentation amplifier performance characteristics

Two identical low-noise amplifiers were designed. The AD620 instrumentation amplifier was used as the input amplifier. It was followed by an RC high-pass filter and a second amplifier. The total gain was equal to 90 dB. The 3 dB bandwidth was 1–800 Hz. The PSD Φ_{e_0} was evaluated with the inputs of the amplifier shorted. The amplifier current noise Φ_{i_0} was measured with a resistance equal to 2 MΩ at the amplifier inputs. The results are reported in Table 1. Such input amplifiers were selected because of their low levels of noise and their low drift ($< 0.2\ \mu V\ min^{-1}$). The influence of a linear drift on the PSD has been studied (GABRIELLI et al., 1986). A $1/f^2$ shape can be obtained for the noise spectral when the drift is significant.

3.2 Experimental set-up

The experimental set-up is represented in Fig. 3. to minimise interference from the exterior, the electrodes and the amplifier were placed in a Faraday cage. Impedance and noise measurements were performed quasi-simultaneously.

Impedance measurements were carried out with a frequency response analyser* coupled to an electrochemical interface†. The amplitude of the current I_o was equal to 1 μA RMS, so that the system could be considered as linear. The PSD measurements were performed with an analyser§. The signal was assumed to be ergodic. The ensemble average was therefore assumed to be equivalent to the time average. The measurement was averaged over 16 elementary spectra. The stationarity of the signal was verified by an oscilloscope and by calculation of the signal power (eqn. 9) at the end of each measurement. We checked that the power calculated by the spectrum analyser remained the same for all the experiments. In this way, the stationarity of the second order was checked.

An example of an experimental result recorded on the skin is given in Fig. 4. Fig 4a shows a typical noise PSD, as well as the amplifier voltage noise and the noise generated by the resistance equal to 2 MΩ. Fig. 4b shows the Nyquist plot of a typical impedance diagram. The PSDs of the signal were then calculated by interpolation of the experimental spectra by the mean square fitting procedure. The correlation coefficients were always higher than 0·95.

3.3 Electrodes

The dry NASICON-based electrodes were assembled as described previously (GONDRAN et al., 1992). Three electrode diameters were tested (5, 7 and 10 mm). The noise of pairs of electrodes was evaluated in saline solutions (NaCl concentration varying from 0·01 to 1 mol.l^{-1}) and on the skin. The electrodes on the body surface were placed on the inner forearm to avoid contamination by EMG signals. The skin was slightly humidified before electrode application, so that the impedance could stabilize more rapidly (GONDRAN et al., 1995a).

The Ag-AgCl electrodes were pregelled electrodes**. The diameter of the gel reservoir was 22 mm. The electrodes were tested face to face and on the skin. Different surface areas of the gel/skin interface were tested.

4 Results and discussion

4.1 Analysis of measured noise as function of instrumentation

As expected, the cross-correlation technique allows a better evaluation of the PSD of low-amplitude signals when the contribution of the term $|Z_e(f)|^2 \Phi_{i_0}(f)$ is negligible. This point is illustrated in Fig. 5, which compares the noise PSD measured by the auto-correlation and cross-correlation functions for a pair of NASICON-based electrodes in saline solution. To determine the contribution of the different noise sources described in eqn. 2, the noise from the amplifier is also indicated in Fig. 5. It corresponds to the term $\Phi_{e_0}(f) + |Z_e(f)|^2 \Phi_{i_0}(f)$ for the one-channel analysis and $2|Z_e(f)|^2 \Phi_{i_0}(f)$ for the two-channel analysis method. The noise measured by the one-channel method is almost at the same level as that generated by the amplifier and corresponds to the amplifier noise at high frequency, whereas that measured by using the cross-correlation function can be attributed to the electrodes across the whole frequency range. When the impedance of the signal source is high, the contribution of $|Z_e(f)|^2 \Phi_{i_0}(f)$ becomes predominant and the cross-correlation method is no longer necessary.

