Non-invasive Wet Electrocochleography
Federico Carpi* and Serena Migliorini

Abstract—To detect electrocochleographic (ECochG) potentials generated by the cochlea in response to auditory stimuli, either transtympanic or tympanic/extratympanic electrodes are currently used. The first are invasive, while the second are arranged in contact or very close to the tympanic membrane (TM). To avoid the discomfort and the risks inherent to the application of such conventional electrodes, this Letter presents an alternative technique. A conducting liquid is inserted into the ear canal to act as a distributed electrical interface between the TM and an external electrode. Thus, ECochG potentials are detected without any direct contact between the solid electrode and the sensitive TM. This technique was tested on ten volunteers with single-click auditory stimuli. Results showed its efficacy to noninvasively detect useful ECochG responses, with accurate morphology and significant amplitude. The technique is comfortable, sedation/anesthesia-free, inherently safe, and easy to perform. It also favors improvements of contact stability, reductions of contact impedance, and relative tolerance to misplacements. As a contraindication, the liquid prevents use on subjects affected by tympanic perforation. All these features encourage further investigations on this technique as a possible additional tool for the ECochG practice.

Index Terms—Conducting, ECochG, electrocochleogram, electrocochleography, electrode, fluid, non-invasive, wet.

I. INTRODUCTION

ELECTROCOCHLEOGRAPHIC (ECochG) investigations represent a fundamental test to evaluate the functionality of the cochlea, by recording bioelectric potentials generated upon its acoustic stimulation with sound clicks or tone bursts [1]–[3]. ECochG recording electrodes (to be used in combination with reference and ground cutaneous electrodes) are divided in two classes: transtympanic and extratympanic/tympanic [1]–[9].

Transtympanic electrodes are the most invasive [1]–[5]. They consist of needles inserted through the tympanic membrane (TM), so as to be arranged on the cochlear promontory [Fig. 1(a)]. This procedure, which must be performed by well-trained physicians in appropriate sterile medical settings, is painful and requires sedation/local anesthesia [1]–[5], [7], [8].

To avoid such invasivity, extratympanic electrodes are also used [1]–[4], [7]–[9]. Although different types are available, basically all of them consist of conductive bodies, inserted into the ear canal deeply, more or less close to the TM [Fig. 1(b)]. In case of a strict contact with the TM, they are called tympanic [1]–[4], [6], [8]. The noninvasivity of extratympanic/tympanic electrodes is paid with some drawbacks, which typically include an inherently lower signal amplitude (due to the higher distance from the bioelectric source), a higher mechanical/electrical instability (due to the electrode position) and a higher electrode impedance (due to both a reduced contact area and a poorly conductive interface with the ear canal skin, whose pores are filled with sebaceous and ceruminous secretions) [2], [4], [8]. To limit the worsening effect of these factors on the SNR, the electrical contact has to be improved with conductive pastes or fluids [8]. Moreover, extratympanic and tympanic electrodes can be still uncomfortable [1], [8] and their application still requires adequate care and skills, due to the sensitivity of the TM [1], [8].

Within such a context, the aim of this Letter is to describe an alternative ECochG technique intended to combine noninvasivity with efficacy, safety, comfort, and ease of use.

II. WET ELECTROCOCHLEOGRAPHY

The concept proposed here relies on a recording electrode able to work without any direct contact with the sensitive TM.
For this purpose, a conducting liquid is inserted in the ear canal, to act as a distributed electrical interface between the TM and the solid body of the electrode; the latter detects the potential indirectly, avoiding any tympanic contact [Fig. 1(c)].

As a conducting liquid, a water-based saline solution can be employed. It has just to be dipped into the conducting liquid. The high conductivity of the latter allows a continuous and stable electrical connection with the TM. Therefore, it is not necessary to insert the electrode deeply into the ear canal. This feature facilitates the electrode application procedure and guarantees its intrinsic safety. The electrode can be laterally masked [Fig. 1(c)], to prevent direct contact with the ear canal skin. This can improve rejection of muscular artifacts, able to worsen the SNR, and measurement reliability.

This technique was implemented as described in the following.

III. MATERIAL AND METHODS

A. Conducting Liquid and Electrodes

The conducting liquid consisted of a standard physiologic solution (water-based 0.9% sodium chloride). A standard Ag/AgCl cup electrode (model EL TPCO, Micromed S.p.A., Italy) was used as the recording conductor; it was laterally masked with an insulating heat-shrinking tube, leaving a 1-cm-wide cleft [Fig. 2(a)] for exposure to the liquid. Reference and ground electrodes also consisted of standard Ag/AgCl cups.

