Does cerebral oximetry always measure brain tissue oxygen saturation? An anatomical study utilizing computed tomography

Rotem Naftalovich1,2, Darrick Chyu3, John T. Denny4, Aysha Hasan5, Enrique J. Pantin4
1Medical Corps of the U.S. Army, U.S. Army Medical Department, 3630 Stanley Road, STE 104, Fort Sam Houston, TX, USA 78234, 2Department of Anesthesiology and Perioperative Care, Rutgers - New Jersey Medical School, Medical Science Building, 185 South Orange Avenue Newark, NJ, USA 07103, 3Department of Anesthesiology and Perioperative Medicine, University of Pittsburgh, A-1305 Scaife Hall, 3550 Terrace Street, Pittsburgh, PA, USA 15261, 4Department of Anesthesiology, Rutgers - Robert Wood Johnson Medical School - Rutgers University, Clinical Academic Building, 125 Paterson Street, New Brunswick, NJ, USA 08901, 5Department of Anesthesiology, St. Christopher’s Hospital for Children, 160 East Erie Ave, Philadelphia, PA, USA 19611

Introduction

Continuous real-time monitoring of cerebral oxygenation by noninvasive near-infrared spectroscopy (NIRS)-based cerebral oximetry is increasingly used in neurosurgical, cardiac and vascular surgeries to estimate regional tissue oxygen saturation, rSO2, (sometimes referred to as ScO2, SctO2 or rStO2) by transcutaneous measurement of the cerebral cortex using forehead probes. To do so, these devices utilize the process of spatial resolution via multiple detectors located at different distances from the light emitter.

Abstract

Background and Aims: to quantify the scalp-cortex distance and determine its variation among patients. We hypothesized that in a significant number of patients, this distance is greater than the maximum penetration depth of current cerebral oximeters.

Material and Methods: A retrospective anatomic study using transverse head CT images selected randomly from 102 patients over the age of 18 years without brain swelling, intracranial mass effect, or brain hemorrhage. Scalp-cortex distances were determined at two separate locations along the craniocaudal axis; most cephalad to the frontal sinus (I0) and also 2 cm cephalad to that location (I2). Multiple measurements were obtained bilaterally at 1, 3, 5, 7, and 9 cm from midline.

Results: The average scalp-cortex distance was 14.3 mm and 15 mm at I0 and I2 respectively. Distances varied more in I2 than in I0; from the measurements, 12.8% vs. 6.8% were over 20 mm, 4.4% vs. 2.2% over 25 mm, 1.1% vs. 0.6% over 35 mm and 0.6% vs. none over 40 mm at I2 and I0 respectively. 1.5% of the measurements at I2 were over 30 mm.

Conclusion: Cerebral oximetry manufacturers all claim to measure cerebral tissue up to a depth of 20-25 mm; 20 mm with the EQUANOX and INVOS compared with 25 mm with the FORE-SIGHT. Scalp-cortex distance is within 25 mm in more than 95% of patients. However, even with the probe placed as per the manufacturer’s recommendations, in a small but significant subset of patients, this distance is greater than the maximum penetration depth of current cerebral oximeters and hence may not reflect actual brain tissue oxygen saturation.

Keywords: Brain, cerebral oximeters, cortex, depth, distance, scalp

Access this article online

Quick Response Code: Website: www.joacp.org DOI: 10.4103/JOACP_395_19

How to cite this article: Naftalovich R, Chyu D, Denny JT, Hasan A, Pantin EJ. Does cerebral oximetry always measure brain tissue oxygen saturation? An anatomical study utilizing computed tomography. J Anaesthesiol Clin Pharmacol 2021;37:537-41.

