Intra- and post-operative monitoring of deep brain implants using transcranial ultrasound

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Summary Transcranial sonography (TCS) of the brain parenchyma meanwhile allows a high-resolution imaging of deep brain structures in the majority of adults. A new application of TCS is the intra- and post-operative visualization with TCS and the TCS-assisted insertion of deep brain stimulation (DBS) electrodes. In pilot studies it has been shown that the TCS-assisted insertion of DBS electrodes into the subthalamic nucleus and the globus pallidus interna is feasible and safe provided the exact knowledge on the extent of electrode TCS imaging artifacts. Even more, TCS can be recommended for the post-operative monitoring of DBS electrode position. Dislocation of a DBS electrode can be easily detected. In a recent longitudinal study we could demonstrate that TCS measures of lead coordinates agreed with MRI measures in anterior—posterior and medial—lateral axis, and that the TCS-based grading of optimal vs suboptimal lead location predicts the clinical 12 months outcome of patients with movement disorders. Currently, an international multi-center study is being planned to further prove the value of TCS in the post-operative monitoring of DBS electrode position. This trial is intended to start in 2012, and is still open for joining. The obvious advantages of TCS will promote its increasing use for the intra- and post-operative monitoring of deep brain implants.

Introduction

Transcranial B-mode sonography (TCS) of the brain parenchyma and the intracranial ventricular system has been performed in children already in the 80s and 90s of the last century [1,2]. Also, the guidance of programming a shunt valve system in the treatment of a fluctuating child hydrocephalus has been shown to be well possible with TCS [3].

In adults, the TCS imaging conditions are much more difficult than in children because of the thickening of temporal bones with increasing age [4]. Nevertheless, due to the technological advances of the past decades a high-resolution imaging of deep brain structures is meanwhile possible even in the majority of adults [5,6]. Present-day TCS systems can achieve a higher image resolution in comparison not only to former-generation systems, but currently also to MRI under clinical conditions [7]. A sophisticated clinical high-end TCS system was shown to gain an in-plane image resolution of intracranial structures in the focal zone of about 0.7 mm × 1.1 mm [7]. With the type of phased-array probes usually applied for TCS in adults, using a center frequency of 2.0—3.5 MHz, the focal zone of maximum resolution is in a distance of 5—7 (4—8) cm from the contact plane of the probe. This means that the best quality images of intracranial structures are obtained in deep brain areas near the midline.
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This opens a new field of TCS application, the intra-operative assistance of deep brain implant placement and the post-operative monitoring of brain implant position. The present paper reviews the current literature and the experience of our lab in the application of TCS for the localization of deep brain stimulation (DBS) electrodes in patients with movement disorders.

TCS imaging artifacts and safety issues

Intracranial devices containing metal parts such as DBS electrodes cause several imaging artifacts on TCS due to their high echogenicity. First, due to poorer lateral image resolution compared to axial image resolution, the DBS electrode appears more extended in lateral direction than in axial direction. Second, reverberation artifacts are generated behind the DBS electrode (Fig. 1). We have performed human skull phantom studies, applying the TCS system Acuson Antares (Siemens; Erlangen, Germany) [8–10]. In lateral direction of insonation, usually applied to monitor DBS electrode depth intra- and post-operatively, the highly echogenic imaging artefact of the metal part of the DBS lead used for globus pallidus interna (GPI) stimulation in dystonia exceeded the 1 mm rubber tip by minimum 0.1 mm (range, 0.1–1.5 mm, depending on image brightness). In axial direction of insonation, the imaging artifact exceeding the real boundary of the DBS lead was smaller (range, 0.3–0.6 mm; resulting seeming DBS lead diameter, 1.9–2.5 mm, depending on image brightness; real diameter, 1.27 mm) [8,10]. It should be stressed that, before any application of TCS for intra-operative guiding the positioning of DBS lead in patients, the sizes of imaging artifacts need to be estimated separately for each different ultrasound system and each different DBS lead type to account for differences of imaging technologies and lead shape [9].

Using a skull phantom, it was also investigated whether the insonation of intracranially located DBS electrodes might be associated with a heating of the electrode. A constant temperature of the intracranial DBS lead was found when exposed to TCS or transcranial color-coded sonography (TCCS) for 30 min each with ultrasound frequencies of 2.0, 2.5, or 3.1 MHz (ultrasound intensity: mechanical index 1.4) [8]. Therefore it is unlikely that a heating of DBS electrodes occurs during TCS application, considering also the effective heat transfer within the brain due to the intense blood perfusion of the brain [9].

