CONVERGENCE TESTING OF A K-SPACE PSEUDOSPECTRAL SCHEME FOR TRANSCRANIAL TIME-REVERSAL FOCUSING

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Introduction

Ultrasound can be applied directly to the brain through the skull for non-invasive therapeutic applications. High intensity focus ultrasound was recently FDA approved for the treatment of essential tremor by ablation of the thalamus [1]. Meanwhile, novel low intensity applications such as neurostimulation and opening the blood brain barrier (BBB) with ultrasound are under active research [2],[3]. However, the skull forms a major obstacle to the effective transcranial transmission of ultrasound. The high sound speed, density and acoustic absorption of bone relative to soft tissue leads to aberration and attenuation of incident waves. This prevents effective focusing and can lead to heating of the skull and damage to surrounding tissue [4].

Time-reversal focusing is a non-invasive method of focusing ultrasound through the skull. It uses simulations of ultrasound propagation from a target in the brain to a virtual ultrasound array. The signals recorded at the transducer surface are then time-reversed, and used to derive drive signals for transcranial ultrasonic therapy [4]. The effectiveness of simulated time-reversal is directly related to the accuracy of the numerical scheme used. This can be affected by a number of factors, the most fundamental being the numerical accuracy of the scheme used to solve the acoustic wave equation.

Clinical software often makes use of ray tracing algorithms to calculate phase shifts. However, more advanced full-wave models have been used and shown to give improved performance [5]. These schemes are numerically convergent, meaning that desired accuracy can be achieved with sufficiently fine spatial and/or temporal sampling, dependent on the scheme.

In the present work, convergence testing was carried out on a model of simulated time-reversal using a model of the skull and a hemispherical transducer. The spatial and temporal sampling criteria required for different errors in refocusing quality to converge were measured. These results will help ensure simulation accuracy in future studies of numerical ultrasound propagation.

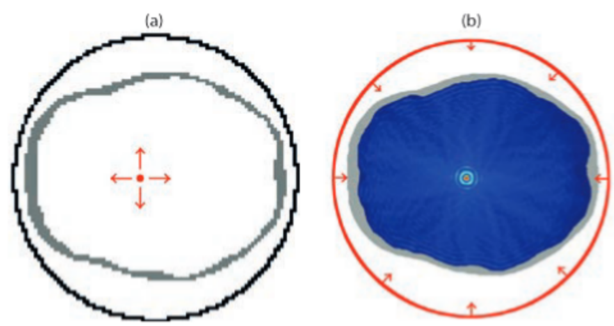

Figure 1.
Convergence testing setup. (a) Forward simulation at low spatial sampling (b) Reversal simulation at high spatial sampling. Source terms are shown in red.

Results and Methods

Numerical convergence testing was carried out for a model of transcranial propagation from a hemispherical transducer, through the skull to a deep brain target. Simulations modelling the propagation of ultrasound from the deep brain to a hemispherical virtual transducer were carried out using variable spatial and temporal discretisation, measured in points per wavelength (PPW). The simulation layout is shown in Figure 1.

Simulations were carried out using the OpenMP version of the open source k-Wave toolbox [6]. The toolbox includes a pseudospectral time-domain (PSTD) scheme with optional correction for the time-domain simulation of acoustic fields. This PSTD method approximates the spatially varying acoustic variables via discrete Fourier transform. This allows the efficient and accurate computation of spatial derivatives.

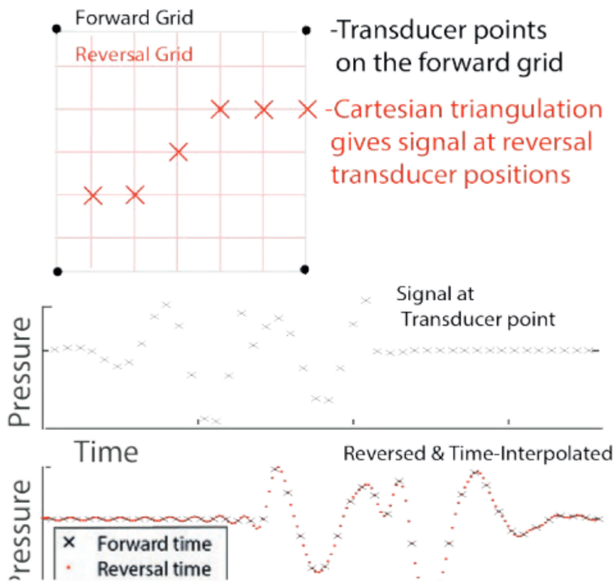

Figure 2.
Spatial and temporal interpolation of time-varying signals as part of the time-reversal process.

