Research paper

Accuracy of high-density EEG electrode position measurement using an optical scanner compared with the photogrammetry method

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ARTICLE INFO

ABSTRACT

Objective: To determine the feasibility and accuracy of a handheld optical scanner to measure the three-dimensional (3D) EEG electrode coordinates in a high-density array of 256 electrodes.

Methods: We compared the optical scanning with a previously validated method, based on photogrammetry. Electrode coordinates were co-registered with the MRI of the patients, and mean distance error relative to the three-dimensional MRI reconstruction was determined for each patient. We included 60 patients: 30 were measured using the photogrammetry method, and 30 age and gender matched patients were measured with the optical scanner.

Results: Using the optical scanner, the mean distance error was 1.78 mm (95% confidence interval: 1.59–1.98 mm) which was significantly lower ($p < 0.001$) compared with the photogrammetry method (mean distance error: 2.43 mm; 95% confidence interval: 2.28–2.57 mm). The real-time scanning took 5–10 min per patient.

Conclusions: The handheld optical scanner is more accurate and feasible, compared to the photogrammetry method.

Significance: Measuring EEG electrode positions in high-density array, using the optical scanner is suitable for clinical implementation in EEG source imaging for presurgical evaluation.

1. Introduction

Accurate measurement of three-dimensional (3D) electrode position is important for EEG source analysis, because it allows computing the lead-field matrix for the individual head models (Clausner et al., 2017). Recording EEG with a high-density electrode array yields a higher accuracy, as compared with the conventional, low-density array (Brodbeck et al., 2011) regardless of the inverse head model (Song et al., 2015). In the case of a single dipolar source examined with dense-array EEG, an inaccuracy of less than 5 mm is acceptable; the source estimation errors in these cases are negligible (Koessler et al., 2008; Beltrachini et al., 2011). However, measuring the 3D positions of all electrodes in a high-density array can be time-consuming, and may induce inaccuracies.

In recent years various methods have been developed for EEG coordinate localization. Classical studies rely on direct measurement with digital calipers (Le et al., 1998), ultrasound measurements (Echallier et al., 1992), photogrammetry (Baysal and Şengül, 2010; Quian and Sheng 2011), 3D scanning (Homölle and Oostenveld, 2019), electromagnetic digitizers (Dalal et al., 2014; Koessler et al.,2007), and MR- based localization techniques (Koessler et al., 2008). Electromagnetic digitalization has been implemented for more than 30 years for sensor localization. Technically the method is based on a transmitter that generates an electromagnetic field collected by two stylus-shaped receivers. One is fixed, and the other is used to click on each electrode (Dalal et al., 2014; Baysal and Şengül, 2010; Koessler et al., 2011). However, these methods have some disadvantages: environmental sen-

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sitivity, time-consuming procedure, requiring individual localization of each electrode, need for a high-level patient-cooperation (Homölle and Oostenveld, 2019). Photogrammetry (PGM) methods reconstruct 3D coordinates from 2D photos captured at different angles and heights using a triangulation algorithm (Homölle and Oostenveld, 2019). Single (Baysal and Şengül, 2010) or multiple camera settings have been validated (Russell et al., 2005). 3D mesh captured from a single camera setting resulted in significantly fewer errors than the measurements with the electromagnetic digitizer (Clausner et al., 2017; Baysal and Şengül, 2010). The geodesic photogrammetric system (GPS), with multiple cameras on a fixed 3D frame seem to overcome the limitations of the single-camera approach. The 3D coordinates are computed from the statistically most plausible intersection points (Russell et al., 2005). Furthermore, photogrammetry is not as susceptible to electromagnetic interference as the digitizer systems, and the shorter examination time compared to the digitizer is more favourable in less cooperative patients (Quian and Sheng 2011).

Optical scanning is a promising new tool for measurement of EEG electrode 3D coordinates. The scanner's principle operation is based on two diodes that project a crossed light on the target surface and two synchronized cameras that capture the projected image. The obtained three-dimensional point cloud can be used to extrapolate the target object's shape (Taberna et al., 2019). The 3D scanner seemed more effective than manufacturer-provided electrode template models (Homölle and Oostenveld, 2019) and electromagnetic digitizer (Koessler et al., 2011).