According to this result, the electrode noise levels in saline solutions were determined by the cross-correlation method whereas on the skin, measurements were carried out with a one-amplifier system. A typical example for a pair of electro-

Table 1 Amplifier noise performance characteristics

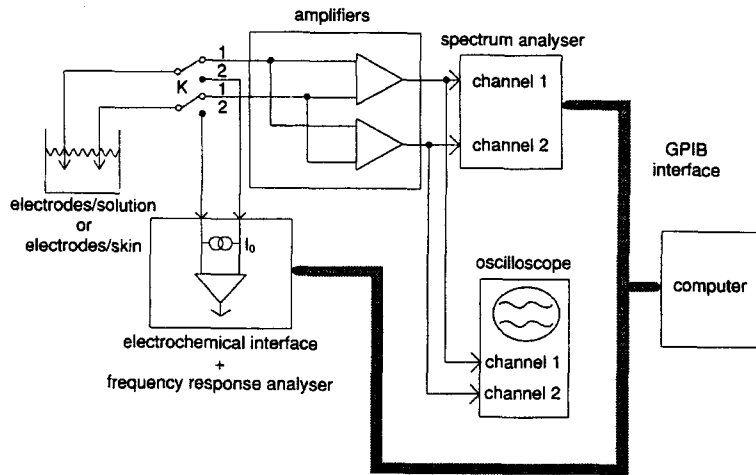| amplifier	Φ_{e_0}, V^2 Hz^{-1}	bandwidth, Hz	Φ_{i_0}, A^2 Hz^{-1}	bandwidth, Hz
1	$10^{-15\cdot2}f^{-0\cdot8}$	0·5–2·5	$10^{-24\cdot7}f^{-1}$	0·5–30
	$10^{-15\cdot9}$	2·5–100	$10^{-24\cdot8}f^{-0\cdot8}$	30–100
2	$10^{-15\cdot2}f^{-0\cdot8}$	0·5–4	$10^{-24\cdot9}f^{-1}$	0·5–100
	$10^{-15\cdot7}$	4–100		

Fig. 3 *Experimental set-up*

des placed on the skin is shown in Fig. 6, which compares the measured noise and the noise from the amplifier. In the frequency range 1–100 Hz, the measured noise can always be attributed to the electrode/skin interface. At higher frequencies and for high values of the electrode/skin impedance real part, the noise is mainly from the amplifier. Godin *et al.* also concluded that the noise generated by the amplifier term $|Z_e(f)|^2 \Phi_{i_0}(f))$ was always predominant in the bandwidth 8 Hz–10 kHz. (GODIN *et al.*, 1991). With the present amplifier design, a significant electrode noise component can be seen at frequencies lower than 100 Hz.
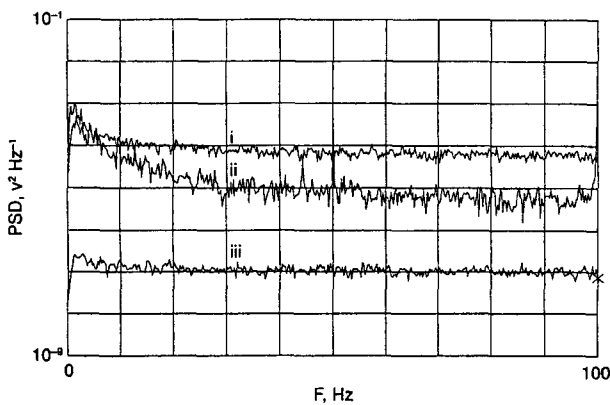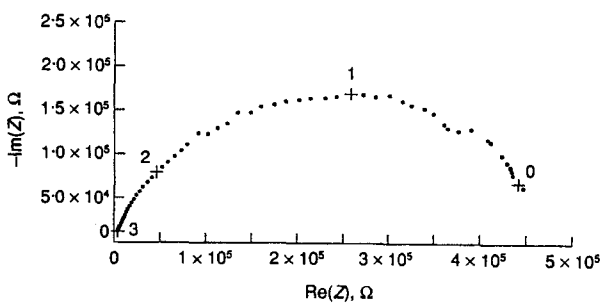
Fig. 4 *Typical experimental results for pair of NASICON-based electrodes placed on skin; signals are measured at output of amplifier; (a) (i) noise spectra; (ii) noise generated by resistance equal to 2MΩ; (iii) amplifier voltage noise; (b) impedance Nyquist plot*

