ECHOBRAIN: Aberration correction in transcranial ultrasonic imaging using CT data and simulation-based focusing algorithms

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ABSTRACT

The improvement of the quality of brain ultrasonography requires accounting for the strong attenuation and deformation of the ultrasonic wave during its crossing. The Total Focusing Method (TFM) algorithm exploits a direct model of beam propagation through 3D complex surfaces in order to simulate and correct the resulting phase aberrations. We illustrate the potential of this adaptive imaging technique on several examples of brain ultrasonography performed on a human skull. The real geometry, used as input data, is obtained by a CT scan realized on the skull associated to a fusion tool available on an ultrafast ultrasound device.

Brain ultrasonography; Total Focusing Method (TFM); Adaptive imaging; Ultrafast ultrasound imaging

1. INTRODUCTION

In US imaging, the access to real-time monitoring of brain parenchyma or brain vasculature could be a major breakthrough in first emergency units or for the monitoring of rehabilitation patients in hospitals. The example of stroke can present the interest of such general research. In France, every year 130,000 people suffer from stroke, which can be ischemic or hemorrhagic. It is essential to distinguish as soon as possible its origin since time is a key factor to protect brain and since ischemia and hemorrhages require radically different treatments. X-rays and MRI brain imaging are the diagnosis techniques currently used but are not easily applicable in the emergency field. In this context, echography presents intrinsic advantages for emergency diagnosis, as it is a more flexible and less expensive ambulatory modality, which could be brought into the vehicle carrying the patient. Likewise, in intensive care units, patients are monitored mainly after surgery and the access to X-rays or MRI for such patients can be very complicated. Beyond early or continuous diagnosis, improvement of US brain imaging could be of great interest for neuroscience.

This project aims to create a breakthrough in the field of brain imaging by innovating in transcranial ultrasound (US) imaging. Such breakthrough will significantly improve the understanding of brain pathologies, brain trauma and physician diagnosis. The aim is to counteract US aberration that are caused by the human skull and that distort brain images. To do this, we have adapted the simulation-based imaging tools developed by CEA-LIST for Non-Destructive Testing (NDT) applications, that is able to calculate and to compensate for the effects of aberration in complex media. Adapted to the skull, it will significantly improve the resolution of the image by maintaining the focusing of US in both emission and reception. The corollary of this approach is that we have a precise knowledge of the patient's skull geometry in front of the imaging probe. This description will be provided by a previously acquired 3D CT scan of the patient. This adaptation is complementary of the imaging approach developed by BIOMAPS.

Full Matrix Capture (FMC) acquisitions on several targets has been performed through an *ex vivo* human skull with an ultrafast fully programmable US device. Knowing the positioning of the probe according to the 3D CT, TFM images with skull aberration correction has been realized and highlight significant improvements in terms of sensitivity, resolution and positioning.

2. STATE OF THE ART

The complex structure of the skull bone, reflected in particular by spatial variations in thickness and density, leads to a strong spatial and inter-individual heterogeneity of its acoustic properties. The crossing of the skull bone leads to a strong attenuation as well defocusing and shifting of the beam.

Correction of these aberrations can be achieved using a phased-array wide-aperture transducer. Delay laws (phase conjugation for harmonic signals), combined or not with amplitude correction [1-3] can then be applied to the different channels to compensate the deformation of the wavefront during skull crossing and thus to maintain optimal focus in the desired area. Time reversal [4] or inverse filter techniques [5] are very powerful to determine the proper phase delays, but remain invasive because they require control points, typically probes, in the area to be imaged. Models of acoustic wave propagation, using a description of the morphology of the skull obtained by computed tomography (CT) [6] or magnetic resonance imaging (MRI) [7] can be used to compute these aberration corrections in a non-invasive way.