Our goal was to compare the accuracy of a commercially available 3D optical scanner (GeoScan Sensor Digitization Device), with the classical, previously validated GPS method, for measuring EEG electrode coordinates, in patients undergoing high-density EEG recordings.

2. Methods

2.1. Subjects, MRI and EEG recordings

We included 60 subjects diagnosed with focal epilepsy, who were referred for high-density EEG recording, as part of their presurgical evaluation. Patients gave their informed consent prior to the recordings. Thirty consecutive patients were measured using the photogrammetry system, and 30 age and gender matched patients were measured using the optical scanner (see 2.2). The high-density EEG array consisted of 256 evenly distributed electrodes on the scalp and cheek (HydroCel GSN, Magstim-EGI, Oregon, USA). The head surface of each patient was reconstructed from 3Tesla MRI scanning (3D T1) using BESA-MRI software (BESA Gmbh, Gräfelfing Germany).

2.2. Measurement of 3D EEG electrode coordinates

For the photogrammetry method, we used the GPS 3.0 sensor digitalization system and GPS solver software (Magstim-EGI, Oregon, USA). Photos were taken from 11 cameras placed on a precision frame (geodesic dome), to instantly record from different angles the 256 EEG electrodes, with the patient places in the centre of the dome (Fig. 1). These were used in the semi-automated post-processing, to construct the 3D position coordinates for the 256 EEG electrodes (Zagorchev et al., 2020).

For the optical scanning method, we used a commercially available, GeoScan Sensor Digitization Device (Magstim-EGI, Oregon, USA). This consisted of a 3D handheld scanner with embedded infrared (IR) light source and two optical sensors. IR light, reflected back by the labels on the EEG electrodes were registered by the two optical sensors on the scanner, which reconstructed their 3D

coordinates in real-time (Fig. 2). The scanning was started at the top of the head, and moved in radial direction. For both methods, the operators had median two years' experience.

2.3. Co-registration and statistics

The 3D electrode coordinates from the photogrammetry system and the optical scanner were co-registered with the reconstructed 3D head surface, using the conventional fiducial points (nasion, left and right pre-auricular points) in the BESA-MRI software (Fig. 3). The distance error between the 3D electrode coordinate and the 3D head surface reconstruction from the MRI was calculated for each electrode, and the mean distance error was determined for each patient. Statistical analysis was performed using TIBC-Statistica software (version 13). Normality of data was assessed using Kolmogorov–Smirnov test. Continuous data was analysed with Student's *t*-test. For non-parametric data we used Wilcoxon matched paired test. We considered statistically significant p values less than 0.05.

3. Results

The photogrammetry group included 11 females and 19 males, mean age of 36.27 years (range 17–68; SD: 13.07). The optical scanner group included 11 females and 19 males, mean age of 33.90 years (range 13–67; SD: 15.07). There was not significant demographic difference between the two groups.

The mean distance error using the photogrammetry method was 2.43 mm (95% confidence interval: 2.28–2.57 mm). Using the optical scanner, the mean distance error was 1.78 mm (95% confidence interval: 1.59–1.98 mm). The difference between the two methods was significant (p < 0.001), the optical scanner being more accurate compared with the photogrammetry system.

4. Discussion

We showed that an optical scanner was more accurate than the previously validated, photogrammetry method, in measuring the 3D coordinates of a high-density EEG electrode array. The method was less time consuming: typically it took 5–10 min to do the scanning and (real-time) reconstruct the 3D coordinates. Due to the long post-processing, the photogrammetry method took much longer time (120–140 min per patient).

EEG source analysis is more accurate when using high-density electrode array, and individual head-models (Brodbeck et al., 2011; Song et al., 2015). To compute the lead-field matrix for the individual head model, the 3D electrode-coordinates are co-registered with the patientś MRI. Therefore, an accurate and feasible method is needed to measure the electrode positions of the patients (Zagorchev et al., 2020). Compared to MEG and fMRI, the lower-priced high-density EEG systems offer a more accessible, non-invasive tool in electical source imaging (ESI) (Kuo et al., 2018).