TCS for intra-operative implant monitoring

While a considerable number of studies have dealt with the intra-operative application of sonography in patients with open cranium [11–15], applications of intra-operative TCS have been rarely described. White et al. reported on preliminary findings using a novel intra-operative brain-shift monitor using shear-mode transcranial ultrasound [16]. Despite the advantages of ultrasound in an intra-operative setting compared to other imaging methods [9], such as high temporal resolution, portability, and non-ionizing mode of radiation, the application of commercially available TCS systems for intra-operative monitoring of DBS electrode placement has been reported only rarely so far.

One early study applied a former-generation TCS system (Sonoline Elegra, Siemens; Erlangen, Germany) during implantation of DBS electrodes into the targeted subthalamic nucleus (STN) in patients with Parkinson’s disease [17]. The authors reported an easy visualization of the 0.8 mm thick electrode. The position of the imaging artefact of the tip of the DBS electrode appeared to be within in the anatomic region of substantia nigra that usually is of high echogenicity in patients with Parkinson’s disease. Additionally, the segment of the laterally running posterior cerebral artery at the corresponding level could also be displayed. The authors found the appearing correct position of the DBS electrode tip on TCS at a place just touching the echo-signals of the substantia nigra. The results of this pilot study were limited by the poorer lateral image resolution of the TCS system applied compared to contemporary TCS systems [7], and the missing estimation of the exact size of the electrode imaging artefacts which caused some uncertainty with regard to the exact electrode tip position.

In a more recent study, a contemporary TCS system (Acuson Antares, Siemens; Erlangen, Germany) was applied intra-operatively to monitor the placement of DBS electrode into the GPI in patients with idiopathic dystonia [8]. In this study not only the visualization of the final DBS electrodes was possible but also the simultaneous visualization of 2–5 closely located microelectrodes used for detection of the optimal trajectory of the final electrode (Fig. 2A). Another advantage of the intra-operative TCS monitoring was that the distance of the DBS electrode tip to the artery at the anatomic target (penetrating branch of the posterior communicating artery) could be assessed (Fig. 2B).
Figure 2  Transcranial sonography (TCS) images of deep brain stimulation (DBS) electrodes obtained during stereotactic implantation. (A) Position of the TCS probe (P) placed at the temporal plane of the patient's head (H). (B) Coronal TCS image of the patient's head. T indicates thalamus; M, midbrain. Two closely located microelectrodes (arrows) of 0.5 mm diameter are visualized in the target region. The inserted panel in the left lower corner shows a photograph of a microelectrode. (C) Coronal TCS image showing the tip of the final DBS lead (white arrow) and its distance to the perforating branch (black arrow) of the posterior communicating artery. The midbrain and thalami are surrounded for better recognition. The inserted panel in the left lower corner shows a photograph of the DBS lead.

This was possible since the extent of the imaging artefact of the electrode had been estimated in advance for the referring TCS system and implant [8]. This even enabled intra-operatively the decision to insert the final DBS electrode somewhat deeper than it would have been done using only the pre-operatively planned navigation data [8]. Simultaneous visualization of the artery at the anatomic target prevented hemorrhages at the target site.

The possibility to intra-operatively optimize the electrode position is of high interest since discrepancies of up to several millimeters between the initial target, selected on pre-operative MRI, and the final DBS lead location are caused mainly by caudal brain shift that occurs after opening the dura [16,18]. Intra-operative MRI may be an option to overcome this discrepancy but is expensive and not widely available [19]. The higher mobility and temporal resolution achieved with TCS may promote an increasing use for the intra-operative guidance of deep brain implant placement [9].

