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(54) **MAPPING ULTRASOUND TRANSDUCERS**

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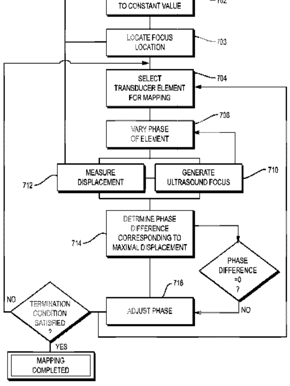
(57) **ABSTRACT**

Ultrasound transducers may be mapped by varying a focus-affecting parameter and adjusting the parameter so as to improve focus quality. In some embodiments, mapping involves successively varying the phase of one transducer element, or group of elements, with respect to a constant phase of the other transducer elements, and determining the phase at which a tissue displacement in the ultrasound focus is maximized.

20 Claims, 5 Drawing Sheets



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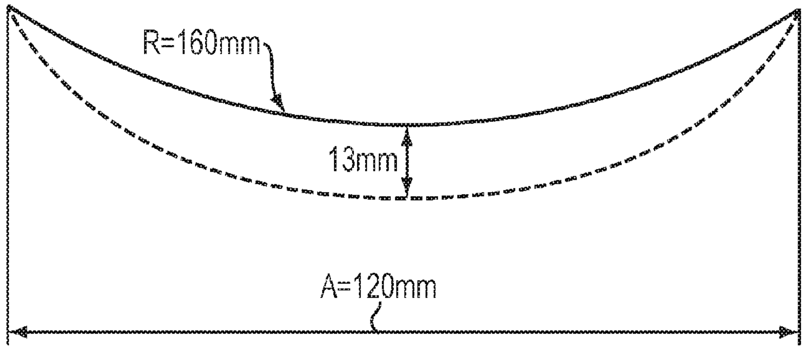
R=160mm
13mm
A=120mm

FIG. 1

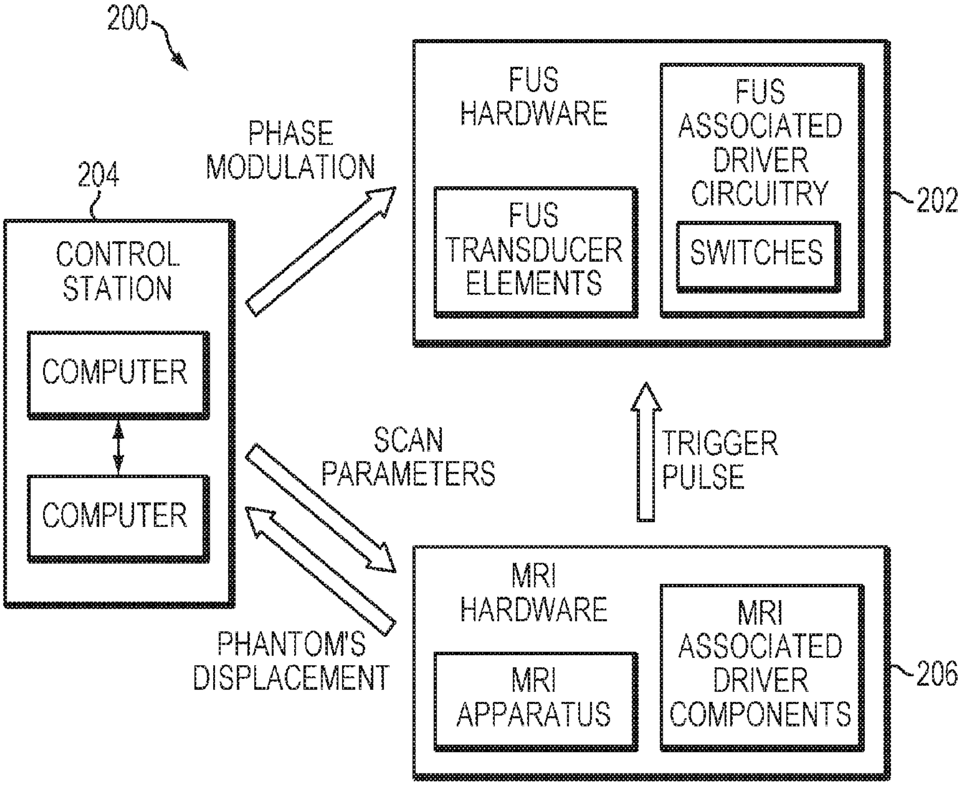
200
204
CONTROL STATION
COMPUTER
COMPUTER
PHASE MODULATION
SCAN PARAMETERS
PHANTOM'S DISPLACEMENT
FUS HARDWARE
FUS TRANSDUCER ELEMENTS
FUS ASSOCIATED DRIVER CIRCUITRY
SWITCHES
202
TRIGGER PULSE
MRI HARDWARE
MRI APPARATUS
MRI ASSOCIATED DRIVER COMPONENTS
206