To the best of our knowledge, this is the first study comparing the sensor positioning accuracy of a 3D handheld optical scanner to photogrammetry in high-density (256 EEG electrode) array. All average error distances were less than 3 mm, i.e. below the acceptable imprecision of 5 mm (Beltrachini et al., 2011). Yet, the accuracy of the optical scanner was significantly higher compared to photogrammetry. It is important to mention here that comparing errors from different studies is especially difficult, because of the different methods used in the studies.

Russell et al. (2005) validated the photogrammetry (GPS) method in a 128 EEG electrode array. They reported accuracy for the GPS localization of 1.27 mm, while the measurement with elec-
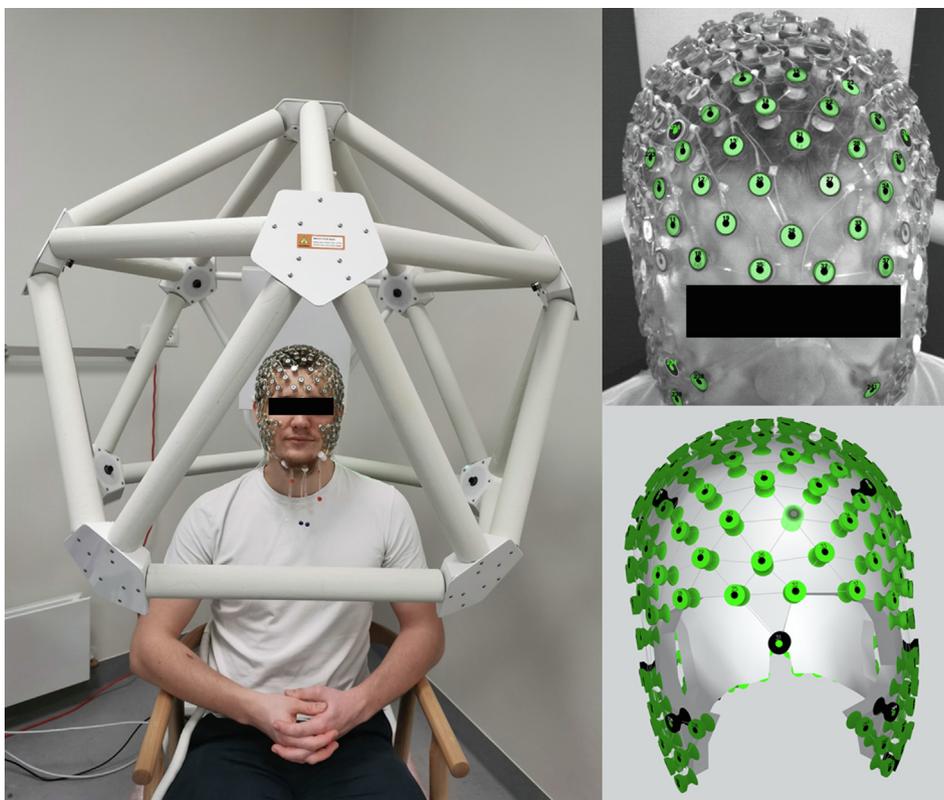
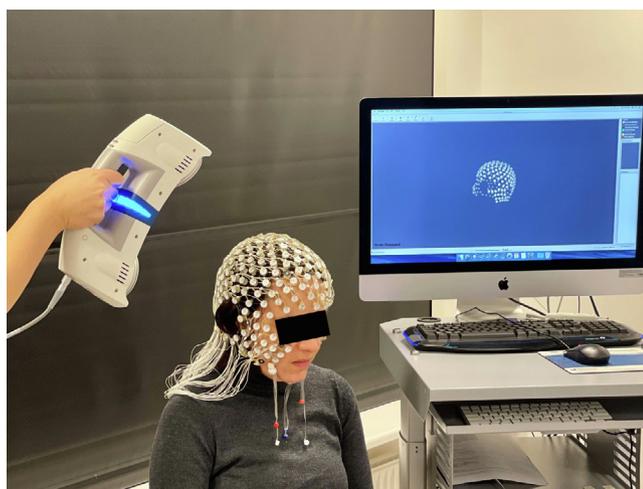**Fig. 1.** Photogrammetry method, using the GPS 3.0 sensor digitalization system and Geosource-3 software.

