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Transcranial Beam Steering with Aberration Correction

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Ultrasound imaging through the intact skull is challenging because of the skull-induced aberrations and signal attenuation. We have designed an experimental ultrasound diagnostic system for noninvasive brain imaging through the intact skull. To overcome skull-induced aberrations and focus efficiently, the system implements the correction procedure based on a beacon approach. This approach is considered classical and highly accurate in comparison with other correction methods. Operation of the system requires two probes working at 3-4 MHz central frequency. The probes are attached coaxially on both sides of the head to the acoustic transparency windows.

Introduction

Investigations of the brain through the skull bones inevitably produce amplitude and phase distortions, due to nonuniformity in the propagation speed of ultrasound (US) in tissues. This leads to widening of the main lobe and increases the side lobes, resulting in degradation of focusing quality and, thus, the spatial and contrast resolution of images.

Degradation of image quality due to the phase distortion is acceptable only at low frequencies (i.e., when the carrier frequency is less than 1 MHz) and small apertures. At the same time, the main way to improve the lateral and longitudinal resolutions of US images is to increase the frequency of the US signal and the size of the aperture. In practice, higher frequencies and wider apertures make the diagnostic system more sensitive to changes in the speed of sound across inhomogeneous tissues covered by the beam.

The distortions that we need to correct are the aberrations of the amplitude and phase and changes in the shape of echoes. Most known algorithms only compensate for phase aberrations and do not address signal shape distortions [1-3]. These algorithms compute time delays and use them for correct focusing in the beamformer. This article describes a system developed for transcranial investigations. The system can correct distortions in US signal amplitude, phase, and shape.

Correction of Aberrations

The diagnostic system developed here is based on a modification [4] of the classical time-reversal "beacon" method [3]. The method provides compensation for the defocusing effects of the skull bones and uses two probes. The first acts as a reference probe, also known as a beacon. The second is a standard imaging sector probe. Both probes are attached to the surface of the head at the opposite acoustic windows (Fig. 1, a-c). The probes can be attached with a headband (Fig. 1d) or a special holder to fix probes for transcranial investigations in patients in a supine position (Fig. 1e).

Before obtaining US images of the brain, a correction procedure should be performed; the procedure consists of generating one pulse and emitting it with the reference probe. The emitted signal, passing through the patient's head, reaches the elements of the sector probe on the other side of the head. Each element of the sector probe

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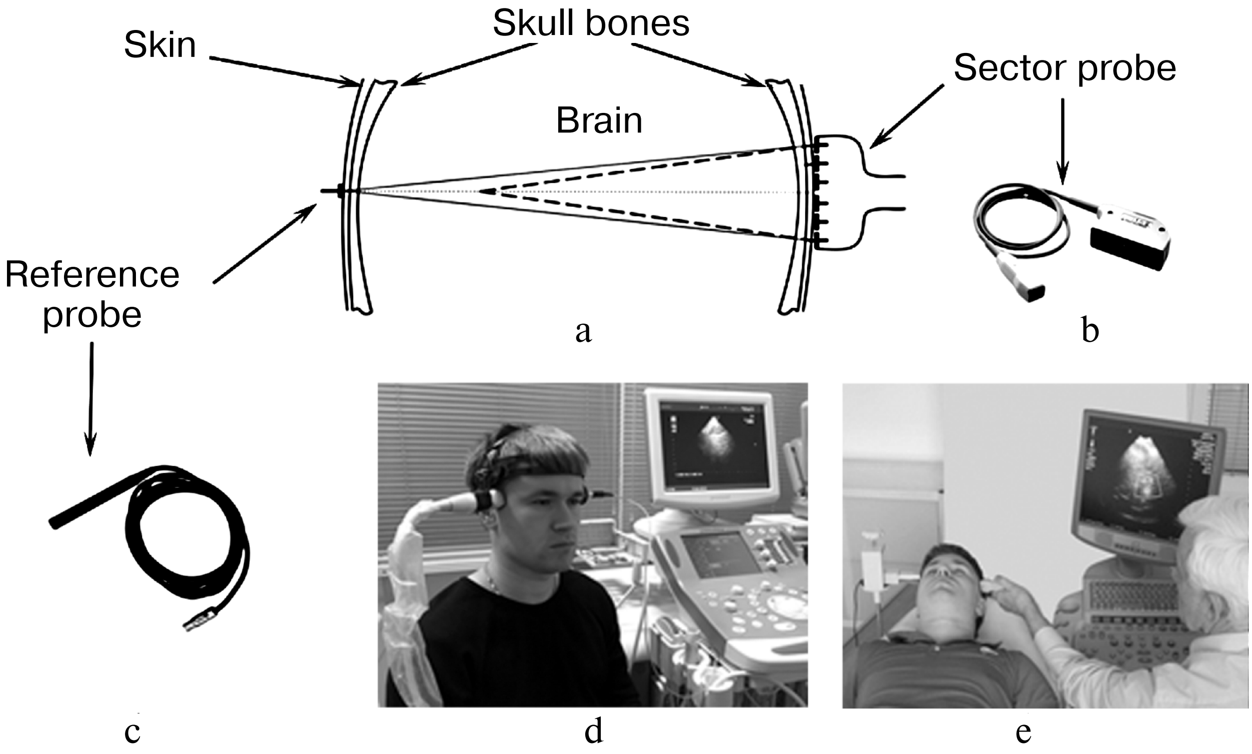