For the past two decades, CEA-LIST (partner 1) has been developing the Non-Destructive Testing (NDT) expertise platform CIVA, including simulation and advanced imaging tools for phased-array ultrasonic techniques. The last includes the Total Focusing Method (TFM) [8] and the Plane Wave Imaging (PWI) [9], which significantly improve NDT imaging in complex configurations, including very attenuating media [10]. Using a Dynamic Ray-Tracing (DRT) model [11], the propagation of elastodynamic waves in 3D complex structures, considering refractions and reflections at different interfaces, with possible mode conversions, are performed in a very fast way compared to full numeric methods.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The global objective of ECHOBRAIN was to adapt the imaging tools developed by CEA-LIST for NDT applications to compensate for the effects of aberration of the skull and significantly improve the quality of brain ultrasonography, knowing the geometry and acoustic properties of the patient's skull in front of the imaging probe. During this first step, a first proof of feasibility has been performed. In particular, we have shown that a very simplified description of the skull bone by means of a homogeneous and isotropic medium making it possible to correct in large part the effects of phase aberration and thus to significantly improve the quality of the images in terms of signal to noise ratio and resolution.

Such homogenization of the skull nevertheless requires defining an average speed. However, the cranial wall is made up of three layers, the outer two being made up of cortical bone, the middle one being made up of trabecular bone. The speeds in these media being quite different, the homogenization can only be local since the speed of the homogeneous medium depends on the relative thickness of these three layers. In order to simplify this homogenization procedure, we have chosen to define the speed from an image quality optimization procedure, the objective function being the maximization of the maximum amplitude of a reference echo. The speed search range is defined by the speeds in the two bone types. This optimization procedure is currently applied by hand but could quickly be automated by means of various known algorithms.

Tab. 1. Comparative performance of Ultrasound with our technology, MRI and CT-scan for transcranial imaging.

Modality	Ultrasound	MRI	CT-scan
Time resolution	Real-time	~10s	~1-2s
Spatial resolution	0.2 mm	2-3 mm	1 mm
Imaging depth	1-5 cm	Full brain	Full brain
Non-invasive	Yes	Yes	Radiative
Availability	Yes	Moderate	Moderate

This simplified description of the propagation medium makes possible to use very fast ultrasonic field propagation simulation codes, based on a ray formalism. The code currently used could be specialized and optimized for this application in order to envisage very fast brain ultrasonography.

On the long term, based on adaptive imaging methods developed for NDT applications at CEA-LIST [13], a completely autonomous imaging system, free from morphological data provided by other imaging modalities (MRI or CT-scan), could be envisaged. It should be able to measure the geometry and the acoustical properties of the skull, to simulate the effects of the aberrations and finally to compensate for them by adaptation of phase and amplitude laws. Virtually, all brain diseases could benefit from this improvement. The societal impact could therefore be significant. Comparison between modalities are presented in table 1.

4. PROJECT RESULTS

The experimental validations have been performed with a programmable ultrafast ultrasound device Aixplorer^{TM} (Supersonic Imagine, Aix en provence, France) on an *ex vivo* human skull immersed in a water tank. The acquisitions were carried out with a linear array (SL10-2, Supersonic Imagine, table 2). The probe and the targets are placed on either side of the skull, the first being in contact. (Fig 1). A fusion device was integrated into the Aixplorer^{TM} device, to visualize the bone layer in front of the probe, previously acquired with CT scan (Fig. 1).

FMC acquisitions consists in recording a set of NxN elementary signals $S_{ij}(t)$, where (i, j) is a transmit and receive element combination, $1 \leq i,j \leq N$.

TFM is an advanced post-processing imaging algorithm allowing ultrasonic array data visualization in 2D and 3D. It ensures a coherent summation of all acquired data inevery point of a given area to be imaged [8]. Mathematically this can be expressed as:

$$I(P) = \sum_{i,j=1}^{N} S_{ij}\left[t_{ij}(P)\right] \qquad (1)$$

where $t_{ij}(P)$ denotes the theoretical Time Of Flight (TOF) corresponding to the propagation time between the i-th transmitter and the j-th receiver, through the point P.

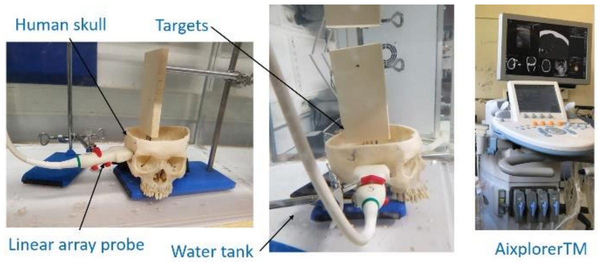

Fig. 1. Description of the acquisition set-up. The fusion device to mix ultrasound images and CT scan in real-time is presented on the Aixplorer^{TM} device screen.