FIG. 2

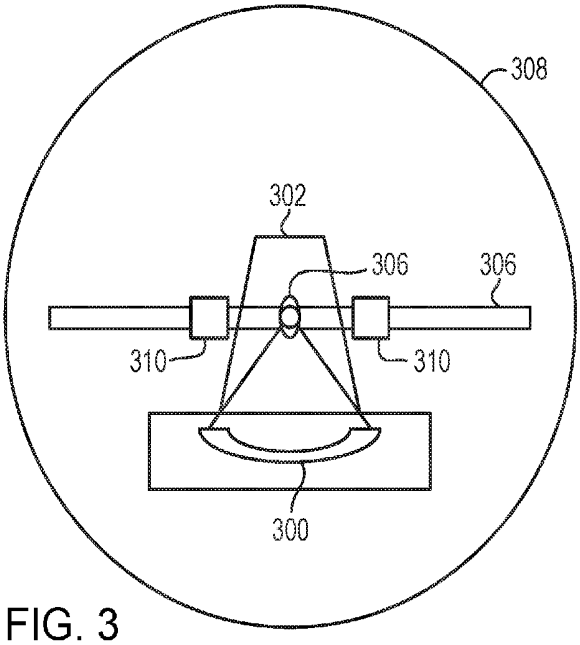

FIG. 3
PRIOR ART

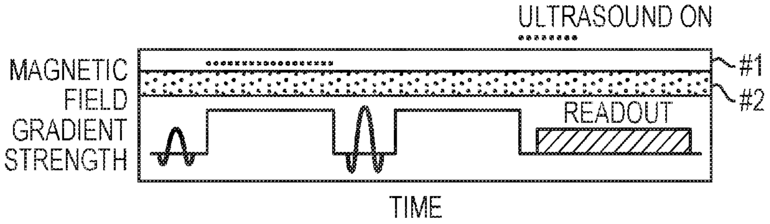

FIG. 4A
PRIOR ART

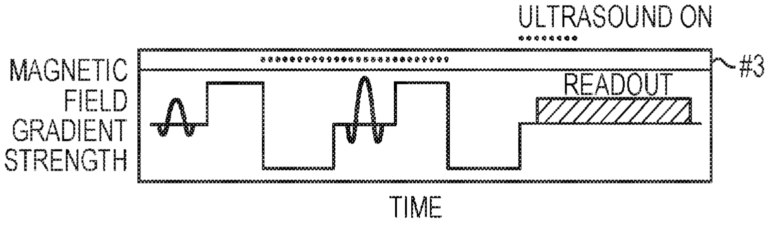

FIG. 4B
PRIOR ART

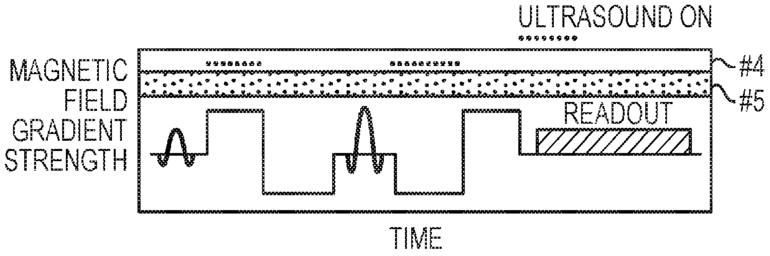

FIG. 4C
PRIOR ART

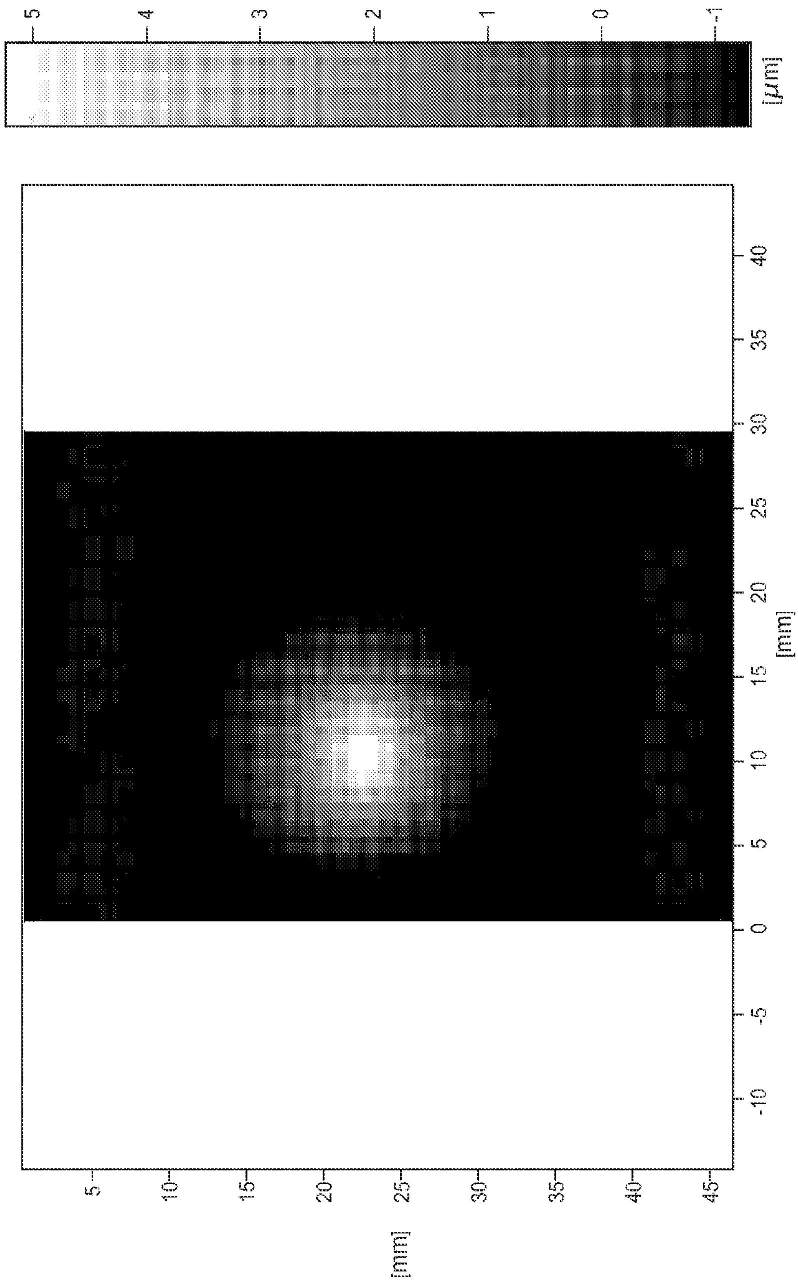

FIG. 5

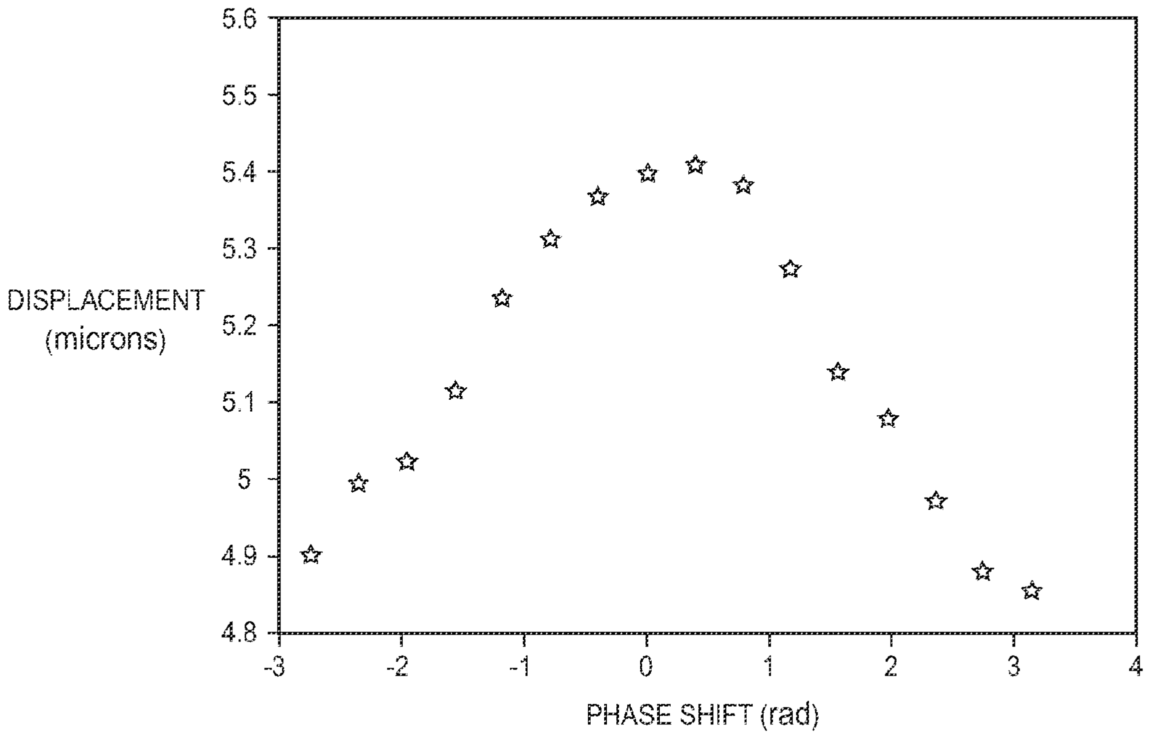
DISPLACEMENT
(microns)
5.6
5.5
5.4
5.3
5.2
5.1
5
4.9
4.8
-3
-2
-1
0
1
2
3
4
PHASE SHIFT (rad)

FIG. 6

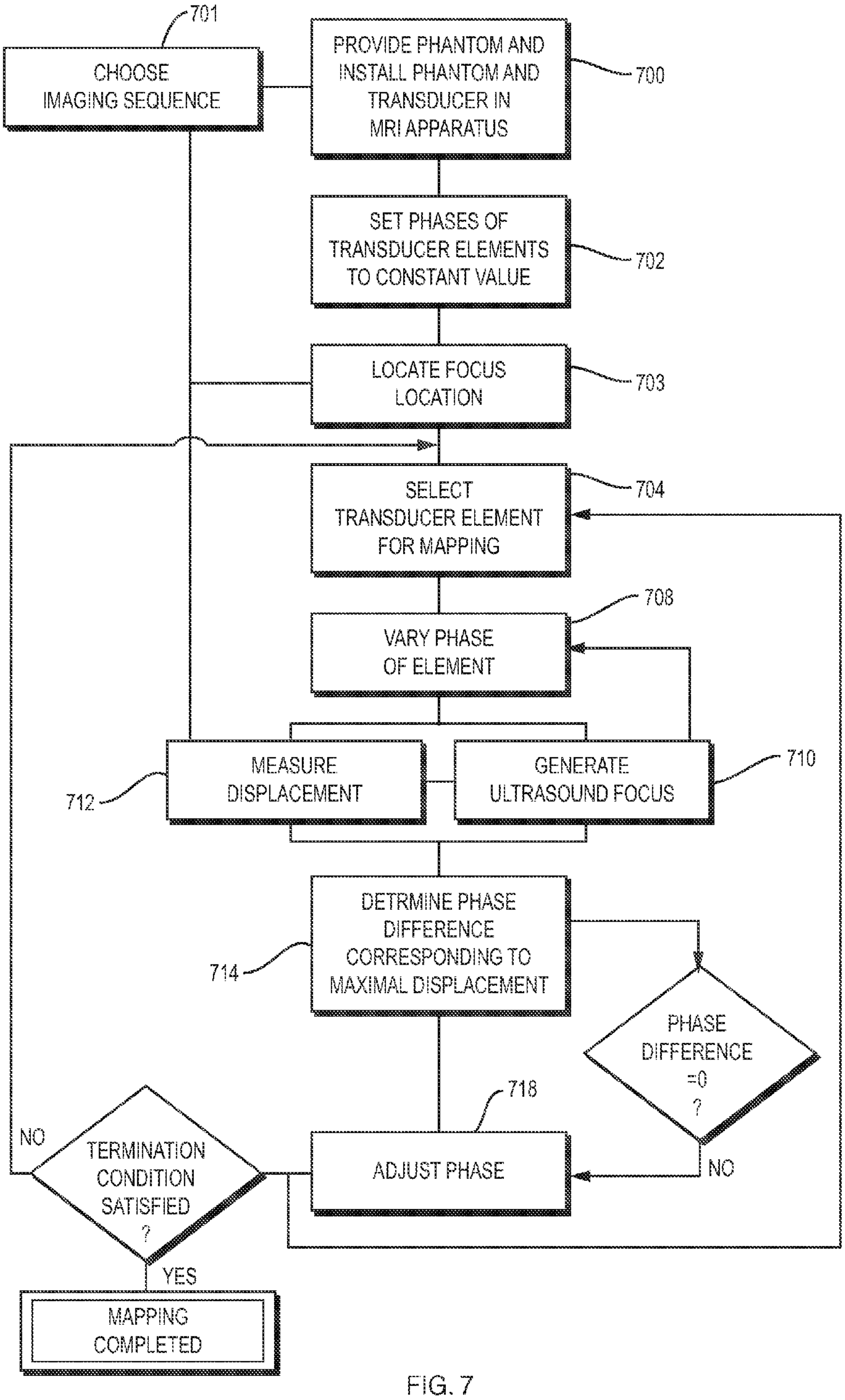
701
CHOOSE IMAGING SEQUENCE
PROVIDE PHANTOM AND INSTALL PHANTOM AND TRANSDUCER IN MRI APPARATUS
700
SET PHASES OF TRANSDUCER ELEMENTS TO CONSTANT VALUE
702
LOCATE FOCUS LOCATION
703
SELECT TRANSDUCER ELEMENT FOR MAPPING
704
708
VARY PHASE OF ELEMENT
MEASURE DISPLACEMENT
712
GENERATE ULTRASOUND FOCUS
710
DETRMINE PHASE DIFFERENCE CORRESPONDING TO MAXIMAL DISPLACEMENT
714
PHASE DIFFERENCE =0 ?
NO
718
ADJUST PHASE
NO
TERMINATION CONDITION SATISFIED ?
YES
MAPPING COMPLETED

