Supplementary Information

Conducting polymer tattoo electrodes in clinical electro- and magneto- encephalography

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Supplementary Methods

*Impedance recordings with diverse TTEs***.** Impedance evaluations are performed with different types of tattoo electrodes to investigate their performance in signal transduction (Supplementary Fig. 1). We studied three kinds of TTEs: TTEs with one or two layers of PEDOT:PSS and TTEs with a gold layer underneath the PEDOT:PSS layer. The impedance recordings are performed from a three electrodes configuration with an electrode sensing area of 1 cm^2 and inter-electrode distance of 2.5 cm. The three electrodes demonstrated very similar behaviour (Supplementary Fig. 1a), in agreement with the TTE equivalent circuit model (see main text), and the electrodes with two layers of PEDOT:PSS reported the smallest impedance among the tattoo electrodes at low frequencies. These results prompted the adoption of two layers of PEDOT:PSS electrodes for the EEG recordings. They are fabricated taking into account the layered structure, shown in Supplementary Fig. 1c, at the interconnection point. Indeed, once the TTE is released on the skin, the electrode and the external contact are forced to stay at the same planar level. The difference in thickness plays a significant role, since a thicker interconnection would lead to a loss of electrical contact (Supplementary Fig.1c). In order to provide wiring of TTE with an external acquisition unit, a clip-like connector is 3D fabricated (Supplementary Fig.1d, bottom image), serving as a relay to a shielded wire with a dedicated jumper to the EEG amplifier.

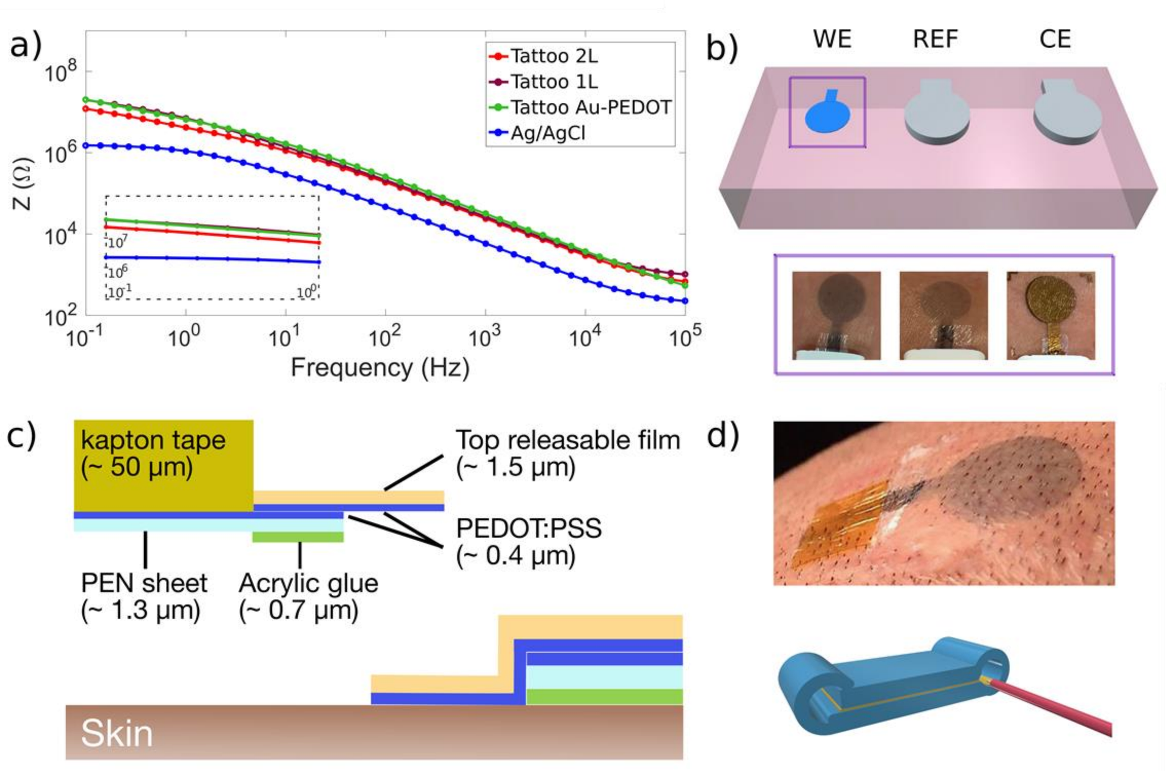
Fabrication of TTE with the gold layer. A standard acrylic transparent sheet (width 47 mm, height 47 mm, thickness 3 mm) is laser-cut (VLS 3.50, 50 W; Universal Laser Systems) with a circular shape (13 mm diameter) and an adjacent rectangular shape (width 3 mm height 7.3 mm) at the lower part of the circumference to create a shadow mask. This mask is placed on top of the tattoo paper and 20 nm of gold is deposited on top of it by evaporation (BOC EDWARDS AUTO500). Another mask made with a rectangular shape (width 3 mm height 47 mm), used for interconnections, was then placed on top of the PEN sheet. PEDOT:PSS is inkjet-printed, on top of the gold pattern, in a circular shape (14 mm diameter), overfilling the actual circular gold footprint. The PEN-Au patterned interconnecting line is laminated onto the tattoo, aligning face-to-face the Au rectangular part and leaving a 5 mm long free end. The glue sheet, from the temporary tattoo kit, patterned with a circular shape of 11.3 mm diameter and corresponding to the sensitive area of the printed tattoo electrode, was added on top of all. A piece of Kapton tape is placed over the 5 mm long free end in order to strengthen the external contact.