Submitted: 23-Nov-2019 Revised: 06-Mar-2020
Accepted: 14-Mar-2020 Published: 06-Jan-2022
underlining idea is that a longer distance between the light emitter and the detector leads to deeper tissue assessment. Given the multiple detectors, an automated algorithm can then subtract the more superficial reading (i.e., the shorter distance between the light emitter and detector) from the deeper one. Regardless of their proprietary algorithms and calibration, the major cerebral oximetry manufacturers all claim to measure cerebral tissue up to a maximum depth in the range of 20–25 mm (~50% of the emitter-detector distance); 20 mm with the EQUANOX\textsuperscript{11} (Nonin Medical Inc; Plymouth, MN, USA) and INVOS (Covidien; Boulder, CO, USA)\textsuperscript{21} compared with 25 mm with the FORE-SIGHT\textsuperscript{33} (CAS Medical Systems Inc; Brandford, CT, USA). If the scalp-cortex distance, i.e., depth of the brain, is greater than the maximum detection depth of the device then the rSO\textsubscript{2} reading would be inaccurate.

Anatomical variations among patients\textsuperscript{4,5}, particularly those relating to the distance between the brain cortex and the skin are clinically important to understand since their knowledge can directly guide proper and better use of brain monitors. For example, variations in skull and scalp thickness have numerous effects on electroencephalography (EEG) and magnetoencephalography (MEG) monitoring.\textsuperscript{5,6} Skull thickness varies greatly\textsuperscript{7,11}, the thickness of the frontal bone measured by histology from cadaver samples ranged from 5.05–8.13 mm in a study of 7 patients.\textsuperscript{12} Similarly, cerebrospinal fluid (CSF) volume varies among patients and appears to be influenced by age likely due to brain tissue atrophy.\textsuperscript{13} Given that variations exist among the population in each of the major anatomical components that make up the scalp-cortex distance, it is, therefore, reasonable to assume that the distance between the scalp and the brain also varies among patients. However, quantification of this distance is not available in the literature.

This study aimed to quantify the distance between the cortex and the scalp and determine its variation among patients. We did this retrospectively using brain computed tomography (CT) imaging.

**Material and Methods**

Trigonometric corrections have been applied to imaging in previous studies to more accurately infer actual anatomic size\textsuperscript{14,15} and are even used to make preoperative corrections for guiding orthopedic surgery.\textsuperscript{16,17} Because the forehead lies obliquely relative to the standard axial imaging plane, CT measurements of brain depth need to be trigonometrically corrected [Figure 1] to more accurately reflect brain depth. The oximeter probe lays flush to the skin on the forehead, i.e., in the plane tangential to the forehead skin and emits light in the plane perpendicular to it.

After approval from the Rutgers Health Sciences Institutional Review Board, data were collected from 102 head CTs selected randomly from the institution’s radiology database of CT images taken after October 2012 and their accompanying official final reads from the radiologists. CT was chosen because it is the gold standard for structural evaluation of the cranium.\textsuperscript{5} The only inclusion criteria was age of at least 18 years. We excluded patients with a history of cerebral edema, intracranial mass effect, intracranial hemorrhage, or head trauma.

For each patient, transverse scalp-cortex distances ($d$) were determined at two separate locations along the craniocaudal axis; the first location being the most cephalad aspect of the frontal sinus ($I_0$) and the second ($I_2$) being 2 cm cephalad to $I_0$. The scalp location on the $I_0$ transverse plane is superior to the eye-brow landmark and roughly correlates to the cerebral oximeter probe location whereby $I_0$ would represent a high placement of the oximeter probe as may occur if it is used concurrently with a Bispectral Index (BIS) monitor or with a Mayfield skull clamp. Since the thickness of the calvarium varies at different points,\textsuperscript{18} multiple measurements were obtained at both the $I_0$ and $I_2$ levels. To do this, we used the imaging software measuring tool and measured $d$ bilaterally at the scalp locations of 1, 3, 5, 7, and 9 cm from midline which was defined by the falx cerebri [Figure 2]. The transverse CT slice thickness (i.e. the distance along the craniocaudal axis between consecutive CT images) was 2 mm. To determine $\Theta$, the consecutive cephalad image was utilized whereby the 2 mm distance represented the segment adjacent to $\Theta$ on a triangle laying in the coronal plane with a hypotenuse being the segment connecting $I_0$ scalp point with the scalp point of
the next consecutive cephalad image. The distance of this hypotenuse segment was measured (the software enables the user to connect points laying on different planes using the mouse cursor; in this case consecutive image slices) and $\Theta$ was then calculated from the equation $\cos \Theta = \frac{adjacent}{hypotenuse}$. The above process for computing $\Theta$ was repeated for each of the measurements at 1, 3, 5, 7, and 9 cm bilaterally. The entire process described above was then repeated for $I_2$.