Fig. 1. The positioning of the probes: a) diagram of the probe positioning; b) sector probe; c) single-element reference probe; d) imaging using the special headband attaching the reference and sector probes to the patient's head; e) attachment of the probes in the supine position.

measures and stores the amplitude, delay, and phase shift of the received signal. The system is then switched to the transmission mode, i.e., the system forms pulses and sends them to each element of the sector probe. Delays, phases, and amplitudes inverse to those measured for each element of the sector probe are calculated for each element of the array. This procedure is called mirroring. The array elements of the sector probe convert the electric signals into US pulses; these pulses are sequentially sent by each element through the patient's head and received on the other side with the reference probe.

Mutual shifts in the delay and phase, as well as the amplitude of signals received by the reference probe, are again measured for each element of the sector probe. If the measured changes are relatively small, then the system decides that the correct compensation for the aberrations is achieved. The measured values of the focusing parameters are then used for forming the beam in which compensation for differences at the required scanning depths and angles is implemented. The device is then used in the scanning mode, with the transmission of US pulses, receipt and amplification of echo signals, transformation, processing, and storage of electrical signals, formation and display of brain images. On the contrary, if the measured changes are significant, these results are used to introduce additional corrections and the correction procedure is repeated.

System Components and Operation

The system is controlled according to the scheme shown in Fig. 2 and consists of the following main elements: a reference probe, a sector probe, a transmit/receive switch, a transmit beamformer, an analog front end with receive beamformer, a digital processing unit, a control and synchronization unit, and a personal computer (PC). The reference probe emits a US pulse in the correction mode. The probe's excitation signal arrives from the transmit beamformer. The sector probe operating in the correction mode receives the US pulses and converts them into electrical signals. In the scanning mode, the excitation signals at the sector probe arrive from the transmit beamformer and are converted into the US pulses at the emission stage; the sector probe carries out the reverse conversion at the reception stage. The beamformer performs focusing on emission and reception by changing the delay and amplitude of the signals in

