# HIGH RESOLUTION ULTRASONIC BRAIN IMAGING: ADAPTIVE FOCUSING BASED ON TWIN-ARRAYS

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# ABSTRACT

Transcranial imaging of the brain is currently limited by the defocusing effect of the skull bone (absorption, diffusion and refraction of ultrasounds. A brief review of the various techniques developed in the last decades to correct the aberrations induced by the skull bone is first presented. A noninvasive brain imaging device is presented that takes into account the defocusing effect of the skull. This device is made of two identical "twin" linear arrays located on each side of the head. It is shown how to differentiate the respective influence of the two bone windows on the path of an ultrasonic wave going from one array to the other, and how to estimate at each frequency the attenuation and phase shift locally induced by each of the bone windows. This information is then used to perform adaptive focusing through the skull Compared to uncorrected wave fronts, the spatial shift of the focal point is cancelled, the width of the focal spot is reduced, and sidelobes level is decreased up to 10dB. Simulated structural transcranial images of a brain model are presented to exhibit the improvement in image quality provided by this new noninvasive adaptive focusing method.

# **1. INTRODUCTION**

Commercial ultrasonic scanners assume constant acoustical properties in the tissues. Transcranial ultrasonic brain imaging on adults is limited by the inhomogeneous aberrating effect of the skull bone [1-3]. In order to improve transcranial brain imaging, adaptive focusing methods have to be developed. Time-shift has been first investigated to compensate phase aberrations [4,5]. But the skull bone is inducing both phase and amplitude aberrations and both need to be corrected. For this purpose, several methods have been successively developed : time reversal [6], dynamic focusing [7,8], and the spatio temporal inverse filter (STIF) [9-11]. However, those techniques require the presence of active sources in the focal plane and thus cannot be used directly for medical imaging.

In this paper a noninvasive extension of the STIF technique is presented. Focusing improvement and image quality enhancement are demonstrated on reconstructed images of cyst models.

## 2. DEFOCUSING EFFECT OF THE SKULLBONE

In order to illustrate the defocusing effect of the skull bone, the following experiment is done: a sagitally cut human skull is located between two identical linear arrays of 128 ultrasonic transducers. The setup is immersed in water. The central frequency of the arrays is 1.5 MHz with a 50% bandwidth.



A prefocused cylindrical wave front calculated to focus on the center of the receiving array in the absence of skull, is emitted from array 1. The resulting signals in focal plane are recorded by the receiving array (fig. 1, left) after propagation through the skull. Pressure amplitudes in focal plane are plotted in a dB scale on figure 1 (right) when focusing through water (a), and through the skull (b): in presence of the skull, the maximum of the pressure is shifted relatively to the targeted point, the main lobe is wider than in water, with high secondary lobes. This focal spot degradation will lead to image distortion and resolution and contrast lowering.

In order to correct for the amplitude and phase aberration, one can achieve a time reversal experiment coupled with amplitude compensation [6-8]: an impulse is emitted by the central element of array 2. After propagation through the skull, the wavefront is recorded on array 1. The signals are then time-reversal, amplitude compensated and reemitted by array 1. The corresponding focusing pattern is plotted in Fig. 2 (c). The focusing quality is improved but not optimum: such a method would perfectly correct the aberrations if the skull bone was infinitely thin. In order to take this into account, one has to use a set of control points in the focal plane as will be explained in the following section.



Figure 2. Defocusing effect of the skull: Left : cylindrical wavefront, and the resulting focusing through skull (instantaneous image of the acoustical pressure; bright zones correspond to high pressures, dark zones to low ones). Right: scan of the temporal maxima of pressure in focal plan (dB scale). a- focusing through water, b- focusing through skull, c-time reversal through the skull.

# 3. THE SPATIO TEMPORAL INVERSE FILTER (STIF): INVASIVE ADAPTIVE FOCUSING

The experimental setup remains unchanged (Fig. 1). But this time the  $128 \times 128$  impulse responses  $h_{ij}(t)$  between any element i of the emitting array and any element j of the receiving array are recorded. All these Green's functions characterize the medium between the emitting and receiving arrays. In that case, if each source i of the echographic array emits a temporal signal  $e_i(t)$ , the temporal signal received on the transducer j in focal plane is

$$f_j(t) = \sum_{i=1}^{128} h_{ij}(t) * e_i(t)$$

where \* represents the temporal convolution operator. After Fourier transform this relation becomes

$$F_{j}(\omega) = \sum_{i=1}^{128} H_{ij}(\omega) E_{i}(\omega)$$

and can be more easily written in a matrix formulation :

 $F(\omega) = H(\omega)E(\omega)$ 

monochromatic propagation matrix.