The field is then updated in a time stepping manner. However, as with most numerical methods, this approach can cause discretisation errors related to numerical dispersion, misrepresentation of medium discontinuities, and staircasing of medium geometries.

In each simulation the skull was mapped as a homogeneous layer based on a parametric mesh derived from a segmented MRI image. A parametric mesh was used to ensure consistency between schemes with different spatial sampling. The skull was assigned a density of 1,990 kg/m^3 and a sound speed of 3,200 m/s. The rest of the simulated domain was assigned the acoustic properties of water.

The signals recorded at the transducer surface were spatially and temporally interpolated, time reversed, and then used as the source term for high resolution reversal simulations. The interpolation step is outlined in Figure 2. Due to the large size of the simulation time-series data (~100 GB) and the memory required to interpolate this data in space and time, the interpolation step was carried out on the UCL Legion computing cluster, on a Dell 2U R820 32 core system with 1.5 TB of RAM.

The reversal simulations were then carried out, and the peak positive pressure field was recorded across the brain volume to evaluate focusing effectiveness. The metrics assessed were the peak spatial pressure amplitude and position, and the -3 dB focal volume. Simulations were carried out on the IT4Innovations Salomon supercomputing cluster. Each simulation was carried out on one node equipped with an 8-core Intel Xeon E5-4627v2@ 3.3GHz CPU, and 256GB of RAM. The largest simulations, used in the reversal step, had a domain size of 1,024^3 grid points and 22,718 time steps, with a total runtime of 112.3 hours. Checkpoint-restart was used to enable the running of sufficiently long simulations. Forward simulations that could not be carried out on a workstation were also run with these computation resources. In total, approximately 105,000 core-hours were consumed.

The resulting dependence of refocusing quality on the spatial sampling of the forward simulations is shown in Figure 3. It demonstrates that > 10 PPW are required to ensure convergence across all metrics, especially for peak pressure reconstruction.

However both -3 dB focal volume, and the position of the peak pressure are less dependent on spatial sampling, with positioning having no dependence. This means that for applications where fine control over the pressure amplitude is less important, coarser forward simulations may suffice.

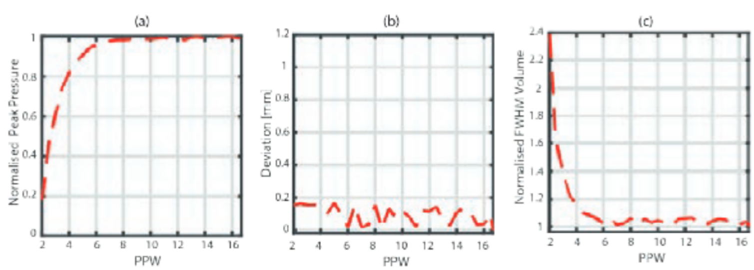

Figure 3.
Results of convergence testing in 3D.
(a) Convergence rate of peak pressure across the brain
(b) Convergence of the spatial position of the peak pressure
(c) Convergence of the -3 DB volume of the focus.

On-going Research / Outlook

This work forms part of a larger body of work relating to accurate simulation of transcranial ultrasound propagation for both time-reversal focusing and the prediction of intracranial fields. The developing applications of ultrasonic neuro-stimulation and opening the BBB are likely to require fine control of ultrasound at the target. Now that the spatial and temporal sampling criteria required to ensure numerical accuracy have been established, further simulation studies can be carried out to examine other sources of error. The next potential source of error arises from the mapping of medium properties. Future work will focus on determining the relative impact of different errors in medium geometry and acoustic properties, and the impact of modelling internal skull heterogeneities in more detail.

Conclusion

The results indicated that 10 spatial points per wavelength are required to ensure numerical convergence when using the k-space corrected PSTD scheme. The field parameter most affected by the numerical accuracy of the forward simulation is reconstruction of the peak pressure at the target, followed by the -3 dB focal volume. Spatial targeting was not significantly affected, indicating that coarse spatial sampling may suffice for certain applications. These results are of immediate relevance for anyone attempting to simulate the transcranial propagation of ultrasound. Confidence in the numerical accuracy of simulations will allow methods for the effective transcranial focusing of ultrasound to advance. Accurate prediction of intracranial fields will also be achievable with sufficient numerical accuracy, which will allow poorly understood phenomena such as neurostimulation to develop.

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