4.2 Electrochemical noise of the electrode

The amplitude distribution of the electrode noise was found to be Gaussian. Figs. 7 and 8 show the PSD of the voltage fluctuations of NASICON-based electrodes in saline solution as a function of the electrode surface area (Fig. 7) and the
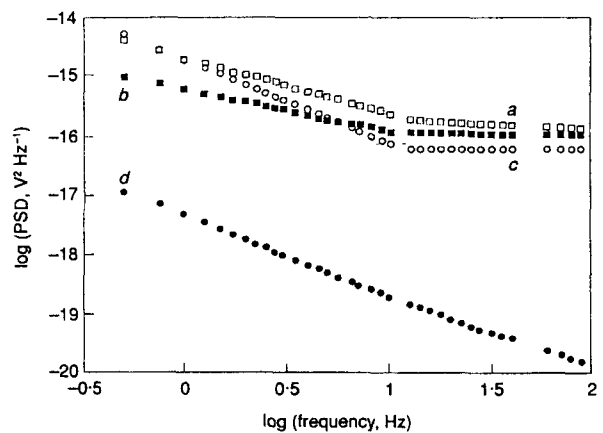

Fig. 5 *(a, c) Noise measured with pair of NASICON-based electrodes in NaCl 0·1 mol.l⁻¹ and (b, d) noise from amplifier; (a, b) one-channel system (auto-spectrum); (c, d) two-channel system (cross-spectrum); electrode surface area = 0.8 cm²*
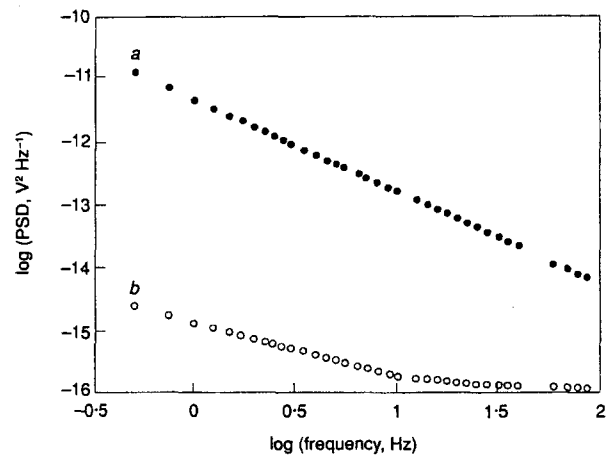

Fig. 6 *(a) Noise measured with pair of NASICON-based electrodes placed on skin and (b) noise from amplifier; Electrode surface area = 0·8 cm²*
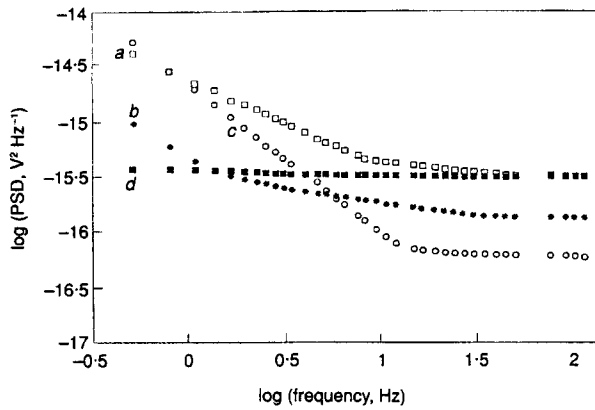
Fig. 7 *Voltage noise power spectral density of NASICON-based electrodes in NaCl 0·1 mol.l^{-1} for different electrode surface areas: (a) 0·2 cm^2; (b) 0·4 cm^2; (c) 0·8 cm^2; (d) represents the thermal noise corresponding to electrode a*
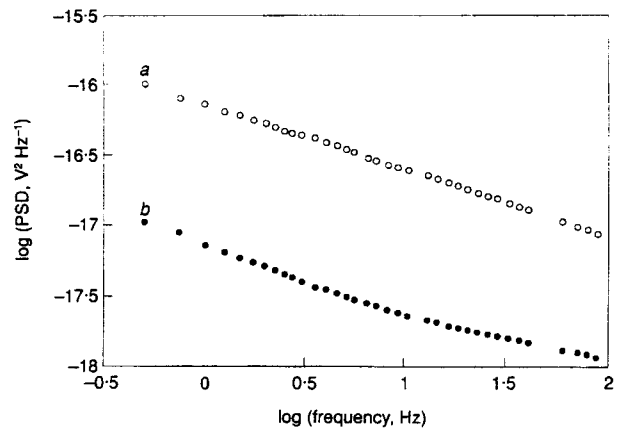

