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COMPARISON OF TRANSCRANIAL FOCUSED ULTRASOUND (TFUS) AND TRANSCRANIAL PULSED STIMULATION (TPS) FOR NEUROMODULATION: A COMPUTATIONAL STUDY

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Abstract
The objective of the study was to investigate transcranial wave propagation through two low-intensity focused ultrasound (LIFU) techniques e transcranial Focused Ultrasound Stimulation (tFUS) and Transcranial Pulse Stimulation (TPS). While tFUS involves delivering long trains of acoustic pulses, the newly introduced TPS delivers ultrashort (~3 ms) pulses repeated at 4 Hz. Only a single simulation study with limited geometry currently exists for TPS.We considered a high resolution 3-D whole human head model in addition to water bath simulations. We anticipate that the results of this study will help researchers investigating LIFU to have a better understanding of the effects of the two different techniques.
With an objective to first reproduce prior computational results, we considered two spherical shaped tFUS transducers previously modeled. We assumed identical parameters (geometry, position, imaging dataset) to demonstrate differences purely due to the waveform considered. For the image-derived head models, we also considered a parabolic transducer as is common in TPS.
Our initial results successfully verified a prior modeling workflow. The tFUS distribution was characterized by the typical elliptical profile with its major axis perpendicular to the face of the transducer. The TPS distribution resembled two mirrored meniscus profiles with its widest diameter oriented parallel to the face of the transducer. The observed intensity value differences were theoretical as the two waveforms differ in both intensity and time. The consideration of a realistic 3-D human head model resulted in only minor distortion of the two waveforms.
This study simulated TPS administration using a 3D realistic image-derived dataset for the first time. While our comparison results are strictly limited to the model parameters and assumptions made, we were able to elucidate some clear differences between the two approaches. We hope this initial study will pave the way for systematic comparison between the two approaches in the future.
Keywords: transcranial focused ultrasound, transcranial pulse stimulation, human head model, numerical simulation

Comparison of Transcranial Focused Ultrasound and Transcranial Pulse Stimulation for Neuromodulation: A Computational Study

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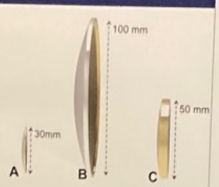
Introduction

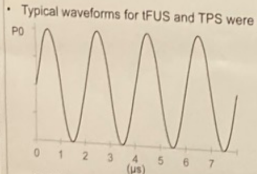
The objective of the study was to investigate transcranial wave propagation through two low-intensity focused ultrasound (LIFU) techniques – transcranial Focused Ultrasound Stimulation (tFUS) and Transcranial Pulse Stimulation (TPS). While tFUS involves delivering long trains of acoustic pulses, the newly introduced TPS delivers ultrashort (~3 µs) pulses repeated at 4 Hz. Only a single simulation study with limited geometry currently exists for TPS. We considered a high resolution 3-D whole human head model in addition to water bath simulations. We anticipate that the results of this study will help researchers investigating LIFU to have a better understanding of the effects of the two different techniques.

Methods

- With an objective to first reproduce prior computational results, we considered two spherical shaped tFUS transducers **(A, B)** previously modeled.
- We assumed identical parameters (geometry, position, imaging dataset) to demonstrate differences purely due to the waveform considered.
- For the image-derived head models, we also considered a parabolic transducer **(C)** as is common in TPS.



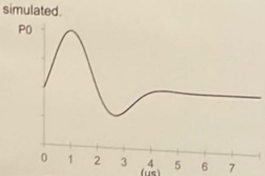
- Typical waveforms for tFUS and TPS were simulated.



tFUS Input parameters:

$P_0 \sin 2\pi f t$

$f = 500\ kHz$



TPS Input parameters:

$P_0\, e^{-\left(\frac{t-1/(4f)}{\sigma}\right)^2} \sin 2\pi f t$

$f = 250\ kHz$

$\sigma = 2\ \mu s$

- An image-derived model of the human head was simulated using tissue-specific material properties.

Material	Speed of Sound ($m\ s^{-1}$)	Density ($kg\ m^{-3}$)	Attenuation coefficient ($Np\ m^{-1}\ MHz^{-1}$)	Non-Linearity Parameter (B/A)
Skin	1624	1109	10.579	4.96*
Muscle	1588	1090	3.356	7.166
Blood	1578	1050	1.143	6.1125
Fat	1440	911	2.053	10.0712
Skull	2814	1908	27.2765	4.96*
CSF	1483	1000	0.025	4.96*
Air/Sinus	343	1.16	0.00979	4.96*
Brain	1546	1046	2.76	6.7
Water	1482	994	0.0126642	4.96

*estimated like water.