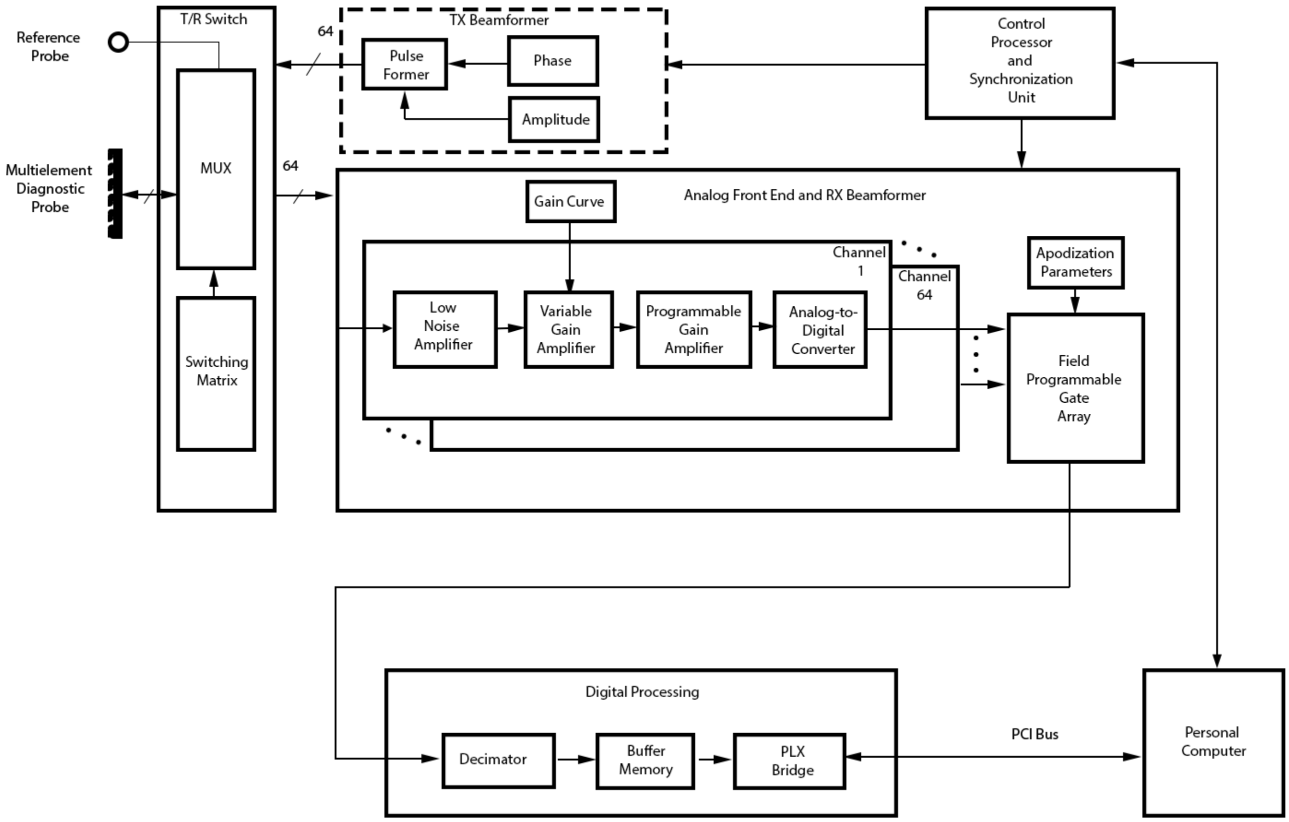

Fig. 2. Block diagram of the diagnostic system (see text for explanation).

the conventional scanning mode. The digital receiver carries out the primary processing of echo signals, i.e., band filtration, signal storage, and synchronous signal detection. The PC processes US data, forms the US image in the conventional scanning mode, and controls the system through the control and synchronization unit. The PC also runs special post-processing of US data obtained in the synthetic aperture mode used for the correction of aberrations.

The system software controls the operating modes and the beam formation for emission and reception, collects US data, forms real-time images, carries out geometrical measurements, computes physiological parameters, and stores or prints the results, as well as sends them to external devices.

Testing

The experimental system was tested using an ATS Laboratories Model 539 phantom (Fig. 3a), which simulates the acoustic properties of soft tissues. The speed of sound in the phantom is 1480 m/s and attenuation is ~0.7 dB/cm·MHz. The phantom's material includes point reflectors for assessment of resolution, along with cyst and tumor simulators.