Fig. 9 *(a) Voltage noise PSD of Ag-AgCl pregelled electrodes placed face to face and (b) corresponding thermal noise; gelskin surface area = 3·8 cm^2*

sodium chloride concentration in the electrolyte (Fig. 8). The PSD of the noise generated by the real part of the electrode impedance $\Phi_{Re}(f)$ is also plotted for a typical electrode in Fig. 7. At frequencies higher than 10 Hz, the electrode noise corresponds to the thermal noise generated by the real part of the impedance, in agreement with the Nyquist theorem. As predicted by the impedance measurements, it is slightly dependent on the salt concentration in the solution, but also depends on the electrode surface area. The higher the surface area is, the lower the noise level. At lower frequencies, an excess noise $\Phi_{exs}(f)$ is found. It was calculated by subtraction of the amplifier noise and the thermal noise generated by the real part of the impedance. It was found to vary as f^{-n} with $0·5 < n < 1·5$. The frequency for which this excess noise appears was higher the salt concentration in the electrolyte was low. No significant variation as a function of the electrode surface area was found. The adjunction of agar in the electrolyte to eliminate natural convection was also found to have no influence. Polarisation currents as low as 1μA were found to have no effect on the PSD of the electrode fluctuations. It can be concluded that the measured noise does not result from a polarisation of the electrodes due to the input stage bias current of the amplifier ($1_B = 10$ nA).

The noise PSD of Ag-AgCl electrodes placed face to face is given in Fig. 9. In the frequency range 0·5–100 Hz, excess

noise is also evidenced. It varies as a function of the frequency according to the relationship

$$\Phi_{exs}(f) = 10^{-16}f^{-0.5} \text{ (V}^2\text{Hz}^{-1}) \tag{11}$$

This noise level is lower than that reported by Fernandez and Pallas-Aveny with the same type of electrode (FERNANDEZ and PALLAS-ARENY, 1992).

More recently, Gabrielli *et al.* checked that electrochemical noise is equal to thermal noise with a redox system at thermodynamic equilibrium (GABRIELLI *et al.*, 1993). Our present results suggest that biomedical electrodes are not in thermodynamic equilibrium with our operating conditions, even in the absence of any applied current. Comparison between Figs. 8 and 9 shows that the electrochemical noise generated by the Ag-AgCl electrodes placed face to face is lower than that of the NASICON-based electrodes in NaCl 0·1M. However, whatever the levels, the electrochemical noise is very low. Typically, the peak-to-peak voltages are of the order of 0·25 μV for the Ag-AgCl electrodes and 0·5 μV for the NASICON-based electrodes (surface area = 0·8 cm^2) in the bandwidth 0·5–100 Hz.

4.3 Electrode/skin interface noise

A typical example of noise PSD measured with NASICON-based electrode and pregelled Ag-AgCl electrodes placed on the skin is given in Fig. 10. For comparison, the thermal noise
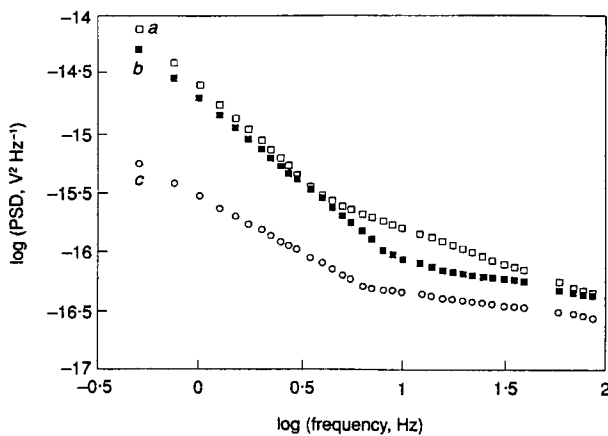