FIG. 7

MAPPING ULTRASOUND TRANSDUCERS

CROSS-REFERENCE TO RELATED APPLICATION

This application is a Divisional Application of Ser. No. 12/904,655, filed Oct. 14, 2010, which claims priority to and the benefit of U.S. Provisional Patent Application No. 61/251,450, filed on Oct. 14, 2009, both of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates, generally, to systems and methods for mapping ultrasound transducers. In particular, various embodiments are directed to improving the quality of the ultrasound focus using experimental feedback.

BACKGROUND

Focused ultrasound (i.e., acoustic waves having a frequency greater than about 20 kilohertz) can be used to image or therapeutically treat internal body tissues within a patient. For example, ultrasonic waves may be used to ablate tumors, eliminating the need for the patient to undergo invasive surgery. For this purpose, a piezo-ceramic transducer is placed externally to the patient, but in close proximity to the tissue to be ablated ("the target"). The transducer converts an electronic drive signal into mechanical vibrations, resulting in the emission of acoustic waves. The transducer may be shaped so that the waves converge in a focal zone. Alternatively or additionally, the transducer may be formed of a plurality of individually driven transducer elements whose phases can each be controlled independently from one another. Such a "phased-array" transducer facilitates steering the focal zone to different locations by adjusting the relative phases between the transducers. Magnetic resonance imaging (MRI) may be used to visualize the patient and target, and thereby to guide the ultrasound beam.

The effectiveness of ultrasound therapy depends on the accuracy of the focus location, the sharpness and shape of the focal zone, and the avoidance of "hot spots" (i.e., regions of high ultrasound intensity) outside the target. Transducer elements that are not properly configured or controlled can lead to improper focus location and reduced focus quality, resulting in less effective therapy, and possibly damage to healthy tissue surrounding the target. It is therefore desirable to correct any mechanical misconfigurations. Improper transducer configuration may result from manufacturing errors, inadvertent shifting of transducer elements from their expected locations during use or repair, deformation of the transducer due to thermal expansion, or a combination of these and other effects. Even slight locational deviations can have significant effects on the quality of the transducer output. For example, as illustrated in FIG. **1**, if the height of a curved transducer surface having a width of 120 mm and a nominal radius of curvature of 160 mm changes by only 1 mm, the ultrasound focus shifts by about 13 mm. In a phased array, deviations of the transducer locations from the intended locations can be compensated for by adjusting the phases with which the elements are driven. This procedure is hereinafter referred to as "mapping" the transducer.

One approach to mapping a phased-array transducer surface involves driving each transducer element individually to produce an acoustic wave pulse in water; measuring the arrival of the acoustic wave pulse in three locations using a hydrophone; determining for each location the time of flight, and thus the distance, from the transducer element; and calculating the coordinates of the element location by triangulation from the three measurements. Based on the intended and the measured actual locations of the transducer elements, the necessary phase adjustments can be calculated. This method is described in U.S. Pat. No. 7,535,794 to Prus et al., which is hereby incorporated herein by reference in its entirety. In addition to a hydrophone, implementation of the method requires other auxiliary equipment, such as an amplifier and data-acquisition module. Further, to avoid damaging the hydrophone, the mapping is typically performed at transducer power levels significantly below those used during normal operation, which can undermine the validity of the adjustments under therapeutic conditions. Alternative transducer mapping methods that do not have these drawbacks are therefore desirable.

SUMMARY

The present invention generally provides methods for mapping a phased-array transducer by generating an ultrasound focus and improving the focus quality based on experimental feedback. In various embodiments, one or more focus-affecting parameters (such as the phase and/or amplitude of one or more transducer elements) are varied, and the resulting variation of the focus quality is measured (e.g., in terms of an integral or peak intensity, focus size, or intensity profile). The focus-affecting parameter(s) are then set to values for which the focus quality is optimized. For example, the relative phases of the transducer elements may be fine-tuned one at a time to maximize the intensity at the focus. In this manner, unwanted phase shifts resulting from electronic delays or other sources may be corrected, and any deviations from the intended locations of the transducer elements may be compensated for without the need to explicitly determine the actual transducer locations.

