Electrode-Skin contact impedance: In vivo measurements on an ovine model

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Abstract.
The problem of electrical impedance between the skin and the electrode is an on-going challenge in bio-electronics. This is particularly true in the case of Electrical Impedance Tomography (EIT), which uses a large number of skin-contact electrodes and is very sensitive to noise. In the present article, contact impedance is measured and compared for a range of electrodes placed on the thorax of an ovine model. The study has been approved by the Westmead Hospital Animal Ethics Committee. The electrode models that were employed in the research are Ag/AgCl electrodes (E1), commonly used for ECG and EIT measurements in both humans and animal models, stainless steel crocodile clips (E2), typically used on animal models, and novel multi-point dry electrodes in two modifications: bronze plated (E3) and nickel plated (E4). Further, since the contact impedance is mostly attributed to the acellular outer layer of the skin, in our experiment, we attempted to study the effect of this layer by comparing the results when the skin is intact and when electrodes are introduced underneath the skin through small cuts. This boundary effect was assessed by comparison of measurements obtained during E2 skin surface contact, and sub-cutaneous contact (E5). Twelve gauge intradermal needles were also tested as an electrode (E6). The full impedance spectrum, from 500 Hz to 300 kHz, was recorded, analysed and compared. As expected, the contact impedance in the more invasive cases, i.e. the electrodes under the skin, is significantly lower than in the non-invasive cases. At the frequency of 50 kHz which is commonly used in lung EIT acquisition, electrodes E3, E4 and E6 demonstrated contact impedance of less than 200 Ω, compared to more than 400 Ω measured for electrodes E1, E2 and E5. In conclusion, the novel multipoint electrodes proved to be best suited for EIT purposes, because they are non-invasive and have lower contact impedance than Ag/AgCl and crocodile clips, in both invasive and non-invasive cases. This further prompted us to design a flexible electrode belt using the novel multi-point electrodes for lung EIT on animal models.

1. Introduction
There is an increasing need in biomedical engineering to consider new electrode technologies. Movement artefacts, baseline variations and contact impedance prevent the recording of the electrocardiogram (ECG) during resuscitation [1], constrain implanted devices for functional electrical stimulation of muscles, the cochlea and the retina [2], and have restricted the use of the electroencephalogram (EEG) and impedance classification of stroke [3; 4]. Dry bio-
signal recordings are currently limited by changes in contact impedance, noise, motion artefacts and baseline voltage variations at the electrode to skin interface [5]. These are the limiting factors in recording ECG and fECG with a handheld device [6; 7]. For conventional bio-potential measurements, electrodes are attached to the patient’s skin after preparation; this includes cleaning, shaving, mechanical abrasion to remove the acellular outer layer of the skin, and moistening. A layer of electrically conductive gel is applied between the skin and the electrodes to reduce contact impedance. Two double layers form between the electrode metal conductor, the gel and the cell membranes of active skin. These present significant resistance and capacitance which results in variable contact impedance between electrodes. High input impedance instrumentation amplifiers are successful at overcoming this contact impedance in controlled environments but skin preparation takes time and requires a compliant subject [8]. In EIT measurements the variations in contact impedance impact on both the current source and voltmeter [9].

The purpose of this paper was to compare electrodes suitable for EIT experiments in an ovine model. Animal experiments are convenient for testing the ability of new devices, particularly in the invasive situations in which we are interested such as with the use of internal electrodes or contrast agents. However the electrodes are generally more difficult to use on animals due to the increased hair and skin oils.

2. Method

This research has the approval from the Westmead Hospital Animal Ethics committee. The animal was anaesthetised and ventilated appropriately. For this experiment, the skin on the thorax of the animal was cleanly shaven. The skin was then abraded with alcohol rub in an attempt to remove the dead epidermis layers and oils. The skin was wiped with alcohol rub after each experiment to ensure the integrity of subsequent measurements.

Electrode models utilised in the experiment included:

- E1: Ag/AgCl electrodes (3M), applied directly onto the skin with gel,
- E2: Crocodile clips, pinched the skin between the clip,
- E3: Bronze multi-point electrodes, applied directly onto the skin,
- E4: E3 plated with a nickel coating
- E5: Crocodile clips, introduced through a pocket made by a cut on the skin of the animal.
- E6: 12 gauge needles, slipped under the skin horizontally.

E1 is the most frequently used electrodes in both humans and animal models for a wide range of applications from ECG to EIT. E2 is commonly used on animal models on which the skin does not adhere well to Ag/AgCl electrodes, for example sheep skin. E3 and E4 are novel multi-point dry electrodes, which are yet to be tested on an ovine model. Further, since the contact impedance is mostly attributed to the acellular outer layer of the skin, in our experiment, we attempted to study the effect of this layer by comparing the results when the skin is intact and when electrodes are introduced underneath the skin through small cuts (E5). Twelve gauge intradermal needles were also tested as an electrode (E6).

The contact impedance of each case was measured using an HIOKI IM3570 impedance analyser. The frequency range was set between 100 Hz and 300 kHz for all of the measurements. A two-terminal impedance measurement was made between electrode pairs. A fixed current of 1mA was injected through the two terminals while voltage was measured across the same terminals. The measured voltage is the average of 16 measurements at each frequency to mitigate the effect of electrode movements and other noise sources.
Figure 1. Electrode-Skin contact impedance spectra of various electrode models, measured on an ovine model: **A** Impedance spectra of all electrodes models E1–6; **B** Impedance spectra of electrodes models E2–6. E1 has considerably higher impedance in the lower frequency range than the other electrodes.
3. Results
As Figure 1 depicts, the contact impedance in the more invasive cases, i.e. the electrodes under the skin, are significantly lower than in the non-invasive cases. At higher frequencies, that is, above 10 kHz, this difference is not as significant as at the lower frequencies. At the frequency of 50kHz which is commonly used in lung EIT acquisition, electrodes E3, E4 and E6 demonstrated contact impedance of less than 200 \( \Omega \), compared to more than 400 \( \Omega \) measured for electrodes E1, E2 and E5. The multi-point electrodes performed particularly well in the typical range of frequencies for EIT, i.e. 10 kHz to 100 kHz.

4. Discussion and Conclusion
The impedance spectra shown in Figure 1 demonstrated that the Ag/AgCl electrodes clearly performed the worst, with contact impedance at 1 kHz almost double that of all other electrode models. The differences rapidly decreased up to 10kHz. This is in agreement with a wide body of previous work [10; 11] which showed that the epidermis layer mainly affects the lower frequency signals. The needle electrodes performed well despite their much smaller size and hence higher current density, while the crocodile clips in pockets, albeit highly invasive, retained a high contact impedance with a relatively flat spectrum.

In all of the impedance spectra, as seen in Figure 1, there was a spike occurred around 50 kHz, which can be attributed to instrumental interference. The experiments were conducted in a clinical settings with many other instrumentations running in parallel, such as fluoroscopy, ventilator, etc. Since the crocodile clips used in E2 and E5 had larger areas of exposed metal, the interference were more prevalent in these two electrodes types than any other.

In conclusion, the novel multipoint electrodes proved to be best suited for EIT purposes, because they are non-invasive and have lower contact impedance than Ag/AgCl and crocodile clips, in both invasive and non-invasive cases. This further prompted us to design a flexible electrode belt using the novel multi-point electrodes for lung EIT on animal models. This device helps to mitigate a number of technical problems which arise while performing EIT in vivo on an animal model, including large values of electrode contact impedance, its high variability, position errors and undetected disconnection of electrodes during the experiment.

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