TTE recording with medically standardized EEG equipment. EEG recordings are also performed with a standardized equipment (EEG-1042 Braintronics), in a hospital evaluation room (Supplementary Fig. 2), to show the performance of TTEs in an actual clinical application. No specific devices or environmental precautions were applied to obtain representatives and low noise EEG recordings. The participant is seated in an evaluation chair with a headrest and asked to close his eyes. After few minutes, TTEs in Cz-Oz location (Supplementary Fig. 2a) record well-recognizable alpha activity (Supplementary Fig. 2b) during the recording session (120s) (Supplementary Fig. 2c), as shown in the zoom on the EEG recording (Supplementary Fig. 2d). The signals are comparable with those recorded simultaneously with standard Ag/AgCl electrodes.

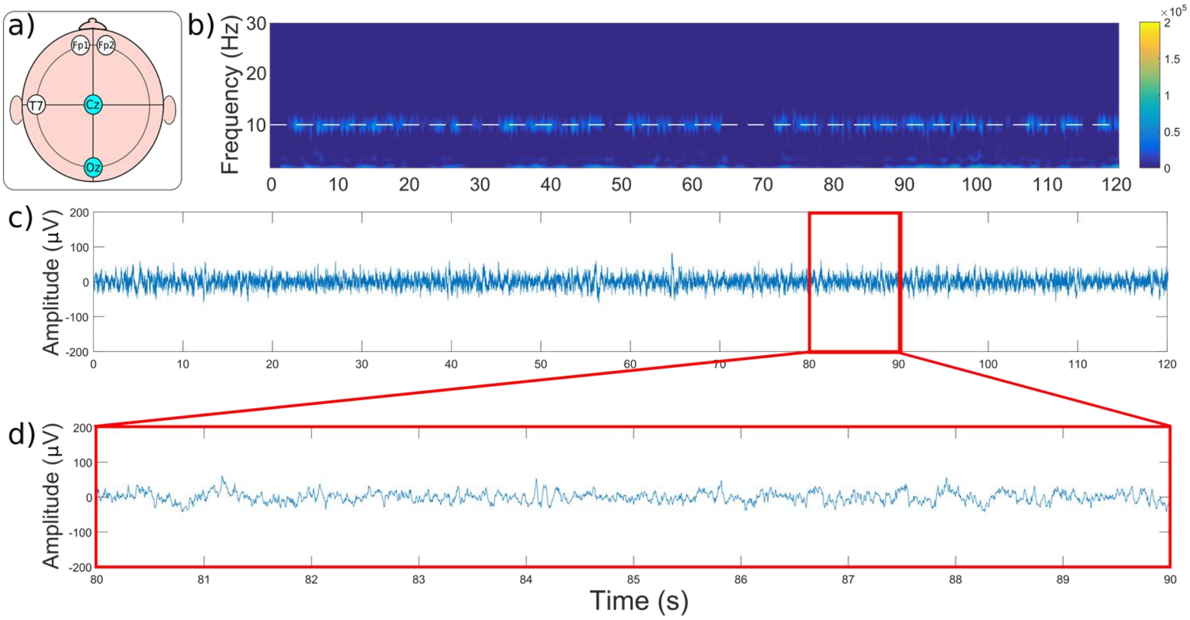
Unipolar signal acquisition with the phantom platform. With the same setup described in the main text, we also recorded unipolar signals, as this is often done in EEG practice (Supplementary Fig.3). Stimulating electrodes sent the same waveforms: the 50 Hz square wave at the left couple of electrodes and the 5 Hz square wave (peak wave) at the right couple of electrodes (Supplementary Fig.3a). The signals shown in Supplementary Fig.3c were acquired from the right Ag/AgCl electrode and two right TTEs that faced the peak wave stimulation (in Supplementary Fig.3b). The two reference electrodes was made of copper, the topmost used for the recording with the Ag/AgCl electrode and the bottom one for the recording with TTEs. This configuration allowed to double the number of recordings from the same area and to compare the signal shape variation in adjacent electrodes in case of the TTEs (Supplementary Fig.3c). The peak source can be clearly identified in case of the TTEs' recordings. The potential distribution over the right couple of Cu electrodes generating the peak signal is realized by sending 2V, with 5 Hz frequency, on the leftmost electrode, while the right electrode is set at 0V. The TTE that recorded the higher signal amplitude was the leftmost one of the couple (the red signal in Supplementary Fig.3b).