During the mapping procedure, the ultrasound focus may be generated in a phantom. To determine the focus quality, the focus may be visualized, for example, by magnetic-resonance acoustic radiation force imaging (MR-ARFI)—an MRI technique measuring minute material displacements that are caused by and indicative of the acoustic field. The displacement increases with the acoustic field intensity. Thus, by adjusting the transducer element phases (and/or amplitudes or other focus-affecting parameters) so as to increase the material displacement in the phantom, the intensity at the focus and, consequently, the focus quality may be improved. Advantageously, MR-ARFI facilitates mapping the transducer at normal operational power levels, which increases the relevance and applicability of any mapping-based adjustments to the subsequent therapeutic operation. Further, the ultrasound focus may be imaged during the mapping procedure with the same MRI or other imaging apparatus (e.g., X-ray-based computer-aided tomography or other tomographic modality) that is used to guide the focus during therapeutic operation, and, consequently, additional (auxiliary) mapping equipment is not needed.

In one aspect, the invention provides a method for improving and/or optimizing the focus of an ultrasound transducer having a plurality of transducer elements. The method includes driving the plurality of transducer elements so as to generate an ultrasound focus, varying a focus-affecting parameter associated with one or more of the transducer elements, measuring a resulting variation on the quality of the focus, and selecting parameter value(s) that result in the best focus quality. The focus-varying parameter(s) may be or include the phase and/or amplitude of one of the transducer elements (or a group of jointly driven elements), or a phase/amplitude gradient or other parameter determining relative phase/amplitude settings of multiple transducer elements that form the whole transducer or a region thereof, or a combination of such parameters. In embodiments in which the location and/or orientation of the transducer or transducer elements are susceptible to direct user control, the focus-varying parameter(s) may, alternatively or additionally, include such location(s) and/or orientation(s). Other focus-varying parameters include, e.g., the drive frequency of the transducer. The quality measurement may involve, for instance, scanning a profile of the focus (e.g., measuring the intensity in the focus region along a line through the focus), measuring the peak (i.e., maximum) intensity of the focus, and/or measuring the integral intensity or size of the focus (i.e., integrating the intensity or area over the cross-section of the focus, where the cross-section is defined, e.g., by the regions in which the intensity is more than a set fraction, e.g., half or 1/e, of the peak intensity).

In certain embodiments, varying the focus-varying parameter(s) and measuring the resultant focus quality includes driving a selected one of the transducer elements at a variable phase while driving the other transducer elements at a constant phase (thereby varying the focus quality); determining the phase difference, if any, between the constant and variable phases where the focus quality is optimized; and, if the phase difference is non-zero, adjusting the relative phase of the selected transducer element based thereon. These steps may be repeated for the remaining transducer elements.

In some embodiments, the quality measurement comprises measuring the displacement associated with the focus using, e.g., ARFI. The ARFI measurement may involve applying a sequence of MR field gradients (such as, e.g., repeated bipolar gradients). The ultrasound focus may generated by an ultrasound pulse synchronized with the sequence of MR field gradients. The method may further involve providing a phantom (which may include a material having low tensile strength and/or a small elastic modulus), and generating the ultrasound focus and measuring the focus quality in the phantom.

In another aspect, the invention is directed to a method for mapping an ultrasound transducer comprising a plurality of transducer elements. The method includes driving the transducer elements so as to generate an ultrasound focus, and measuring a displacement associated with the focus by ARFI. Further, it involves varying the displacement by driving one of the transducer elements at a variable phase while driving the other transducer elements at a constant phase, and determining the phase difference, if any, between the constant and variable phases at which the displacement is maximized. If the phase difference is non-zero, the relative phase of the selected transducer element is adjusted based on the phase difference. The phase difference may also be used to determine the location of the selected transducer element. The application of a variable phase and determination of the phase difference between the variable and constant phases may be repeated for the remaining transducer elements. The ultrasound focus may be generated, and the displacement be measured, in a phantom, which may have a low tensile strength and/or a small elastic modulus. Acoustic-radiation force imaging to measure the displacement may involve applying a sequence of MR field gradients, e.g., a sequence including repeated bipolar gradients. The transducer elements may be driven so as to generate an ultrasound pulse synchronized with the sequence of MR field gradients.

The above-described mapping method(s) may be varied by grouping transducer elements and mapping a group, rather than an individual element, at a time. Accordingly, in yet another aspect of the invention, a selected group of transducer elements is driven at a variable phase while other groups of transducer elements are driven at a constant phase, and the phase difference between the constant and variable phases that maximizes the displacement associated with the focus may be determined and form the basis for adjusting the relative phase of the selected group of transducer elements.

In a further aspect, the invention is directed to a method for controlling an ultrasound transducer having a plurality of transducer elements. The method includes mapping the ultrasound transducer as described above by driving the transducers to generate an ultrasound focus; varying a focus-affecting parameter associated with at least one of the elements and measuring a resulting variation on a quality of the focus; and selecting a value of the parameter associated with a best focus quality. In particular, in some embodiments, mapping may include measuring a displacement associated with the focus (e.g., using ARFI), and determining, for each of the transducer elements, the relative phase associated with that element by driving the transducer element at a variable phase while driving the other transducer elements at a constant phase and determining the phase difference between the constant and variable phases that maximizes the displacement. The method further includes controlling the transducer based on the mapping step (e.g., by adjusting the relative phase of each transducer for which the phase difference is non-zero). Controlling the transducer may include driving the elements to produce outputs converging at a focus corresponding to a target treatment region. Mapping may be carried out using a phantom, and may be repeated in between therapeutic applications of ultrasound.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing will be more readily understood from the following detailed description of the invention in conjunction with the drawings, wherein:

FIG. **1** is a schematic drawing illustrating the effect of a change in the transducer surface on the focus location;

FIG. **2** is a block-diagram illustrating, on a high level, a system for performing transducer mapping in accordance with some embodiments of the invention;

FIG. **3** a schematic diagram illustrating, in more detail, the configuration of a transducer mapping system in accordance with some embodiments;

FIGS. **4A-4C** illustrate various MR-ARFI sequences in accordance with some embodiments;

FIG. **5** is an image of material displacements in an ultrasound focus region in accordance with some embodiments;

FIG. **6** is a graph illustrating material displacement in the focus center as a function of the phase of an individual transducer element, as it may be used in mapping methods in accordance with various embodiments; and

FIG. **7** is a flow chart illustrating an approach to mapping an ultrasound transducer array in accordance with various embodiments of the invention.