TCS for post-operative localization of implants

Despite advances in stereotactic pre-operative MRI techniques [20], there are discrepancies of up to 4 mm (average 2 mm) between the initial selected target and the final DBS lead location caused mainly by caudal brain shift that occurs once the cranium is open [18]. Moreover, the DBS lead may get displaced post-operatively, e.g. by delayed brain shift or head injury [21,22]. Therefore, poor post-operative outcome or unexpected change in neurological state requires brain imaging to check the lead location. Computed tomography (CT) is frequently used for this purpose but has the disadvantages of patient’s exposure to radiation and considerable imaging artifacts caused by the metal tip of the electrodes. On the other hand, performing MRI in patients with neurostimulators may be associated with several risks such as heating of electrodes, magnetic field interactions, functional device disruption, and induced electrical current, which might lead to irreversible tissue damage [23]. Therefore, head MRI in DBS patients was recommended to be performed only if a number of technical restrictions and guidelines were followed. Provided sufficient imaging conditions (sufficient bone window, contemporary high-end ultrasound system), TCS may be a good alternative for the post-operative monitoring of the DBS electrode location. Compared to the intra-operative setting, it is even easier to localize DBS electrodes post-operatively on TCS since the patients and the investigator are in a much more comfortable setting. Especially, there is less constriction in finding the optimal temporal acoustic bone in order to achieve high-quality brain images. Measuring electrodes as well as DBS electrodes were easily identified at different targets [9,10,24,25]. Typical aspects of DBS electrodes targeting the pars ventralis intermedius (VIM) of the thalamus and the STN are shown in Fig. 3. It is recommendable to define some landmarks that can be used as reference points for estimating the exact position of the DBS electrode tip. Typical measures are the shortest distance of the electrode tip from the midline and/or the outer boundary of the third ventricle (VIM, GPI, STN), the distance of the electrode tip from the pineal gland (VIM, GPI), and the position of the electrode in relation to highly echogenic neighboring structures such as the internal capsule (VIM, GPI) and the substantia nigra (STN).
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Figure 3  Transcranial sonography (TCS) images obtained for the post-operative control of deep brain stimulation (DBS) electrode position in two patients. (A) Semi-coronal TCS scan through the brain of a patient with severe essential tremor in whom DBS bilaterally of the nucleus ventralis intermedius (VIM) of the thalamus was performed. The thalami are surrounded for better recognition. The lead tips of the bilateral DBS electrodes are visualized in the right and the left thalamus (virtual tip position: arrows; true tip position: arrow heads). FH denotes frontal horn of lateral ventricle, P, pineal gland, T, thalamus. (B) Axial (transverse) TCS scan in a patient with Parkinson’s disease in whom DBS bilaterally of the subthalamic nucleus (STN) was performed. The midbrain and the bilateral markedly echogenic (“hyperechogenic”) substantia nigra are surrounded for better recognition. Considering the lower lateral than axial image resolution on TCS, the real position of the lead tips of the bilateral DBS electrodes is exactly within the STN (arrow heads), even though on the TCS image the virtual lead tip is within the substantia nigra (arrows).

We have recently proposed criteria for grading optimum vs suboptimum DBS electrode position for the DBS targets VIM, GPI and STN [10].

In our experience, the detection of slight differences of 2 mm and more between right- and left-sided electrode with respect to their distance to midline, but also in their rostro-caudal position, is possible with TCS [10]. Electrode dislocation can easily be diagnosed with TCS [9].

Conclusions and outlook

The results of the studies published so far [8—10,17,24,25] support the use of TCS for the monitoring of intracranial electrode position. It can be expected that the obvious advantages of TCS in comparison to other neuroimaging methods, such as high mobility, short investigation times, non-invasiveness and less corruption by patients movements, will further promote the use of TCS for the intra- and post-operative monitoring of deep brain implants, especially in patients with movement disorders [9]. The major current limitation of TCS application is, beside its dependence on the quality of transtemporal acoustic bone windows, the necessity of a highly qualified investigator. The investigator performing intra-operative TCS for guiding therapeutic decisions needs to be well trained beforehand in the pre- and post-operative routine setting [9]. Moreover, the applied TCS system as well as the assessed brain implant should be studied in advance for the exact size of their imaging artifacts using a skull phantom as described earlier [8,10].

The upcoming technologies allowing the in-time fusion of intra- and post-operative TCS images with pre-operative MRI images may facilitate an easier and less investigator-dependent application of intra-operative TCS.

Currently, an international multi-center study is being planned to further prove the value of TCS in the post-operative monitoring of STN DBS electrode position which is intended to start in summer 2012. Centers with both, experience in TCS and DBS, are invited to join this trial. For more details regarding this study, interested colleagues may contact the author of this article via email.

References


