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Experimental evaluation of targeting accuracy of an ultrasound-guided phased-array high-intensity focused ultrasound system

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ABSTRACT

Bowl-shaped phased array therapeutic probes are becoming a standard module in magnetic resonance imaging-guided high-intensity focused ultrasound (MRgHIFU) systems because single beam focus can be electronically steered and multiple foci can be simultaneously synthesized. B-mode imaging provides only two dimensional image, therefore phased array HIFU probes are rarely used in ultrasound imaging-guided HIFU (USgHIFU) systems. An 144-element phased-array USgHIFU system was developed, and a B-mode probe was mounted in a rotating platform and harnessed to track the focus steered in three-dimensional volume. In this study, the targeting accuracy of this system was estimated experimentally using beef-embedded phantoms with four reference markers. The plane of treatment crossing the reference markers was reconstructed by acquired image sequence, and targeting area was predetermined as circular treated zone in the center of a square with corners in the middle of the markers. After sonication the contour of lesion was compared with the outline of planned targeting area. For three treated zones with a diameter of 5.8 mm, 9.7 mm, and 13.5 mm, the ratio of the thermal lesion area in the relevant treated zone to the planned targeting area was 89%, 92%, and 96%, respectively. The displacements between centers of the lesions and of the planned treated zones were no more than 1 mm. Moreover, the maximal crossing of borders outside the targeting area was lower than 2 mm. The targeting accuracy of this system was found to be around 1 mm being comparable to other image-guided HIFU systems. Therefore, the rotation-based 3D image reconstruction is effective for the targeting, treatment planning, and monitoring by using our system. Besides, such arrangement of treated zones is simple but useful in treatment planning.

1. Introduction

High-intensity focused ultrasound (HIFU) is increasingly used in tumor treatment due to the non-invasive feature [1]. Accurate targeting is essential for image-guided HIFU systems to deliver the appropriate energy to the specific location [2]. Magnetic resonance imaging (MRI) and B-mode ultrasound imaging are used to guide the HIFU beam focus into the targeting area under imaging control [3]. For MR-guided HIFU (MRgHIFU) systems, three-dimensional (3D) coordinate transformation can be established between HIFU transducer and MR image with specific localizer [4]. Targeting area is selected on coronal image, then a safe beam path should be installed from transducer to targeting area, and finally treatment plan will be generated by physicians. Temperature elevation and the associated thermal dose can be simulated with the sonication parameters during treatment planning. The temperature mapping on the coronal and sagittal images obtained by MR thermometry can be used to monitor the energy deposition during HIFU sonications [4]. For extracorporeal ultrasound-guided HIFU (USgHIFU) systems, a typical design is that the imaging probe is mounted in the central hole of HIFU transducer. The geometric focus of HIFU transducer is thus constantly located on the central axis of the US image [5]. As HIFU transducer is mechanically moved along the direction perpendicular to the imaging plane, the image of the whole tumor can be reconstructed and the treatment plan can be made with the targeting area selected on each image [6,7]. Hyper-echo appearing on the image is regarded as an empirical indicator of successful ablation [8]. And the ablation of the whole tumor can be accomplished after the treatment plan on each slice of image is performed [6,7].

Taking advantage of flexible focus steering and simultaneous multiple-focus generation, HIFU phased array has been studied extensively and it is promising in creating uniform lesion and reducing treatment time [9]. Various therapeutic phased arrays have been designed for image-guided HIFU systems [10–12], however, only few studies were focused on phased array USgHIFU systems. Directly mounting

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ultrasound probe in the central hole of phased array may cause the obstacles in targeting, treatment planning and monitoring, because US image can only provide two-dimensional (2D) information but the focal spot should be steered in 3D volume during sonications. One solution is to use 3D volume probe for imaging instead of conventional probe [13]. However, it still needs several seconds to acquire and process the volume data, and the manufacturer-dependent software module is required to access the 3D data. It is difficult for user interface (UI) to freely access the imaging data for treatment planning, therefore it becomes complex to integrate the 3D ultrasound imaging probe into the current USgHIFU systems. Another solution is to switch imaging planes through a rotating platform that holds the conventional probe, as a result, the imaging plane can be rotated to track the steered focal spot [14,15]. The rotating B-mode imaging probe is coaxial with the HIFU phased-array transducer. The image of treatment plane, which is perpendicular to the HIFU beam axis, was reconstructed by the images through the rotation of the B-mode probe. The targeting area can be selected on the treatment plane during treatment planning, and the focal spots can be mapped into the coordinates of the phased array. Besides, real time monitoring can be realized by rotating the probe to the specific angle, the plane of which contains the sonication spot.

A phased array USgHIFU system has been developed based on our previous work [15]. The purpose of this study was to evaluate the targeting accuracy of the system. Transparent beef-embedded phantoms with four reference markers were made. The plane crossing the centers of reference markers was selected as the treatment plane in the reconstructed image. Targeting area was predetermined as a treated zone being in the middle of the square with corners in the center of the markers on the treatment plane, and the thermal lesion visible after sonication was compared with the planned treated zone in terms of several parameters.