DETAILED DESCRIPTION

FIG. **2** illustrates in block-diagram form an exemplary system for performing transducer mapping in accordance with various embodiments hereof, and the interplay between the different system components. The system includes, first, the focused ultrasound transducer hardware **202**, which itself includes the transducer array, a frequency generator for providing an electronic drive signal, and drivers for the transducer elements. (As used herein, the term "transducer" refers to the entire array, as distinguished from the individual transducer elements.) Each driver contains electronic circuitry for setting the phase of the respective transducer element(s), and optionally also for adjusting the amplitude(s) of vibrations. In some embodiments, each transducer elements is independently controllable by a separate associated driver. In alternative embodiments, driver elements are organized (e.g., via hardwiring or configurable switches) into multiple groups of elements driven collectively by the same driver. The drivers are controlled by a control station **204**, which may include a computer system specially designed for use with the transducer hardware, or a general-purpose computer (or cluster of computers) having suitable (and conventional) driver software installed.

The mapping system **200** further includes MRI (or other tomographic or imaging) hardware **206**, i.e., an MRI apparatus and related driver components, which is likewise controlled by the control station **204**. Again, control functionality for the MRI hardware **206** may be implemented in a special-purpose computer system, or in conventional driver software installed on a general-purpose computer system. The transducer hardware **202** and MRI hardware **206** may be controlled by the same computer within control station **204**, or by separate computers that are in communication with one another. Further, computational functionality for processing and analyzing the images acquired with the MRI hardware **206** may be integrated with the MRI apparatus, or implemented (e.g., as a separate software module) in control station **204**.

During the mapping procedure, the control station **204** sends control signals to the ultrasound transducer hardware **202** to vary one or more parameters affecting the focus properties. For example, the control station **204** may cause a phase modulation of a particular transducer element or group of elements. Further, the control station **204** provides scan parameters, or other signals triggering and/or controlling image acquisition, to the MRI or other imaging hardware **206**. The relative timing of the ultrasound generation and/or modulation with respect to image acquisition may be specified in an imaging sequence, which may be programmed into the control station **204**. The control station **204** may then send trigger signals to the ultrasound transducer hardware **202** and the MRI hardware **206**, ensuring correct timing between the signals in accordance with the imaging sequence. Alternatively, the control station **204** may communicate a time-delay parameter, which specifies the time delay between the RF pulses and ultrasound pulses, to the MRI hardware **206**, which sends a corresponding trigger pulse directly to the ultrasound transducer hardware **204**.

The acquired images are processed to determine one or more parameter(s) indicative of the focus quality, which are used in the control station **204** for subsequent mapping steps. For example, in MR-ARFI-based systems, a material displacement indicative of the intensity in the focus is computationally extracted from the images, and the transducer is iteratively adjusted so as to increase the material displacement. Similarly, if thermal MRI is employed, the mapping process involves maximizing the temperature, and thus intensity, in the focus. In general, any imaging technique that provides images suitable for determining focus quality may be used. Depending on the contemplated ultrasound application, the "quality" of the focus may be expressed by different parameters. For therapeutic applications involving targeted tissue destruction, for example, the focus quality may be measured in terms of a peak intensity or total power delivered (corresponding to an integrated intensity over the focus cross section). If the target area is small, the focus size may be relevant (a smaller focus area generally corresponding to higher focus quality). In some applications (e.g., tissue heating for palliative purposes), homogeneity of the intensity focus area may be important, and focus quality may, accordingly, be measured, at least in part, by the "smoothness" of an intensity profile through the focus.

FIG. **3** schematically illustrates an experimental setup for mapping an ultrasound transducer using tissue displacement as an indicator of focus quality. During the mapping procedure, the transducer **300** is driven so as to focus an ultrasound wave pulse into a phantom **302**, which comprises or consists of a material that responds to acoustic pressure in a detectable manner. The ultrasound wave exerts acoustic radiation pressure onto the phantom material along its path. At the focus **304**, where waves from the individual transducer elements converge, this pressure is highest, resulting in a temporary local displacement of the material in the longitudinal direction and/or in shear waves that propagate radially away from the focus. By using a soft phantom that responds to acoustic pressure with large enough shear strain (e.g., with a shear strain of at least 10^{-2}), a detectable displacement field that directly reflects the acoustic field may be obtained. Suitable phantom materials have high tensile strength (e.g., higher than 100 kPa) and small elastic moduli (e.g., Young's modulus less than 1 MPa), and may include or consist of jelly-like materials such as, e.g., Silicone Gel RTV6166, provided by General Electric Co., Waterford, N.Y.

The material displacement may be visualized in an imaging plane **306** using an imaging techniques such as, e.g., magnetic-resonance-based acoustic radiation force imaging (MR-ARFI). In MR-based imaging methods, the object to be imaged (here, the phantom) is placed in a relatively uniform static magnetic field having a field strength of, typically, between about 1.5 and about 3.0 Tesla. Such a field may be generated, for example, by a large cylindrical electromagnet coil **308**. The static magnetic field causes hydrogen nuclei spins to align and precess about the general direction of the magnetic field. Radio frequency (RF) pulses and magnetic gradients are then superimposed on the static magnetic field to cause some of the aligned spins to alternate between a temporary high-energy non-aligned state and the aligned state, thereby inducing an RF response signal, called the MR echo or MR response signal, in the RF antenna **310**.