Fig. 8 *Voltage noise power spectral density of NASICON-based electrodes for different sodium chloride concentrations; electrode surface area = 0·8 cm^2; (a) 0·01 mol l^{-1} (b) 0·1 mol l^{-1}; (c) 1 mol l^{-1}*
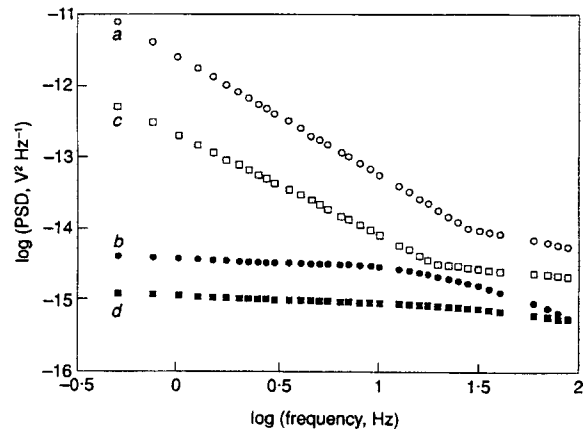

Fig. 10 *Voltage noise PSD (a) NASICON-based electrode and (c) Ag-AgCl electrodes placed on skin; Electrode/skin surface area = 0·8 cm^2; (b) and (d) are corresponding thermal noises*

Table 2 *Excess noise PSD a f^{-n}(V^2 Hz^{-1}) for eight patients with NASICON-based electrodes*

patient	a	n
1	$10^{-11.6}$	1·6
2	10^{-11}	2·1
3	$10^{-11.3}$	1·8
4	$10^{-11.3}$	2
5	10^{-11}	2·1
6	$10^{-11.3}$	1·5
7	$10^{-10.6}$	2·1
8	$10^{-10.5}$	2·1

electrode surface area = 0·8 cm^2

generated by the real part of the impedance is also indicated. For the patient corresponding to this Figure, the noise measured at high frequency is of the same order of magnitude as the thermal noise. For patients with higher electrode/skin impedance, the noise measured at high frequency results from the amplifier. In the frequency range 1–100 Hz, the noise generated by the electrode/skin interface is higher than the Nyquist noise generated by the impedance. This excess noise was determined with the NASICON-based electrodes (surface area = 0·8 cm^2) on eight patients. Results are reported in Table 2. A relationship of the type

$$\phi_{exs}(f) = af^{-n} \quad (\text{V}^2/\text{Hz}^{-1}) \tag{12}$$

is obeyed. The value of a is highly dependent on the patient and in the range from 2×10^{-12} to 5×10^{-11} V^2 Hz^{-1}. The magnitude of the peak-to-peak voltage associated with these fluctuations is of the order of 10–60 μV. The shape of the spectra differs from that typically observed with surface EMG signals (INBAR and NOUJAIM, 1984). This excess noise cannot be attributed to EMG signals but rather related to the skin/electrode interface.

The impedance and noise levels were studied as a function of the electrode surface area. Results for two patients are reported in Fig. 11. As expected, the impedance decreases as the electrode surface area increases, and a proportionality between Z and the reverse surface area is found with good accuracy. For small values of electrode surface area, the noise level decreases when the electrode surface area increases, indicating that the noise is related to the nature of the skin/electrode interface. However, no clear relationship can be established. In particular in Fig. 11, the electrode/skin noise level seems to reach a limiting value when the electrode surface area increases. This result could be explained by the presence of residual EMG signals, as EMG signals would be almost surface-independent, or rather increase as the electrode surface area increases. This signal would contribute more for a large surface area. The presence of EMG in the observed excess noise has also been proposed by others (GODIN et al., 1991; FERNANDEZ and PALLAS-ARENY, 1992).

The electrode/skin interface noise level was also evaluated on abraded skin. Skin abrasion was found to decrease the excess noise level, indicating that excess fluctuations might be associated with out-of-equilibrium processes in the stratum corneum layer of the skin.

From the results, two tentative explanations could be proposed. First, the excess noise could result from a non-stationary process. This could be a slow drift of the electrode voltage, for example. If, over the time scale of the experiment, the voltage drift is approximately linear with time, the PSD varies as f^{-2}, according to

$$\Phi_e(f) = \frac{Ta^2}{4\pi^2 f^2} \tag{13}$$

where T is the time of integration and a is the magnitude of the linear drift. The voltage drift deduced from our measurements and eqn. 13 would be in the range 3–15 μVs^{-1}. This could not have been detected during measurement using an oscilloscope.