Tab. 2. Probe features

Number of elements	192
Central frequency	6 MHz
Pitch	0.2 mm
Element width	0.16 mm
Element elevation	14 mm

TFM imaging is implemented in the CIVA software and can be performed using several propagation modes, including longitudinal or transverse waves. For heterogeneous tissues, the theoretical TOF in (1) are obtained from a computation of the ultrasonic field transmitted at each point of the image, including refraction at each interface, using a DRT model.

In the first validation, the targets consist in 4 misaligned metal rods of different diameter (1,5 to 3 mm). To obtain a reference, a first acquisition without any obstacle between the probe and the targets has been performed. In the second acquisition, the skull was interposed between the probe and the targets, the latter remaining in the same position. Exploiting this data, two images can be reconstructed. In the first one, no aberration correction is applied since TOF are computed considering a propagation only in the water. In the second one, TOF are computed considering the propagation through the skull whose geometry and positioning are known. The skull medium is considered as homogeneous and isotropic, the velocity, 2200 m/s, being selected to optimize the image quality.

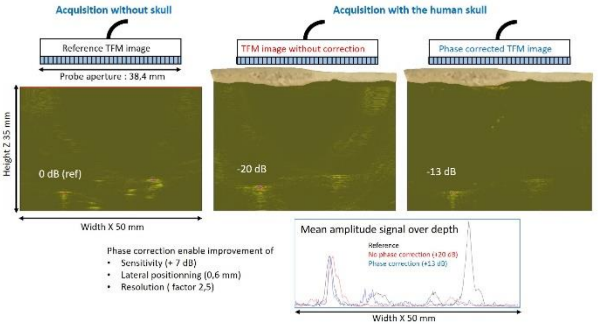

Fig. 2. Experimental results on a set of metal rods.

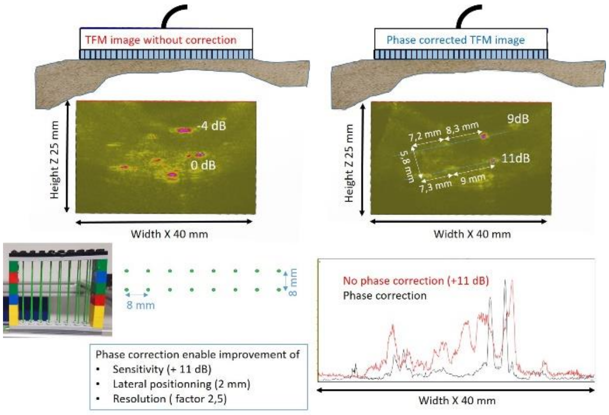

Fig. 3. Experimental results on a matrix of nylon threads.

Compared to the reference image, if we focus on the most significant target, without aberration correction, we observe a loss of sensitivity of about 20 dB and a lateral positioning error of 0.6 mm. The aberration correction applied on the same data enable a 7 dB increase in sensitivity and a correction of the lateral positioning.

The remaining 13 dB sensitivity loss are mainly due to the loss of the transmitted acoustic energy at both interfaces on the skull bone and cannot be recovered. Finally, a reduction of a 2.5 ratio of the lateral dimension of the echoes is observed on the echodynamic curve, corresponding to a significant improvement of the lateral resolution.

A second acquisition has been performed with a set of 1 mm in diameter nylon threads, arranged in a matrix with a pitch of 8 mm (Fig. 3). Only one acquisition has been realized. The TFM images obtained with and without aberration have been compared (Fig 3). The six targets located in front of the probe can be imaged in both cases but the correction of the aberrations enables a significant improvement of the image quality. In this case, a 2810 m/s velocity has been applied.

An increase of 11 dB of the sensitivity and an improvement of the resolution by a factor of 2.5 are obtained. The targets are located on two parallel lines 5.8 mm apart, instead of 8 mm. This is due to a disorientation of the matrix according to the imaging plane. The distance between two adjacent targets on a same line is close to 8 mm.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The main steps required for scaling our Technology Readiness Level (TRL) are as follows:

- Improvement of the numerical performances of the TFM code to obtain a fast imaging tool.