where  $E(\omega) = [e_1(\omega), e_2(\omega), \dots e_N(\omega)]$  is the column vector of the Fourier transform of the emitted set of signals and  $F(\omega) = [f_1(\omega), f_2(\omega), \dots f_N(\omega)]$  is the Fourier transform of the received signals. The transfer matrix  $H(\omega) = \{H_{ij}(\omega)\}_{1 \le i,j \le N}$  describes the propagation in the medium from the array to the set of control points for a chosen frequency component and thus is called the

Inverting the above matricial relation, one can compute the Fourier components  $E(\omega)$  of the signals to emit from emitting array in order to focus on the Fourier

components  $S(\omega)$  of the desired focal spot on receiving array (the target):

$$E(\omega) = H^{-1}(\omega)S(\omega)$$

where  $\tilde{H}^{-1}$  is the pseudoinverse of H [10]. The temporal signals e(t) to emit in order to obtain the desired temporal signals s(t) in focal plane are calculated by an inverse Fourier transform. The focusing signals E calculated to focus on a spatio-temporal dirac S at central position of the receiver array in focal plane and the subsequent focusing, are presented in fig. 3.



Figure 3. STIF focusing: Left: the STIF focusing signals and the resulting focusing through skull. Right: scan of the temporal maxima of pressure in the focal plane (dB scale). a- cylindrical law through water, b-cylindrical law through skull through skull, c- STIF through skull

The STIF proves that there exists a set of signals that is able to focus through the skull with a focusing pattern close to the one obtained with a cylindrical law through a homogeneous medium. However it requires the presence of acoustic transducers in the focusing region for the acquisition of the propagator: this technique is invasive and cannot be used directly to perform in vivo imaging. A non invasive approach is presented in the following part.

# 4. TOWARDS A NONINVASIVE ADAPTIVE FOCUSING METHOD

The experimental setup has to be noninvasive: the "twin" echographic arrays are now located on each side of the full skull, as shown in fig. 3 (top, left). Array 1 is the emitting array and array 2 provides control points on the controlateral position. Array 1 will be used to image the right half of the brain. By switching the role of arrays 1 and 2, array 2 would be used to image the other half of the brain.

The global propagator  $H(\omega)$  through the entire skull from array 1 to array 2 can be acquired. Our goal consists now in deducing an approximation of  $H_1(\omega)$ corresponding to the propagation through the first half skull only. (see fig. 4). We will denote  $H_2(\omega)$  the propagation through the second skull bone. Two independent  $H1(\omega)$  and  $H(\omega)$  differ because of:

 $\alpha$ ) the effect of the skull bone in regard to array 2  $\beta$ ) the 2cm difference in depth

 $\beta$  is well known. We will thus concentrate on the cancellation of the effect of the second skull bone.



Figure 4. Experimental dispositive and illustration of the formalism. Arrays 1 and 2 are located on each side of the skull.

H( $\omega$ ), H<sub>1</sub>( $\omega$ ) and H<sub>2</sub>( $\omega$ ) are linked by the relation: H( $\omega$ )=H<sub>1</sub>( $\omega$ )×H<sub>2</sub>( $\omega$ )

Now the aim is to estimate the propagator  $H_2$ : multiplying the above equation on the left by the inverse of  $H_2$ , one obtains an estimate of  $H_1$  that can be later inverted to perform approximate STIF through  $H_1$ .

 $H_2$  will be approached by a propagator  $H_2^g$  (the upper index g standing for "guessed"), that will be written as a diagonal, multi-frequency propagator in which element (j,j) is an amplitude and phase factor describing the acoustical effects of the small portion of skull bone in front of element j of array 2:

 $H_2^g(\omega)_{ij} = A_i^g(\omega) \exp(j\phi_i^g(\omega))\delta_{ij}$ 

This approach is valid if the second half skull is infinitely thin and stuck to the second array, which is never realized in practice but that is approached as much as possible working on a thin zone (near the temple) of the skull bone, and putting the array as close as possible to it.

# 4.1. Estimation of the absorption factor induced by second skull wall

The absorption factor  $A_j(\omega)$  by which is multiplied the fourier component  $\omega$  of the signal crossing the portion of second skull wall in front of transducer j of array 2 is estimated as follows: a signal of amplitude 1 is sent from the transducer j of array 2. The transmitted signal is received on array 1, time-reversed, and sent back to array 2. The amplitude  $A^{TR}_{j}(\omega)$  of the fourier component at frequency  $\omega$  of the signal then received on receiver j of array 2 is proportional to  $(A_j(\omega))^2$  (the wave has crossed two times the skull in front of receiver j of array 2) and the proportionality factor, that characterises global absorption by first skull wall, does not depend on j.