Distortions created by the temporal bone of the skull in transcranial investigations were simulated by specially designed aberrators. Aberrators were made from silicon with the speed of sound 1200 m/s. The liquid silicon was poured into moulds and solidified. The moulds were made of ABC plastic by a 3D printing process. Apart from these cast forms, 3D printing was used to make a special holder (Fig. 3b) for the aberrators, which was put on the sector probe to secure the position of the aberrator relative to the probe. Figure 3c shows the sector probe with the holder and aberrator.

Figure 3d shows a US image obtained using one of the aberrators and clearly showing distortion. Data obtained during the correction was used to construct an aberration profile (Fig. 3e). Further, this data was used to compute compensatory corrections. The corrected image (Fig. 3f) was comparable in quality to the image acquired without aberrators.

The aberrator in the next experiment consisted of ex vivo temporal bone (Fig. 3, g-j). The recovered profile in Fig 3i shows that the phase shift is twice the value obtained in the previous experiment (Fig. 3e). Signal intensity at sites of the bright reflections increased by 11 dB in images after correction, which is 4 dB more than in the experiment with silicon aberrators.

During verification of the functioning of the elements and units in the experimental system and preliminary testing, the need to develop a diagnostic system and corresponding correction to the design documentation and software was identified. This resulted in the following work: 1) modification of a reference probe to maximize the width of the beam; 2) optimization of the reference probe excitation signal parameters and band filter parameters in the receiver system to maximize the measurement accuracy of the phase characteristics in the correction mode; 3) introduction of the reference probe beam assessment mode using the sector probe; 4) development and preparation of a special headband for positioning and fixing the probe in the required spots; 5) development of software for accurate consideration of the computed