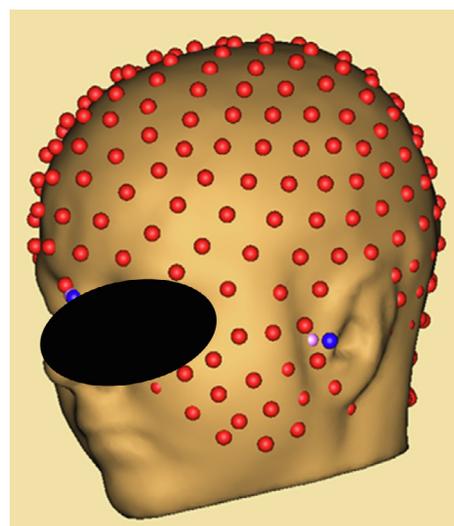**Fig. 2.** Optical scanning method, using the GeoScan Sensor Digitization Device.

Fig. 3. The high-density EEG array (256 electrodes) co-registered with the head-surface of the patient, reconstructed from the 3Tesla MRI scan.

tromagnetic digitizer was somewhat lower (1.02 mm), but the difference was not statistically significant. These accuracy results seem to be numerically better than what we obtained. However, Russell et al. calculated the reference standard values on a spherical object with a known radius, the electrode distances were measured with a digital caliper, while the distance differences between the reference and measured values were expressed as root mean square errors (Russell et al., 2005).

Other studies examining 3D scanning and photogrammetry accuracy rely on different quantitative indices. These pertain to alignment error (AE) and positioning error (PE), defined as the Euclidean distance between the coordinates of the automatically detected electrode positions and their closest points on the MR-

based head shape (AE), or its correspondence in the list of manually detected electrodes (PE) (Taberna et al., 2009; Marino et al., 2016). The localization accuracy applies to the ratio between the number of electrodes with PE below 5 mm in the case of 3D scanning studies (Taberna et al., 2019) or 1 cm in the case of PGM studies (Marino et al., 2016) and the total number of electrodes in the montage.

3D scanning of high-density (128 channel) EEG caps from different manufacturers showed an AE of less than 3 mm: 2.86 mm for HydroCel Geodesic Sensor Net; EGI, 1.91 mm for Waveguard original cap; ANT Neuro, and 2.96 mm for actiCAP; Brain Products

(Taberna et al., 2019). Our results with the optical scanner were more accurate in terms of AE (1.78 mm). In an ESI study, the authors published the photogrammetry data; they used the same 256 array, and found errors between 4.29 mm and 5.31 mm. These differences were significantly larger than our results, which could be explained with a smaller study population, since the measurements represent the data of two participants only (Marino et al., 2016). Similar results (below the recommended limit of 5 mm inaccuracy) can be obtained with MR scanning (Marino et al., 2016).

A possible limitation of our study was that the two methods were applied to different patient groups. However, the two groups were age and gender matched, and it is unlikely that this has influenced the results. Another limitation is that we measured the distance error relative to the 3D head surface reconstruction from the patientś MRI. These reconstructions do not contain the hair of the patients. Although the technicians attempted to remove as much as possible hair between the electrodes and the skin, this was not possible in all cases, which is a potential source of minimal error.

5. Conclusion

The handheld optical scanner provides an accurate 3D measurement of electrode positions in a high-density EEG array, exceeding previously validated photogrammetry methods. Due to its accuracy and feasibility (only 5–10 min per patient), the method is suitable for implementation in clinical practice, for EEG source imaging in presurgical evaluation of patients with drug-resistant focal epilepsy.

Acknowledgements

Conflict of interest

The authors do not have conflicts of interests related to this work.

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