The amplitude  $A_{j}^{g}(\omega)$  of second skull wall will then be estimated as the square root of the amplitude of the received signals after this time-reversal process :

$$A_j^g(\omega) = \sqrt{A_j^{TR}(\omega)}$$

4.2. Estimation of the phase shift induced by second skull wall

The estimation of the phase shift  $\phi_i^g(\omega)$  by which is

affected the fourier component  $\omega$  of a wave crossing the portion of second skull wall in front of transducer j of array 2, is done as follows: an impulse is sent successively from transducer 1,2,... 128 of array 2. The corresponding B-scans R1, R2... R128 received on array 1 are recorded and correlated two by two ( $R_1$  with  $R_2$ ,  $R_2$  with  $R_3$  and so on). The maximum of correlation of R<sub>i</sub> with R<sub>i+1</sub> occurs at a time that corresponds to the travel-time difference between the portion of second skull wall in front of elements i and i+1 of array 2 respectively (the crossing of first skull wall has nearly the same influence on the wavefront coming from transducer j and j+1 of array 2). The travel-time differences between all pairs of adjacent transducers of array 2 are thus computed, then integrated to have access to the absolute travel time for any portion of skull wall in front of any transducer of array 2. From the deduced travel times  $(\Delta t)_{j=1...128}$ , the phase shifts induced by second skull wall are calculated as:

$$\phi_i^g(\omega) = \omega \Delta t_i$$

4.1. Using the guessed propagator  $H_1^g$  for noninvasive focusing

The "guessed" propagator  $H_1^{g}$  approaching  $H_1$  is given by:

$$H_1^g = \left(H_2^g(\omega)\right)^{-1} H(\omega)$$

and the set of signals  $E_{niIF}$  calculated by this non invasive approximation of the STIF signals that are emitted in order to focus through first half skull  $H_1$  on the target S in focal plane are :

$$E_{niIF}(\omega) = \hat{H}_1^g(\omega)^{-1} S(\omega)$$

They are close to the STIF solution if  $\widetilde{H}_1^{g^{-1}} \approx \widetilde{H}_1^{-1}$ , i.e. if  $H_1$  is well deduced from H.

#### 5. RESULTS

The experimental sequence is the following: the propagator H is first acquired through the entire skull, then the emission signals are calculated as described in the previous section. The non invasive STIF signals and the resulting focusing are presented in fig. 5 (left). The focusing is compared to the focusing obtained by sending a prefocused "cylindrical" wave front (fig. 6, right). The noninvasive adaptive focusing method applied here corrects from distortion :the focal point is at the desired location: the phase shifts induced by the skull have been properly corrected

The residual pressure on both sides of the main lobe is lowered by 10 dB (contrast enhancement).

The focusing quality is not as good as the one obtained with the invasive STIF (Fig. 3) but is similar to the one obtained with the invasive time reversal technique coupled with amplitude compensation (Fig. 2).



Figure 5. Noninvasive STIF focusing: left: the non invasive STIF focusing signals and the resulting focusing through skull. Right: scan of the temporal maxima of pressure in the focal plane (dB scale). a-cylindrical law through water, b-cylindrical law through skull, c-noninvasive STIF through skull

The method is applied to calculate the signals to emit in order to focus on any point in focal plane.

The imaging potential of the focal spots obtained through the skull using different techniques (pre-focused wave fronts, invasive and non invasive STIF) is investigated. The medium to image is presented in fig. 6.a: randomly distributed point-like scatterers surround a 10-mm diameter spherical inclusion free of scatterers, that could model a hydric cyst inside the brain. This medium is then computationally convolved with the recorded focal spots.

The reconstructed image is totally destroyed when focusing with cylindrical laws (fig. 6.b). The inclusion becomes visible on the image obtained with the signals given by the noninvasive STIF (fig.6.c), illustrating the potentials of this technique for structural imaging. As a reference, on fig.6.d is represented the image obtained with invasive STIF.





Figure 6. Simulated images of an inclusion free of scatterers inside the brain. a- the zone to image; b- prefocused signals, c- noninvasive STIF, d- invasive STIF. The x and z axis are respectively parallel and perpendicular to the focusing array.

## 6. CONCLUSION

The introduction of the Spatio Temporal Inverse Filter demonstrated the existence of a set of signals to be sent from an echographic array outside the skull that, after crossing the skull wall, is able to focus with the same quality as prefocused signals through a homogeneous medium. The computation of this set of signals required an invasive device. A totally non invasive twin arrays device and a derived technique, the non invasive STIF have been presented. Such a strategy allows approaching the focusing set of signals given by the classical invasive STIF.

Applications of precise, adaptive, non invasive focusing of ultrasounds go beyond structural imaging. Quantitative blood flow measurements inside the brain could be envisioned. with the same approach.

#### 7. AKNOWLEDGEMENTS

This work was supported by grant QLG1-CT-2002-01518 (UMEDS: Ultrasonographic Monitoring and Early Diagnosis of Stroke) from the European Commission.

## 8. REFERENCES

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