In MR-ARFI, transient-motion or displacement-sensitizing magnetic field gradients are applied to the phantom by gradient coils, which are part of standard MRI systems and are typically located near the cylindrical electromagnet coil **308**. When the ultrasound pulse is applied in the presence of such gradients, the resulting displacement is directly encoded into the phase of the MR response signal. For example, the gradient coils and transducer may be configured such that the ultrasound pulse pushes phantom material near the focus towards regions of the magnetic field with higher field strengths. In response to the resulting change in the magnetic field, the phase of the MR response signal changes proportionally, thereby encoding in the signal the displacement caused by the ultrasound radiation pressure.

To achieve high image contrast, the ultrasound pulse, encoding gradients, and RF pulse are precisely timed with respect to each other according to a suitable displacement-encoding sequence. FIGS. **4A-4C** illustrate five exemplary MR-ARFI sequences that may be used in embodiments of the invention. These sequence diagrams illustrate the order in which the displacement-encoding magnetic field gradients (thin solid lines), ultrasound pulses (dotted lines), and RF pulses (thick solid lines) appear in time. Three different field gradient sets are shown: two single lobes (a), repeated bipolars (b), and inverted bipolars (c). For gradient set (a), ultrasound may be applied during either the first or the second lobe. Similarly, for gradient set (c), ultrasound may be applied during the first or the second halves of the bipolars. In general, MR-ARFI sequences utilize magnetic field gradients that are synchronized with the ultrasound pulses. In preferred embodiments, a sequence like the repeated bipolar sequence (b) shown in FIGS. **4**A-**4**C may be used.

An example of an MR-ARFI image of an ultrasound focus region is shown in FIG. **5**. As shown, the material displacement with respect to an equilibrium position varies between about −1 μm and 5 μm, as indicated in the color-coding of the image. In general, the stronger the acoustic field intensity, the greater will be the maximum displacement at the center of the focus. The acoustic field intensity, in turn, is maximized when the elements of the ultrasound transducer emit acoustic waves that are all in phase at the focus position. If a transducer element is out of phase with respect to the others, the focus intensity in the center decreases. This relationship can be exploited to optimize the focus, and thus to map and adjust the transducer elements. Assuming, for example, that all but one of the transducer elements are properly configured, the correct phase of the last element can be determined by tuning the phase over a full cycle (e.g., between $-\pi$ and $+\pi$), measuring for each phase the displacement in the focus center, and then setting the phase to the value corresponding to the maximum displacement. FIG. **6** depicts the results of such an adjustment procedure. In the illustrated example, the material displacement over the full phase cycle of one element varies between about 4.85 μm and about 5.4 μm. The maximum displacement occurs at about 0.12 rad. Consequently, the focus intensity and quality can be improved by introducing a phase shift of 0.12 rad for the tested transducer element.

In certain embodiments, mapping of the full transducer array is accomplished by varying and adjusting the phase (and/or amplitude) of each element, one at a time, while driving the remaining elements at constant phase. Typically, after each element has been mapped independently, the focus quality has significantly improved. Since the necessary phase adjustments of the transducer elements are all interrelated, however, the focus may not yet be optimal after one iteration. Therefore, in some embodiments, the procedure may be repeated iteratively. With each iteration, the phase adjustments made to maximize the displacement in the focus will, generally, decrease. Thus, a termination condition may be defined by setting a threshold value for phase adjustments, below which further adjustments are deemed immaterial or not clinically necessary. The number of iterations required to reach the termination condition may depend on the order in which the transducer elements are mapped. A mathematical algorithm, for example a "greedy algorithm" as known to persons of skill in the art, may be used to select a mapping order that results in fast convergence of the phase settings. In certain alternative embodiments, the transducer elements may be grouped, and groups of elements may be mapped simultaneously.

FIG. **7** illustrates a representative method for mapping an ultrasound transducer array in accordance with various embodiments of the invention. The method involves, in a first step **700**, providing a phantom, and installing the transducer array and phantom in an MRI apparatus. Further, an imaging sequence defining the duration and relative times of ultrasound pulses, RF pulses, and encoding gradients is chosen (step **701**). The phases of the transducer elements are then set to a constant value (step **702**), and the focus location is determined by identifying the position of the phantom's maximal displacement in the MR-ARFI image (step **703**). An iterative phase-adjustment process is subsequently started by selecting one element (or one group of elements) for mapping (step **704**). The selected element is driven at a variable phase (step **708**), and for each phase setting, the transducer elements are collectively driven to generate an ultrasound focus in the phantom (**710**). Substantially simultaneously, or after a time interval overlapping with the generation of the ultrasound focus, the displacement of phantom material in the focus region is measured by MR-ARFI in accordance with the imaging sequence (step **712**). Typically, this step is repeated until the variable phase of the selected transducer element has covered a range of phases spanning an interval of 2π. In step **714**, the phase difference between the constant phase and the phase of the selected transducer element that maximizes the displacement is determined (step **712**). If the phase difference is non-zero, the phase of the transducer element is adjusted by this difference (step **718**). Steps **704** through **718** are then repeated until each transducer element has been mapped. If the phase adjustments made in step **718** fall below a predetermined threshold value, or an alternative termination condition is satisfied, the mapping is complete. Otherwise, the mapping procedure for the array may be repeated, starting with the adjusted phase settings of the transducer elements.

The method described above may be varied in several ways. For example, the phase differences may first be determined for all the elements, without adjustments being made, and following this mapping procedure, all the phase adjustments may be made at once. In this case, an iterative phase adjustment is not needed because the reference phase, i.e., the phase of the transducer as a whole, disregarding the element under mapping, is nearly the same for all elements. Further, in some embodiments, the phases of the transducer elements may be adjusted simultaneously, rather than in succession, by varying a drive parameter affecting some or all of the elements. For example, the relative phases between transducer elements may be expressed in terms of a functional dependence of the phase on the position of a transducer element along one or two axes of the transducer array, and such functional dependence, in turn, may be characterized by one or few mathematical parameters (e.g., a linear phase gradient and/or coefficients of higher-order components of the phase modulation in one- or two-dimensional space). Rather than modulating the phase of an individual element, then, the coefficients in the functional dependence may be varied, and the corresponding effect on the focus quality observed.