B. Location of the Electrodes

The recording electrode was arranged in the ear canal and dipped into the liquid [Fig. 2(b)]. The ground electrode was located on the forehead [Fig. 2(c)], while the reference electrode (equipped with an ear clip) was fixed to the ear lobe [Fig. 2(b)]. Two types of electrode configurations were tested, by placing the reference electrode alternatively on the ipsilateral and contralateral ear lobe. The resulting two configurations (hereinafter referred to as ipsilateral and contralateral) are represented in Fig. 3.

C. Application of the Electrodes

To test wet electrocochleography, each volunteer was first equipped with the reference and ground electrodes, which were coupled to the skin by means of a standard conductive gel for biopotentials (electroconductive gel, Farmacare, Italy). Then, the volunteer was laid on one side on a patient’s table, so as to provide the head with a comfortable and stable position. While keeping the head opportunely rotated, the ear canal was first filled with the conducting liquid and the recording electrode was then inserted, as shown in Fig. 2(b).

The quality of the electrical contact of each electrode could be continuously monitored by checking the electrode impedance, as foreseen by standard measurement protocols for ECochG signals (and any other biopotential).

The electrodes considered in this work could be reused for different volunteers, following a sterilization performed in ethylene oxide (as recommended by the manufacturer).

D. Acoustic Stimulation and Signal Acquisition

ECochG responses were elicited by means of single clicks (with duration of 100 µs), as a standard type of auditory stimulus [1]–[9]. Two sound levels, 30 and 60 dB (dB HL), were tested as a low and medium/high value, respectively, according to ECochG practice [1]–[9]. However, it is worth stressing here that 30 and 60 dB cannot be considered as the stimulation levels that actually reached the TM, due to attenuation of air-born acoustic waves within the liquid. Thus, calibration of stimulus in wet conditions should be necessary for comparisons with standard practice. Although studying such an effect goes beyond the aims of this Letter, it will be required for future comparative assessments (Section V-D).

Sound stimulation was generated by the audio interface board of a workstation, driven by an open-source audio software (Audacity 1.2.6). Single clicks were obtained with the following software settings: time = 300 beats/min, beats per measure = 1, number of measures = 1. The stimulation was delivered through a headphone (model Stereo Headphones SHP2000, Philips, The Netherlands), as shown in Fig. 2(c).

ECochG signals were recorded by using a biopotential acquisition system (model Biopac MP150, Biopac Systems, Inc., USA), operated with the following settings: bandpass filtering: 0.4–40 Hz, amplification gain = $5 \times 10^3$.

E. Testing Procedure

ECochG tests were performed on a set of ten volunteers (Table I). For each of them, one ear (left) was tested in four different conditions of stimulation/detection, resulting from the combination of the earlier mentioned two sound levels (30 and 60 dB) and two electrode configurations (ipsilateral and contralateral). For each condition, five EcochG waveforms were recorded and mean values of SP (summating potential)- and AP
IV. RESULTS

A. Signal Morphology

Recordings from all the volunteers exhibited the typical morphology of ECochG waves. As an example, Fig. 4 reports two consecutively recorded signals, which show typical SP- and AP-wave deflections. Other waves (e.g., N2) visible in these and other acquired signals (not presented here) were not analyzed in this work, so they will not be discussed in the following.

B. Amplitude Comparison for Different Sound Levels

Fig. 5 presents SP- and AP-wave amplitudes, recorded in the different test conditions. Data show that, for each electrode configuration (either ipsilateral or contralateral), the higher sound level (60 dB) elicited SP and AP waves with higher amplitude, for each volunteer.

C. Amplitude Comparison for Different Electrode Configurations

Fig. 5 lets us also to compare SP- and AP-wave amplitudes obtained from the two electrode configurations (ipsilateral and contralateral) at the same sound level (either 30 or 60 dB). Comparisons show that ipsilateral recordings provided lower amplitude of both the SP and AP waves, for the majority of volunteers (specifically: 7 and 8 out of the total 10 volunteers for the SP amplitude at 30 and 60 dB, while 9 and 10 out of the total 10 for the AP amplitude at 30 and 60 dB).

V. DISCUSSION

A. Signal Morphology and Amplitude

Results revealed that wet electrocochleography is able to detect morphologically accurate potentials, showing characteristic SP- and AP-wave deflections (Fig. 4): this is a fundamental requisite for the usability of a new technique.

Both the SP- and AP-wave amplitudes were found to increase with sound level, for both the ipsilateral and contralateral configurations (Fig. 5): this outcome was expected, according to basic ECochG principles [1]–[3].

Contralateral recordings provided response amplitudes ten- dentially higher with respect to the ipsilateral configuration (Fig. 5). This evidence is consistent with literature reports [2] and might be attributed to the greater distance between primary and secondary electrodes: the contralateral condition was closer to a monopolar, rather than bipolar, measurement.