- The Westervelt-Lighthill Equation was solved using an FDTD toolbox (Sim4Life) resulting in pressure as a function of time. Intensity was calculated from pressure.

Discussion

Our initial results successfully verified a prior modeling workflow. The tFUS distribution was characterized by the typical elliptical profile with its major axis perpendicular to the face of the transducer. The TPS distribution resembled two mirrored meniscus profiles with its widest diameter oriented parallel to the face of the transducer. The observed intensity value differences were theoretical as the two waveforms differ in both intensity and time. The consideration of a realistic 3-D human head model resulted in only minor distortion of the two waveforms.

This study simulated TPS administration using a 3D realistic image-derived dataset for the first time. While our comparison results are strictly limited to the model parameters and assumptions made, we were able to elucidate some clear differences between the two approaches. We hope this initial study will pave the way for systematic comparison between the two approaches in the future.

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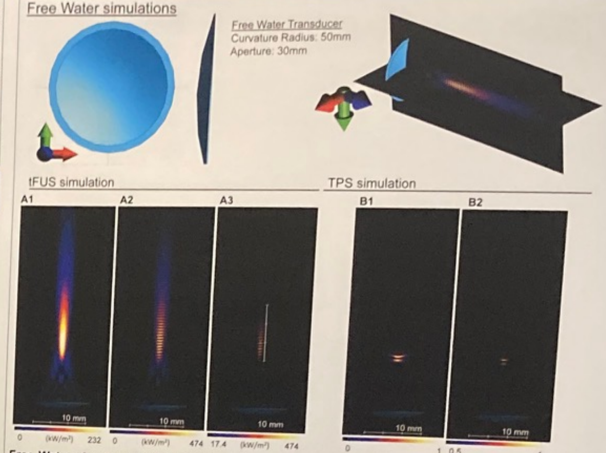
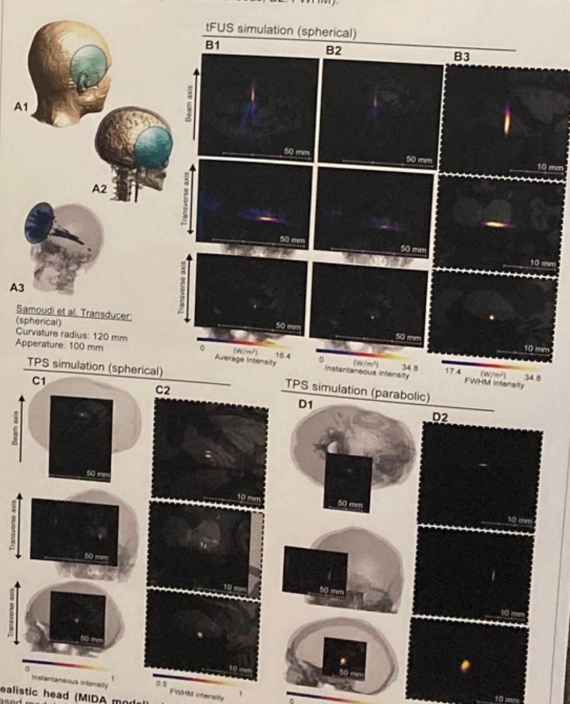
Results



Free Water simulations. 3D simulation of acoustic intensity sampled at the YZ plane through the focal point at the temporal peak. Both tFUS and TPS employed the same spherical head model transducer. A) tFUS intensity distributions in the YZ plane (A1: Average; A2: Instantaneous; A3: FWHM) B) TPS intensity distributions in the YZ plane (B1: Instantaneous; B2: FWHM).



Realistic head (MIDA model) simulations. A1) depicts transducer location with respect to the MIDA based model. A2) The scalp and skull tissues are made semi-transparent to reveal underlying brain tissue. A3) Beam profile for tFUS B) Axial, coronal, and sagittal view of tFUS intensity (B1: Average; B2: Instantaneous; B3: FWHM). C) TPS simulation using the same spherical SEFT as used in tFUS (C1: Instantaneous; C2: FWHM). D) TPS simulation using transducer specific to its delivery (D1: Instantaneous; D2: FWHM). Similar to the free water simulations, TPS plots are normalized as the driving function used was originally calibrated on a more complex multi-part model of a specific size transducer. The TPS data therefore only illustrate spatial and depth profile. Representative cross-section plots included here correspond to the location of maximum induced intensity.