After all the $d$ and $\Theta$ values were obtained, the respective $d'$ for each was then calculated using the equation $\cos \Theta = \frac{adjacent}{hypotenuse}$. The parameter of interest, $d'$, does not represent the scalp-cortex distance along the $I_0$ or $I_2$ planes (that distance is $d$ which is an overestimation of the true distance) but rather the orthogonal distance from the scalp on those planes to the point on the cortex of the consecutive cephalic image.

### Results

On average the patients studied were 64 years of age (18–94), 165.7 cm (132.1–195.6) tall, and weighed 78.42 kg (26–185.8). The average orthogonal scalp-cortex distance was 14.3 mm and 15 mm at $I_0$ and $I_2$, respectively. These orthogonal scalp-cortex distances varied more in $I_2$ than in $I_0$; from the measurements, 12.8% vs. 6.8% were over 20 mm, 4.4% vs. 2.2% over 25 mm, 1.1% vs. 0.6% over 35 mm and 0.6% vs. none over 40 mm in $I_2$ and $I_0$, respectively. Of note, 1.5% of the measurements at $I_2$ were over 30 mm.

If the trigonometric correction is not applied (i.e. examining $d$ instead of $d'$), 9.5% of measurements at $I_0$ were over 20 mm and 2.3% of them over 25 mm. At $I_2$, 21% were over 20 mm and 8.7% over 25 mm when uncorrected.

### Discussion

This anatomical variance in brain depth likely contributes to the lack of consensus and the poorly defined role that cerebral oximetry devices currently have in cardiovascular and neurosurgical anesthesia.\[19\] Furthermore, this variation in brain depth is expected to contribute to the varying error magnitude observed among subjects with all of the available cerebral oximeters.\[20\] The above results indicate that in a significant number of patients, their brain lays deeper than the maximum detection depth of the device. This is particularly the case with the EQUANOX and INVOS and if the probe is placed higher on the forehead. Consequently, we recommend a lower placement of the probe. This is important to consider in elderly patients who may have brain atrophy.

A slight difference in brain depth can mean that the brain tissue is deeper than the maximum depth detected by the device and hence the rSO$_2$ reading is not measuring cortex oxygenation in which case the anesthesiologist would be under the impression that the monitor reading reflects brain tissue oxygenation when in fact it does not. This is a clinical problem and identification of the subset of patients for which the rSO$_2$ reading is not indeed rSO$_2$ may be of interest. Some would incline to believe that the incidence of false rSO$_2$ reading is lower than the ~5% incidence where the brain tissue is deeper than the maximum depth detected by the device (2.2–6.8% with the probe placed slightly above the eyebrow). Regardless, a false rSO$_2$ may very well go unnoticed by the clinician.

Even though the study excluded patients with a history of cerebral edema, intracranial mass effect, intracranial hemorrhage, or head trauma, it did not investigate the medical record extensively to identify medical conditions that could lead to calvarial thickening. For example, calvarial thickening can occur in chronic ventricular shunting, acromegaly, in chronic antiepileptic use such as with phenytoin, in hyperparathyroidism, Paget’s disease and even with anemia. We do not believe that the typical user of these devices would routinely evaluate such conditions in their decision of whether or not to use the device. Our opinion is based on the fact that the INVOS manual published by Covidien claims no contraindications for the use of their cerebral oximeters (e.g. Operations Manual INVOS® System, Model 5100C).