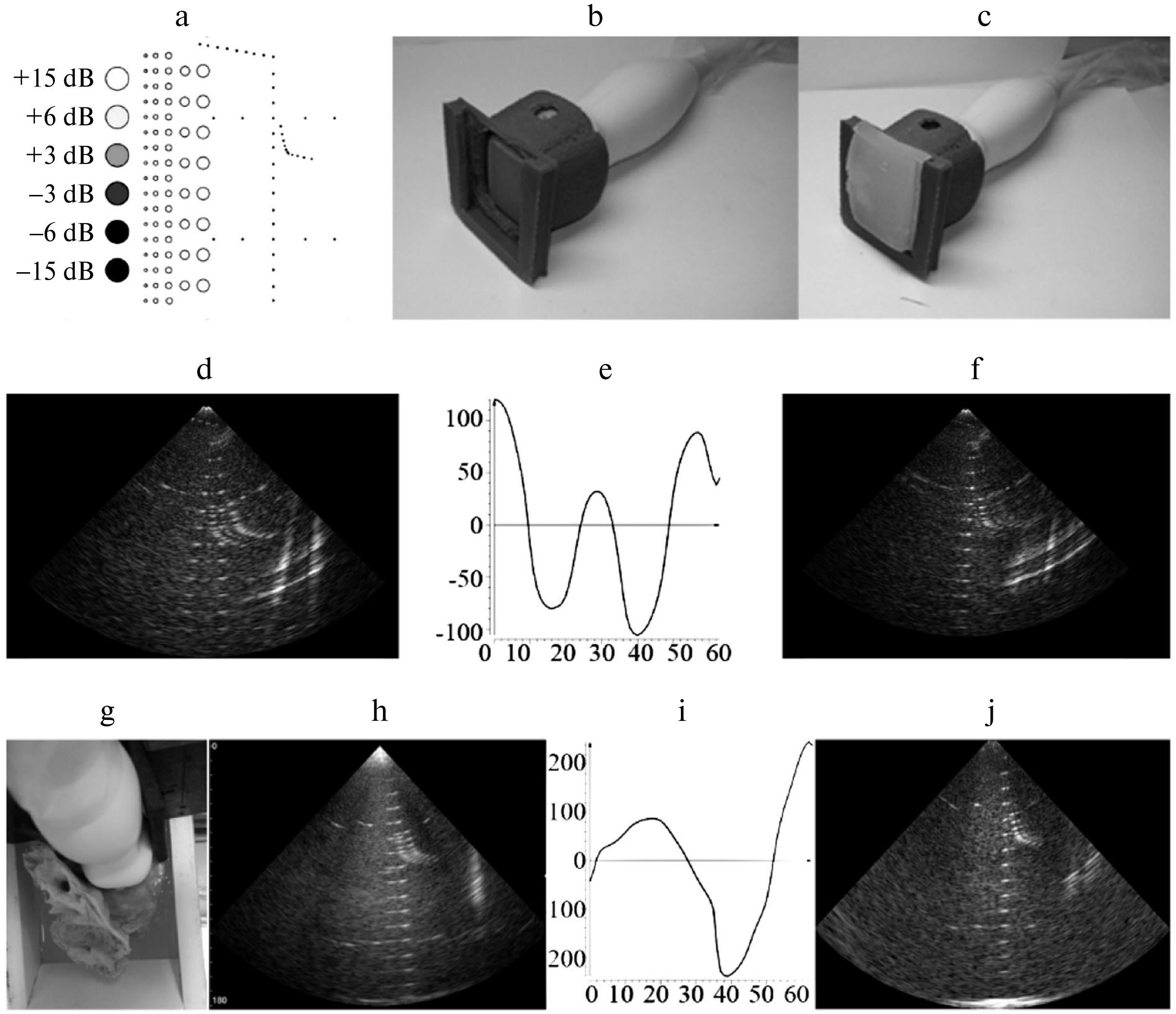

Fig. 3. Illustrations for experiments: a) diagram of the phantom; b) sector probe with the aberrator holder; c) attachment of an aberrator to the sector probe; d) sonogram of the phantom obtained with one of the aberrators; e) aberrator structure distortion profile (the ordinate shows phase shift, °; the abscissa, phased array element number); f) sonogram after correction; g) use of ex vivo temporal bone as an aberrator; h) sonogram of the phantom obtained through the bone; i) aberration profile of the bone; j) sonogram of the phantom after correction of aberrations.

shape of the undistorted phase front of the reference probe signals at the aperture of the sector probe and amplitude distortions of signals caused by skull bones.

Because the system was based on a field programmable gate array architecture which is easy to reprogram, most of the abovementioned changes were made at the software level. Experiments were performed with a variety of reference probes with the attachment of acoustic masks to their apertures with the intention of maximizing the width of the beam. These experiments helped to establish the required beamwidth of the reference probe and the desired measurement accuracy of phase spreads on elements of the sector probe. The chosen reference probe emitted pulses at 3-4 MHz and had an aperture surface of ≤2 mm.

To increase the signal-to-noise ratio and the accuracy of the phase measurements, the option of increasing the pulse duration of the reference probe to 9 frequency cycles was implemented. As increases in the duration of emitted pulses lead to a proportional narrowing of the spectrum of the emitted signal, ensuring the maximum signal-to-noise ratio requires a corresponding change to be made to the frequency filter bandwidth in the receiving path of the sector probe in the correction mode. The option of setting the required frequency filter bandwidth in the receiving path of the system was implemented.

Since the spectrum of the US pulses shifts with depth towards the low frequencies, normally a compensation for the central frequency alterations is introduced. However, in the correction mode, changes in the central frequency for signal reception lead to phase measurement errors. For this reason, a signal emission and reception mode at a fixed carrier frequency was introduced in the correction mode as well.

Conclusions

This work involved creating and testing an experimental system that should form a basis for a diagnostic ultrasound apparatus for investigating the brain and cerebral vessels and producing high-quality images by correcting phase and amplitude distortions. Leading medical and technical specialists have participated in the development of the system. Experts from the N. N. Burdenko Science Research Institute Neurosurgery and the Neurology Science Center, Russian Academy of Medical Sciences, positively assessed the results of our work for creating the new technology for transcranial ultrasound investigations of the brain. The main technical solutions are protected by patents [4, 5]. The system is currently limited to operating in the grayscale mode. We intend to use our experience in signal processing [6-9] to add conventional Doppler modes in the device.

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