Based on a recent algorithm providing a fast-ultrasonic field computation that yields nearly interactive results for complex cases [14], this optimization phase could be considered through fine algorithm tuning, extended SIMD instructions usage and GPU (Graphic Processor Unit) implementations of some highly parallel and computationally intensive parts of the process.

- Implementation of an automatic procedure for homogenization of the propagation speed in the skull. Several methods, such as Particle Swarm Optimization (PSO) or genetic algorithms will be studied, the cost function being based on the quality of the reconstructed image.

- *In vivo* validations on patients for whom a CT or MRI image is available.

- Development of an iterative method for extracting the internal and external profiles of the skull facing the probe. This algorithm will be based on recent adaptive TFM methods developed at CEA-LIST for NDT applications [13]. In a first step, considering linear probes, 1D profiles will be extracted. In the longer term, in the case of a matrix probes, 2D surfaces extraction will be considered. The validation will be obtained by comparison of the profiles extracted with ultrasonic procedure to those obtained from CT or MRI data.

- *Ex vivo* and *in vivo* validation of the complete autonomous imaging system.

5.2. Project Synergies and Outreach

The consortium will be reinforced by application to common grant associating two new partners: The company Supersonic Imaging (Aix en provence , France) that developpe the Aixplorer^{TM} device used in our study. Their participation to the consortium will allow us to directly implement in the system our development and should paves the way if success, to a commercial output of our technology. The second partner will be IBrain laboratory from Tours university at Tours Hospital (France), that works specifically on ultrasound for brain and will allow us to directly work on patient during preclinical and clinical studies. By adding these two partners we should be able to reach at least TRL6.

For the dissemination of our results in phase 2 we propose to report every two months our development, and especially report our published articles and patents filled. We also be attached to provide you highlight that can be publicly displayed to show advances in our project.

5.3. Technology application and demonstration cases

An ultrafast ultrasound device prototype integrating our technology will be developed to directly go in preclinical and clinical applications. Such device will pave the way to increase physician interest for the monitoring of brain pathologies that should of a high societal challenge. Moreover a showroom proposed every year in July (Digihall days, http://www.digihall.fr/) by our partner (CEA) will present our technology to a large community of researchers and industries. Regarding scientific research this will of high interest since it will give access to a quasi-real-time technology that will allow to investigate brain function and beyond clinical and emergency applications, reach neuroscience. The industry will be also benefit since a company will integrate this in its device and will recruit people to produce, developed and market our technology into a commercial product.

5.4. Technology commercialization

By adding to our partnership, the company that developed the ultrafast ultrasound device that we use, a direct commercial partner of our technology is then possible. By reaching TRL 7 or 8 paves the way to increase greatly their interest. We have begun to discuss with them about our technology.

5.5. Envisioned risks

The core risks that our project will face are:

- Optimization of the TFM method insufficient to consider "real time" imaging. Adaptive image interpolation algorithms could be developed to accelerate the image formation process. The principle would be to gradually refine the TOF calculation mesh only in areas with significant gradients.

- Difficulty of convergence of the automatic propagation speed optimization. In this case, "manual" optimization of the image quality by means of a cursor controlled by the operator could be considered.

- The main difficulty of the project lies in defining a robust, fast and reliable algorithm for extracting the profiles of the skull facing the probe. Image processing algorithms comparable to those developed for NDT, will first be evaluated to extract the real profiles. If the performance turns out to be insufficient, a simplified parametric description of the surfaces, requiring the extraction of a limited number of parameters, could be considered. The optimization of these geometrical parameters could be part of the homogenization procedure of the skull properties.

5.6. Liaison with Student Teams and Socio-Economic Study

In our future partnership, master students will be involved to provide ideas that could inspire us to address Societal Challenges. Sylvain Chatillon, our partner from CEA will be fully involved in this action. Our consortium granted by two new partners (Supersonic Imagine, Tours hospital) and students (Postdoc, Ph. D., MSc.) will be in direct link with the expert that will drive the socio-economics study. This expert will have access to the latest developments, technical meeting, budget meetings and will participate to the market study.

6. ACKNOWLEDGEMENT

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