Another limitation of this purely retrospective anatomic study is that we did not correlate the anatomical variation of brain depth with rSO$_2$. Such correlation can be done in a prospective study of patients undergoing perioperative cerebral oximetry monitoring with preoperative CTs and should take...
into consideration hemoglobin concentration, the thickness of the CSF layer, and other factors affecting brain tissue saturation. An even more ideal imaging modality would be a high-resolution 3D reconstruction in which case trigonometric correction would not be needed.

Light can only travel in a straight line, with angles for reflections and refractions. Even though the device emits light perpendicularly to the skin, the light path is not perpendicular to the skin throughout since the receiver is located on the forehead, lateral to the emitter. Therefore, at least some of the light penetrates the brain tissue at an angle. The brain surface is not a smooth sphere but rather rugged due to gyri and sulci, the effects of this on the device readings are difficult to predict due to certain properties of the light such as scattering and a non-collimated beam.

We only quantified total scalp-cortex distance. The effect of anatomical variations on $rSO_2$ readings is complicated by light beam refraction which occurs as photons travels across different mediums (e.g., skin-bone or CSF-brain tissue). As a result, it is not solely the linear distance between the probe and the cortex that matters but also the proportion of each medium from the total distance. Nonetheless, in patients where the brain cortex lays deeper than the maximum detection depth of the cerebral oximeter, total depth, as opposed to the proportion of each medium, is a more critical factor to the device efficacy.

The decision to use cerebral oximetry depends on the surgical case involved, clinical judgment, and clinician preference. Broadly speaking, it is used in elderly patients with neurovascular disease or stroke risk. We did not select for such patients in our study. As a result, the group of patients we studied differs from the population of patients who typically undergo surgery with cerebral oximetry but it is a fair representative sample. The average age of our patients was 64 years which is lower than the average age of patients in these surgeries; 68.8 years for cardiovascular surgery patients in Germany and over 70 years for CABG patients in the USA. Furthermore, the age distribution of our patients was likely wider than those undergoing surgery. Given the normal cerebral atrophy associated with age, it is hence reasonably possible that patients undergoing cardiovascular surgery are older than our studied population, have more brain atrophy and hence their scalp-cortex distances are even larger than our results.

We anticipate that $rSO_2$ readings, or errors, would vary whether the probe is placed at the recommended location above the eyebrow vs. on the eyebrow itself. Moreover, $rSO_2$ readings would be more accurate if the probe is placed on the eyebrow but we did not measure the scalp-cortex distance at the eyebrow, nor did we study the effect of eyebrow hair on the device light.

Our findings show that the anatomical scalp to cortex distance is within 25 mm in more than 95% of patients; i.e., the scalp-cortex distance is greater than the maximum penetration depth of current devices in less than 5% of patients. This distance is larger when measured higher on the forehead, 2 cm above the cephalad edge of the frontal sinus, as compared to at the cephalad aspect of the sinus. Such higher forehead placement is likely to decrease the accuracy of the device, at least in a subset of patients with deeper brains. It appears that, even with probe placement as per the manufacturer’s recommendations, in a small subset of patients the cerebral oximeter reading may not reflect actual brain tissue oxygen saturation.

**Acknowledgments**

We thank the Department of Anesthesiology of Rutgers, Robert Wood Johnson Medical School for supporting this study.

**Financial support and sponsorship**

Nil.

**Conflicts of interest**

There are no conflicts of interest.