Secondly, the excess noise is of electrochemical origin, coming from the ionic nature of the skin (fluctuation in the ion concentration or mobility, for example). This noise should decrease as the electrode surface increases, as observed for electrodes of small surface area (Figs. 10 and 11). The noise variation as a function of the electrode/skin interface area could suggest that, for large surface electrode areas, some residual EMG signal contributes to the electrode/skin interface noise. According to Fig. 11, this assumption would result in a residual EMG signal peak-to-peak voltage of the order of 5 μV.

5 Conclusions

From the results, it can be concluded that great care must be taken in amplifier design to obtain reliable data. The cross-correlation method must be used to evaluate noise of electrochemical origin from electrodes. The noise generated by the electrode/skin interface can be determined with a one-channel analysis method.

The electrochemical noise from the electrode/electrolyte interface is negligible. Typically, peak-to-peak voltage fluctuations as low as 0·3 μV are observed for the Ag-AgCl electrodes and 1 μV for the NASICON-based electrodes in contact with 0·1 M NaCl solution.

On the skin, the noise level depends on the patient and the skin preparation rather than the electrode. At high frequency (> 100 Hz), the electrode/skin interface noise is in agreement with the Nyquist theorem. It is therefore related to the real part of the impedance of the electrode/skin interface. The noise generated by the electrode/skin interface can therefore be diminished by reducing the impedance of this system.
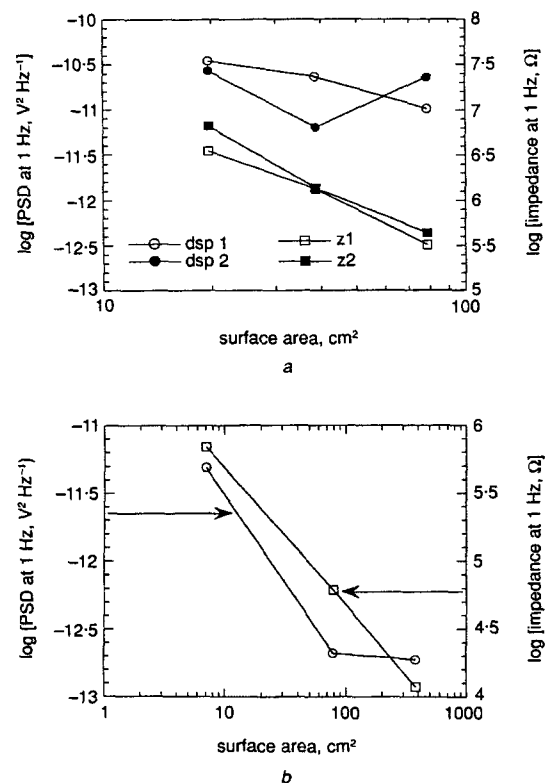

Fig. 11 *Variation of impedance and noise PSD at 1 Hz on skin as function of electrode surface area: (a) NASICON-based electrodes; (b) Ag-AgCl electrodes*

Depending on the amplifier design ($\Phi_{i_0}(f)$ value), the noise from the amplifier (component $|Z_e(f)|^2\Phi_{i_0}(f)$) can become predominant. This situation was observed by Godin et al. (GODIN et al., 1991).

At low frequencies ($F < 100$ Hz), excess noise is evidenced. The origin of this noise is still unclear. Non-stationary and out-of-equilibrium processes in the skin can be suggested. Whatever the origin of this noise, it leads to peak-to-peak voltage fluctuations of the order of 5–60 μV. This represents the minimum value that the electrophysiological signals must have to be detected in this frequency range. It was shown that increasing the electrode surface area does not lead to this extra noise decreasing and that residual EMG signal could contribute to the extra noise. A limiting value of the order of 5 μV is obtained. Abrasion of the skin is the best way to diminish this excess noise.