Supplementary Figures

Supplementary Fig. 1. Impedance recording using three diverse TTEs. **a** Impedance recording of TTEs made with: two layers of PEDOT:PSS (Tattoo 2L), one layer of PEDOT:PSS (Tattoo 1L), and Au with one PEDOT:PSS layer (Tattoo Au-PEDOT). Recordings in comparison with Ag/AgCl electrode. Insert shows impedance at 0Hz. **b** The three electrodes configuration adopted during impedance recordings. Top: schematization of the experimental set-up, with WE as the working electrode, REF- reference and CE-counter electrodes. Down: pictures of the three TTEs tested as WEs, from left: Tattoo 2L, Tattoo 1L and Tattoo Au-PEDOT. **c** Schematization of the TTE layered structure, developed in case of a flat contact. **d** Top: picture of a TTE placed on the scalp. bottom: 3D rendering of the dedicated clip-like connector.



Supplementary Fig. 2. Alpha-wave recording with TTEs in a clinical environment. **a** Schematic representation of the electrodes location on the head, according to the 10-20 international system, with highlighted Cz-Oz derivation adopted for the alpha waves recording. **b** Time-frequency plot with visible alpha activity at around 10 Hz. **c** EEG recorded for 120s of the alpha wave test (eyes closed). **d** Zoom on the EEG recording, where the typical pattern of alpha waves is well recognized.



Supplementary Fig. 3. Phantom setup in unipolar recordings. **a** Input signals from the bottom stimulating electrodes: the 50 Hz square wave sent to the left electrodes couple (top) and the 5 Hz square wave sent to the right electrodes couple (bottom). **b** The phantom experimental setup. In the bottom view, the stimulating Cu electrodes array, that are placed under the agarose gel. The aligned electrodes are adopted to deliver the signal and the larger 2 are used as reference electrodes. At the bottom, the zoom of two TTEs laminated on the agarose gel. At right (top view), the picture of the phantom with the 2 Ag/AgCl electrodes and 4 TTEs placed for the signal recording. The stimulating electrodes can be seen through the gel **c** Unipolar signal recordings acquired from the electrodes on the phantom surface (indicated by *), coupled with the bottom reference located underneath each type of electrodes. From the top: signal from the right first TTE (*right TTE), signal from the right second TTE (*left TTE), signal from the right Ag/AgCl electrode (*Ag/AgCl).