Alternatively or in addition to phase variations, amplitude variations of individual elements or groups of elements (including variations of the functional dependence of the amplitude on a position along the array) may also be employed to improve the focus quality. Further, in some embodiments, the transducer elements may be movable with respect to the one another within certain ranges (e.g., as a consequence of being mounted on electronically controllable microtranslator stages, pivots, etc.). The experimental adjustment procedure described above may then be used to fine-tune the positions and/or orientations of the transducer elements. The overall shape, position, and orientation of the transducer may likewise be controllable, e.g., via clasps, movable bearings, etc.

Although the present invention has been described with reference to specific details, it is not intended that such details should be regarded as limitations upon the scope of the invention, except as and to the extent that they are included in the accompanying claims.

What is claimed is:

1. A method for mapping an ultrasound transducer comprising a plurality of transducer elements so as to improve a focus thereof, the method comprising:

(a) driving the plurality of transducer elements so as to generate an ultrasound focus;

(b) using acoustic radiation force imaging, measuring a displacement associated with the focus;

(c) grouping the transducer elements;

(d) driving a selected group of transducer elements at a variable phase while driving the other groups of transducer elements at a same constant phase, thereby varying the displacement;

(e) determining a phase difference, if any, between the same constant phase and the variable phase where the displacement is maximized; and

(f) if the phase difference is non-zero, adjusting a relative phase of the selected group of transducer elements based thereon.

2. The method of claim **1** further comprising scanning a profile of the focus.

3. The method of claim **1** further comprising measuring a size of a cross-section of the focus.

4. The method of claim **1** further comprising measuring an integral intensity of the focus.

5. The method of claim **1** further comprising measuring a peak intensity of the focus.

6. The method of claim **1** wherein the acoustic radiation force imaging comprises applying a sequence of MR field gradients.

7. The method of claim **6** wherein the sequence of MR field gradients comprises repeated bipolar gradients.

8. The method of claim **7** wherein step (a) comprises generating an ultrasound pulse synchronized with the sequence of MR field gradients.

9. The method of claim **1** further comprising repeating steps (d) through (f) for the remaining groups of transducer elements.

10. The method of claim **1** further comprising the step of providing a phantom, the driving step generating an ultrasound focus in the phantom and the measuring step measuring a focus quality in the phantom.

11. The method of claim **10** wherein the phantom comprises a material having low tensile strength.

12. The method of claim **11** wherein the phantom comprises a material having a small elastic modulus.

13. A system for mapping an ultrasound transducer so as to improve a focus thereof, the system comprising:

ultrasound transducer hardware for generating an ultrasound focus, the ultrasound transducer hardware comprising an ultrasound transducer having a plurality of transducer elements and associated driver circuitry, the transducer elements being organized in multiple groups of elements;

magnetic-resonance-imaging (MRI) hardware comprising an MRI apparatus and associated driver components for acquiring images of a region comprising the ultrasound focus; a control station in communication with the ultrasound transducer hardware and the MRI hardware, the control station being configured to

control (i) image acquisition with the MRI hardware and (ii) generation of the ultrasound focus with the ultrasound transducer hardware in accordance with an imaging sequence that specifies the relative timing between image acquisition and ultrasound generation;

process acquired images to determine therefrom a displacement associated with the focus;

send control signals to the ultrasound transducer hardware to vary a phase of a selected group of transducer elements while driving the other groups of transducer elements at a same constant phase; and

adjust the phase of the selected group of transducer elements relative to the same constant phase of the other groups based on a phase difference between the same constant phase and the variable phase where the displacement is maximized.

14. The system of claim **13**, wherein the driver circuitry is hardwired to create the groups of transducer elements.

15. The system of claim **13**, wherein the driver circuitry comprises switches for configuring the groups of transducer elements.

16. The system of claim **13**, wherein the control station comprises separate, intercommunicating computers for controlling the ultrasound transducer hardware and the MRI hardware, respectively.

17. The system of claim **13**, wherein the imaging sequence specifies a sequence of MR field gradient synchronized with ultrasound generation.

18. The system of claim **13**, wherein controlling image acquisition and ultrasound-focus generation in accordance with an imaging sequence comprises sending trigger signals to the ultrasound transducer hardware and the MRI hardware.

19. The system of claim **13**, wherein controlling image acquisition and ultrasound-focus generation in accordance with an imaging sequence comprises communicating a time-delay parameter to the MRI hardware, the MRI hardware being configured to send a trigger signal based on the time-delay parameter to the ultrasound transducer hardware.

20. A method for controlling an ultrasound transducer comprising a plurality of transducer elements organized into groups of elements, the method comprising:

(a) mapping the ultrasound transducer by (i) driving the plurality of transducer elements so as to generate an ultrasound focus in a phantom, (ii) varying a focus-affecting parameter associated with at least one of the groups of elements while driving the other groups of transducer elements at a same constant value of the focus-affecting parameter and measuring a resulting variation on a quality of the ultrasound focus using magnetic-resonance acoustic radiation force imaging, and (iii) selecting a value of the focus-affecting parameter associated with a best focus quality; and

(b) controlling the ultrasound transducer based on the mapping step so as to focus ultrasound into internal body tissue.

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摘要(译)

可以通过改变影响焦点的参数并调整参数来映射超声换能器，以便改善聚焦质量。在一些实施例中，映射涉及相对于其他换能器元件的恒定相位连续地改变一个换能器元件或元件组的相位，并确定超声波焦点中的组织位移最大化的相位。