References

BARKER, G. C. (1969): 'Noise connected with electrode processes,' *J. Electroanal. Chem.*, 21, pp. 127–136

BLANC, G., GABRIELLI, C., and KEDDAM, M. (1993): 'Fluctuations in electrochemical systems. I General theory on diffusion limited electrochemical reactions,' *J. Chem. Phys.*, 99, pp. 7372–7239

CALLEN, H. B., and WELTON, T. A. (1951): 'Irreversibility and generalized noise,' *Phys. Rev.*, 83, pp. 34–40

DE VRIES, H. A., BURKE, R. K., HOPPER, R. T., and SLOAN, J. H. (1976): 'Relationship of resting EMG level to total body metabolism with reference to the origin of tissue noise,' *Am. J. Phys. Med.*, 5, 585–590

FERENANDEZ, M., PALLAS-ARENY, R., RIU, P. J. and LOZANO, A. (1991): 'Electrode noise in high resoloution ECG.' *IV Int. Symp. on Biomedical Engineering*, Pensicola, Spain, pp. 103–104

FERNANDEZ, M., and PALLAS-ARENY, R. (1992): 'Electrode contact noise in surface biopotential measurements.' 14th Ann. Int. Conf. of IEEE Engineering in Medicine and Biology Soceity. Paris, pp. 123–124

FERRIS, C. D., and STEWART, L. R. (1974): 'Electrode-produced signal distortion in electrophysiological recording systems,' *IEEE Trans.*, BME-21, pp. 318–326

FITCH, P. (1973): 'Signal/noise ratio in the recording of human nerve-action potentials,' *Med. Biol. Eng.*, 11, pp. 146–154

FLASTERSTEIN, A. H. (1966a): 'Voltage fluctuations of metal electrolyte interfaces in electrophysiology,' *Med. Biol. Eng. Comput.*, 4, pp. 583–588

FLASTERSTEIN, A. H. (1966b): 'A general analysis of voltage fluctuations of metal-electrolyte interfaces,' *Ibid.*, 4, pp. 589–594

FLEISCHMANN, M., and OLDFIELD, J. W. (1970): 'Generation-recombination noise in weak electrolytes,' *J. Electroanal. Chem.*, 27, pp. 207–218

GABRIELLI, G., HUET, F., and KEDDAM, M. (1986): 'Investigation of electrochemical processes by an electrochemical noise analysis. Theoretical and experimental aspects in potentiostatic regime,' *Electrochim. Acta*, 31, pp. 1025–1039

GABRIELLI, C., HUET, F., and KEDDAM, M. (1993): 'Fluctuations in electrochemical systems. II-Application to a diffusion limited redox process,' *J. Chem. Phys.*, 99, pp. 7240–7252

GODIN, D. T., PARKER, P. A., SCOTT, R. N. (1991): 'Noise characteristics of stainless-steel surface electrodes,' *Med. Biol. Eng. Comput.*, 29, pp. 585–590

GONDRAN, C., SIEBERT, E., FABRY, P., NOVAKOV, E., and GUMERY, P. Y. (1992): 'NASICON based electrodes for bioelectric signal measurements.' 14th Ann. Int. Conf. of IEEE Engineering in Medicine and Biology Society, Paris, pp. 2706–2708

GONDRAN, C., SIEBERT, E., FABRY, P., NOVAKOV, E., and GUMERY, P. Y. (1995a): 'Non-polarisable dry elecrode based in NASICON ceramic,' *Med. Bio. Eng. Comput.*, 33, pp. 452–457

GONDRAN, C., SIEBERT, E., YACOUB, S., and NOVAKOV, E. (1995b): 'Dry electrode based on NASICON ceramic for surface biopotential measurements: skin-electrode impedance and noise', *Innov. Tech. Biol. Med.*, 16, pp. 113–118

INBAR, G. F., and NOUMAIM, A. E. (1984): 'On surface E.M.G. spectral characterization and its application to diagnostic classification,' *IEEE Trans.*, BME-31, pp. 597–604

NIGHTINGALE, A. (1958): 'Electrical noise from polarization cells and from human tissues,' *Nature*, 181, pp. 192–193

NIGHTINGALE, A. (1959): 'Background noise in electromyography,' *Phys. Med. Biol.*, 3, pp. 325–338

NYQUIST, H. (1928): 'Thermal agitation of electric charge in conductors,' *Phys. Rev.*, 32, pp. 110–113