2. Materials and methods

2.1. USgHIFU setup

The USgHIFU system mainly includes several components: therapeutic-imaging applicator, HIFU driving unit, diagnostic ultrasound scanner, UI console and HIFU driving console. The block-diagram of the system is shown in Fig. 1(a). The integrated therapeutic-imaging applicator shown in Fig. 1(b) consists of a 144-element therapeutic phased array probe and a 3.5 MHz B-mode ultrasound imaging probe. The phased array transducer is constructed with piezoelectric (PZT-8) circular elements with diameter of 10 mm and resonance frequency of 1.39 MHz. The B-mode ultrasound imaging probe is a convex array probe placed in an 80-mm central circular hole of the spherical phased array HIFU transducer with the aperture and radius of curvature equal to 18 cm and 14 cm, respectively. The elements of the phased array HIFU transducer are arranged in the shape of rings and each ring includes 24 elements. Arrangement scheme of elements was designed based on our previous work [16]. In addition, both the amplitude and the phase of the electrical signal that excited each element of the phased array can be independently controlled by the HIFU driving unit to steer the focal spot flexibly in 3D volume. The measured ellipsoidal −6 dB focal region of the HIFU beam (FWHM of the acoustic pressure) had an axial length of 9.6 mm and a diameter of 1.2 mm.

One distinguishing feature of the applicator is the rotating imaging probe. The axis of rotation and the central axis of the ultrasonic image overlap with the z-axis of the HIFU probe. The ultrasound imaging probe is able to rotate in the range from −90° to 90° with a step of 1° to cover the 3D volume in which the energy of HIFU beams will be delivered. Therefore, the positions in the images and the focal spots can be mapped to each other without coordinate registration. The appearance of hyper-echo induced by sonication can be real-time monitored by rotating the probe to the respective angle.

Before treatment, a sequence of images at different angles is acquired by rotating the imaging probe. The treatment plane is obtained by 3D reconstruction of the sequence of images [14]. Fig. 2 shows the diagram of US guidance for treatment planning and monitoring. Targeting area is contoured in the image of treatment plane by the physician, and filled with focal spots during treatment planning. The probe is rotated to the imaging plane with the specific angle to monitor the ablation when performing treatment plan.

2.2. Phantom preparation

A beef-embedded phantom with four ball-shaped reference markers was produced. Fig. 3 shows a top view of the phantom. The tough resin markers were served as references surrounding the around 10 mm-thick beef sample. The markers with diameter of 10 mm were located in the four corners of the 40-mm square and were linked by thin sticks. Both, the reference markers and thin sticks were produced by 3D printer from the same material as one unit, which was embedded into transparent cylindrical gel. The acoustic attenuation coefficient of the gel is much smaller than that of tissue, only the targeting area inside the phantom could be ablated. Therefore, this transparent phantom enabled direct observation of the formed lesion without slicing the phantom after HIFU sonication. The phantom was produced using the method described in the previous study [17]. It was made in a cylindrical container and one half of the pre-made degassed solutions were mixed and poured into the container, and then the reference markers as well as beef sample were placed on the top of the gel after the mixed solution

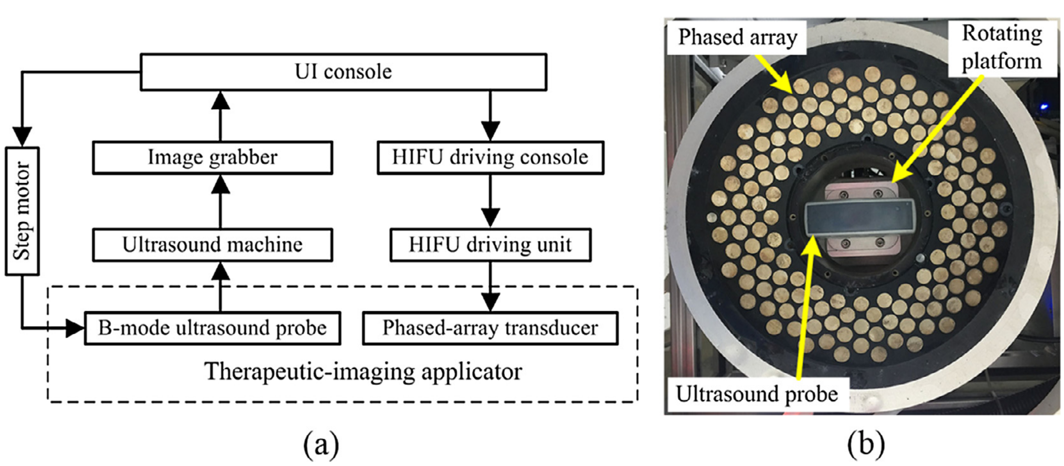

Fig. 1. Block-diagram (a) of the USgHIFU experimental setup and photo (b) of the integrated therapeutic-imaging applicator. The abdominal B-mode ultrasound imaging probe connected to the rotating platform is mounted in the central hole of the bowl-shaped HIFU transducer.