**References**

1. Frequently Asked Questions on EQUANOX Cerebral Oximeter.
2. Radak D, Sotirovic V, Obradovic M, Isenovic ER. Practical use of near-infrared spectroscopy in carotid surgery. Angiology 2014;65:769-72.
3. Frequently Asked Questions on FORE-SIGHT® Cerebral Oximeter.
4. Todd TW, Kuenzel W. The Thick-of the Scalp. J Anat 1924;58:231-49.
5. Hagemann D, Hewig J, Walter C, Naumann E. Skull thickness and magnitude of EEG alpha activity. Clin Neurophysiol 2008;119:1271-80.
6. Cuffin BN. Effects of local variations in skull and scalp thickness on EEG's and MEG's. IEEE Trans Biomed Eng 1993;40:42-8.
7. Boruah S, Paskoff GR, Shender BS, Subit DL, Salzar RS, Crandall JR. Variation of bone layer thicknesses and trabecular volume fraction in the adult male human calvarium. Bone 2015;77:120-34.
8. Federspil PA, Tretbar SH, Bohlen FH, Rohde S, Glaser S, Plinkert PK. Measurement of skull bone thickness for bone-anchored hearing aids: An experimental study comparing both a novel ultrasound system (SonoPointer) and computed tomographic scanning to mechanical measurements. Otol Neurotol 2010;31:440-6.
9. Moreira-Gonzalez A, Papay FE, Zins JE. Calvarial thickness and its relation to cranial bone harvest. Plast Reconstr Surg 2006;117:1964-71.
10. Arntsne T, Kjaer I, Sonnesen L. Skull thickness in patients with skeletal Class II and Class III malocclusions. Orthod Craniofac Res 2008;11:229-34.
11. Ross MD, Lee KA, Castle WM. Skull thickness of Black and White races. S Afr Med J 1976;50:635-8.
12. Ruan J, Prasad P. The effects of skull thickness variations on...
human head dynamic impact responses. Stapp Car Crash J 2001;45:395-414.

13. Blatter DD, Bigler ED, Gale SD, Johnson SC, Anderson CV, Burnett BM, et al. Quantitative volumetric analysis of brain MR: Normative database spanning 5 decades of life. AJNR Am J Neuroradiol 1995;16:241-51.

14. Maguire P, Siclari M, Lesser A. Femoral imaging artifacts associated with dorsal recumbency craniocaudal radiographic positioning. Description of a modified bisecting angle technique. Vet Comp Orthop Traumatol 2014;27:288-96.

15. Dymond IW, Ashforth JA, Dymond GF, Spirakis T, Learmonth ID. The usage of image trigonometry in bone measurements. Hip Int 2013;23:590-5.

16. Berjano P, Cecchinato R, Damilano M, Morselli C, Sansone V, Lamartina C. Preoperative calculation of the necessary correction in sagittal imbalance surgery: Validation of three predictive methods. Eur Spine J 2013;22(Suppl 6):S847-52.

17. Aurouer N, Obeid I, Gille O, Pointillart V, Vital JM. Computerized preoperative planning for correction of sagittal deformity of the spine. Surg Radiol Anat 2009;31:781-92.

18. Okada E, Delpy DT. Near-infrared light propagation in an adult head model. II. Effect of superficial tissue thickness on the sensitivity of the near-infrared spectroscopy signal. Appl Opt 2003;42:2915-22.

19. Zacharias DG, Lilly K, Shaw CL, Pirundini P, Rizzo RJ, Body SC, et al. Survey of the clinical assessment and utility of near-infrared cerebral oximetry in cardiac surgery. J Cardiothorac Vasc Anesth 2014;28:308-16.

20. Bickler PE, Feiner JR, Rollins MD. Factors affecting the performance of 5 cerebral oximeters during hypoxia in healthy volunteers. Anesth Analg 2013;117:813-23.

21. Yoshitani K, Kawaguchi M, Miura N, Okuno T, Kanoda T, Ohnishi Y, et al. Effects of hemoglobin concentration, skull thickness, and the area of the cerebrospinal fluid layer on near-infrared spectroscopy measurements. Anesthesiology 2007;106:458-62.

22. Nicolini F, Agostinelli A, Vezzani A, Manca T, Benassi F, Molardi A, et al. The evolution of cardiovascular surgery in elderly patient: A review of current options and outcomes. Biomed Res Int 2014;2014:736298.

23. Puskas JD, Thourani VH, Marshall JJ, Dempsey SJ, Steiner MA, Sammons BH, et al. Clinical outcomes, angiographic patency, and resource utilization in 200 consecutive off-pump coronary bypass patients. Ann Thorac Surg 2001;71:1477-83.

24. Akiyama H, Meyer JS, Mortel KE, Terayama Y, Thornby JI, Konno S. Normal human aging: Factors contributing to cerebral atrophy. J Neurol Sci 1997;152:39-49.