Exceptions to this superiority of contralaterally detected am-plitudes were recorded in 30 and 20% of cases for the SP wave at 30 and 60 dB, respectively, while in 10 and 0% of cases for the AP wave at 30 and 60 dB, respectively (Fig. 5). Such a decreasing trend in the number of exceptions while shifting attention from SP to AP wave and from low to high stimulus can be readily explained: an AP wave elicited by a higher sound level is prone to show a higher SNR (because of an inherently higher amplitude of the response), thus making measurements less affected by noise.

B. Properties of Wet Electrocochleography

The main properties that the proposed technique seems to exhibit as peculiar features are summarized in the following.
1) **Noninvasivity:** The recording electrode does not pierce nor touch the highly sensitive TM.

2) **Comfort and no need for sedation/anesthesia:** The absence of any perforation of the TM or contact of it with the solid body of the electrode improves comfort and avoids the need for sedation/anesthesia.

3) **Intrinsic safety and ease of use:** The specific arrangement of the electrode, which is not only extratympanic but also displaced from the eardrum more than any other extratympanic electrode, makes its application procedure inherently safe and easy. Actually no specific skills are required to the operator in order to apply the electrode. This allows ECochG procedures to be performed even by non-specialized personnel, without any risk for the patient.

4) **Improved contact stability:** Electrical contact is favored by a continuous impedance matching, enabled by the interface liquid distributed between the TM and the electrode. This is likely to promote the morphological quality of the signal.

5) **Tolerance to misplacements:** The liquid-enabled impedance matching also makes the technique less sensitive to erroneous applications of the electrode (which are able to compromise the electrical contact). This makes the procedure less dependent on the operator’s skills.

6) **Reduced contact impedance:** The highly conducting and distributed liquid at the eardrum/electrode interface favors not only improvements of contact stability but also reductions of contact impedance. This is likely to reduce sensitivity to motion artifacts and voltage drop at interface, both factors concurring to improve the SNR.

With standard tympanic electrodes, lowering the contact impedance requires viscous conductive pastes/fluids at the electrode’s tip [8]. However, in this case the contact impedance is likely to be higher in comparison with an interface mediated by a conducting liquid, for two main reasons: first, viscous pastes/fluids penetrate with more difficulty into the narrow skin pores that are also filled with a nonconductive mixture of sebaceous/ceruminous secretions (which persist even after uncomfortable cleaning) [8]; second, the total effective contact area is reduced, due to not only a limited surface density of effective contact “points” (because of the earlier mentioned worsening of contact quality) [8] but also a limited nominal contact area (determined by the extension of the paste/fluid-coated surface).

On the contrary, a liquid not only can improve the quality of the contact itself (because of a higher ability of skin pore penetration) but also, owing to its wide distribution, it brings in contact with the electrode the overall surface of the TM, not just a part of it. Moreover, the electrode’s area involved in signal extraction is given by the overall surface exposed to the liquid, in any direction (i.e., both frontally and laterally), not just a portion of the tip. An additional facilitation in this respect is offered by the greater overall surface of applicable electrodes. In fact, compared to traditional techniques, wet electrocochleography can be performed with a bigger electrode, as it should be located just at the entrance of the ear canal, making it not necessary to fit with more stringent anatomical limitations that would be imposed by narrower sites of application at (or close to) the eardrum (Fig. 1).

**C. Contraindication to the Use of Wet Electrocochleography**

Due to the insertion of a liquid inside the ear canal, the technique is not advisable to patients that present a perforation of the TM. This should be assessed through preventive otoscopy, always performed before ECochG testing [2].

**D. Future Work**

This initial work represents the first technical investigation (while not any clinical validation) on the proposed wet technique, aimed at demonstrating its feasibility and disclosing its salient features. The next methodological step might be aimed at obtaining a performance comparison between wet and standard ECochG techniques. For this purpose, attenuation of air-borne acoustic stimulus within the liquid should be properly considered with accurate calibration.

**VI. CONCLUSION**

This Letter described a novel technique for electrocochleography, using a conducting liquid as a distributed electrical interface between the TM and an external conductor. Tests on ten volunteers allowed a preliminary validation of the feasibility of the technique and its efficacy to provide accurate morphology and significant amplitude of ECochG responses. These are obtained with no solid body that pierces or contacts the TM, no need for sedation/anesthesia, inherent safety, and ease of use. The technique is prone to favor improvements of contact stability, reductions of contact impedance, along with relative tolerance to misplacements. Such properties encourage further investigations on this approach as an additional means to detect ECochG potentials.

**REFERENCES**


