Correction for the Oblique Focus in MR-Guided Focused Ultrasound for the Treatment of Essential Tremor

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Introduction

Magnetic resonance guided focused ultrasound (MRgFUS) has shown promising results in the treatment of essential tremor[1,2]. MR-based targeting and temperature monitoring ensured precise lesioning of the ventral intermediate nucleus (VIM) in the thalamus. However, although the centres of VIM were precisely targeted, oblique lesion volumes angled to the main acoustic axes were observed in our initial patients, with the two most severe ones close to 45 degrees in the coronal plane. In this study, we investigated the reason for this oblique focus, reproduced results in a skull phantom, and demonstrated solutions for correcting the obliqueness using MR thermometry.

Methods

Six patients with medication-refractory essential tremor have been treated with a MRgFUS brain system (ExAblate 4000, 650kHz central frequency, Insightec, Tirat Carmel, Israel) and a 3 T MR scanner (MR750, GE Healthcare, Milwaukee, WI, USA). To reproduce the oblique focus observed in the patient treatment (Fig.1), a skull was filled with milk-agar based phantom[3] and positioned similarly as in the patient treatment. MR thermometry was applied in three orthogonal dimensions separately to visualize the obliqueness of the focal volume (TR 27.6 ms, TE 12.8 ms, slice thickness 3 mm, FOV 28cm, 256x128, temporal resolution 3.5s).By default, the acoustic power from each transducer element was calculated by the 'Uniform Intensity on the Skull Surface' (UIS) algorithm. This power distribution was intended to evenly distribute acoustic power over the skull surface, thereby minimizing local skull heating. Then the acoustic power from each element was assigned by customized algorithms investigating different power contribution and the corresponding focal obliqueness. The algorithms include uniform intensity on transducers, and various degrees of inversion of the default UIS algorithm.

Results

The oblique focal volume was reproduced in the skull phantom in the coronal plane (Fig.2). No obliqueness was observed in the sagittal and axial planes. Since the VIM target was positioned close to the geometric focus of the FUS array, the head was off-centre in the left-right dimension relative to the array. Therefore, the obliqueness was in the left-right dimension and always angled towards the side closer to the skull. The equal distribution of power on transducers (Fig.3a) did reduce the obliqueness, but did not completely remove it. With 50% inversion (Fig.3b) and 100% inversion (Fig.3c) of the UIS algorithm, the obliqueness was further reduced, as shown in MR thermometry.

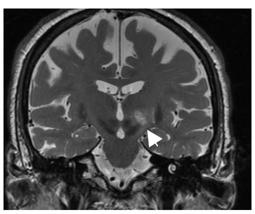

Fig.1 Day 1 follow-up T2 image showing oblique lesion volume in the coronal plane. Acoustic axis was in the vertical direction.

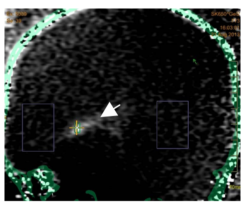

Fig.2 MR thermometry image showing oblique focal volume in the skull phantom with the default power algorithm: uniform intensity on the skull surface (UIS).

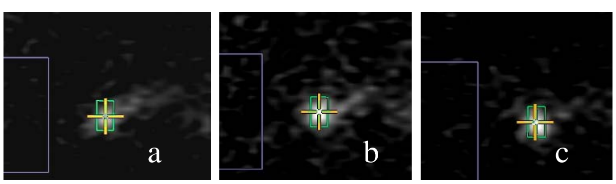

Fig.3 MR thermometry images showing power algorithms for correcting the oblique focus: a) uniform intensity on transducers; b) 50% inversion of the default UIS; c) 100% inversion of the UIS. The obliqueness was reduced compared to Fig.2.

Discussion

The VIM target is close to the lateral edge of the thalamus. Therefore, an oblique focus poses the risk of extending the lesion into the internal capsule fibers. In the clinical trial, because the head was positioned asymmetric in the left-right dimension relative to the FUS array, the power from the transducer elements was unequal in the left-right dimension caused by the UIS algorithm to evenly distribute skull heating. However, this results asymmetric power deposition at the focus.

With equal power from transducers, the obliqueness was reduced, but was not completely removed. We suspect this was caused by higher reflection of acoustic power by the skull at the side further from the focus due to higher incident angles. The significance was related to the shape and position of the skull. Furthermore, in the case when electronic steering of the acoustic beam is necessary, the off-axis power levels from transducer elements also cause a power asymmetry at the focus.

With 100% inversion of the default UIS algorithm, i.e. the transducer elements with lower power levels under UIS were modulated proportionally higher, and vice versa, the obliqueness was removed based on MR thermometry. However, this inversion may cause higher skull heating at the skull closer to the focus. The magnitude of skull heating will be investigated through phantom studies and computer simulations. Computer simulation may provide more information since skull heating is difficult to measure over a large volume in a skull phantom.

In the patient treatment, we expect that there will be a practical tradeoff between the obliqueness of the focus and the feeling of pain by the patient due to the skull heating. Therefore, MR thermometry images, especially at the coronal plane, are important to visualize the focal volume at low to medium power levels. These sonications below the thermal damage threshold can then be used to adjust the power distribution to achieve a desired focal spot orientation.

References

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