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(54) **METHOD AND APPARATUS FOR RAPID ACQUISITION OF ELASTICITY DATA IN THREE DIMENSIONS**

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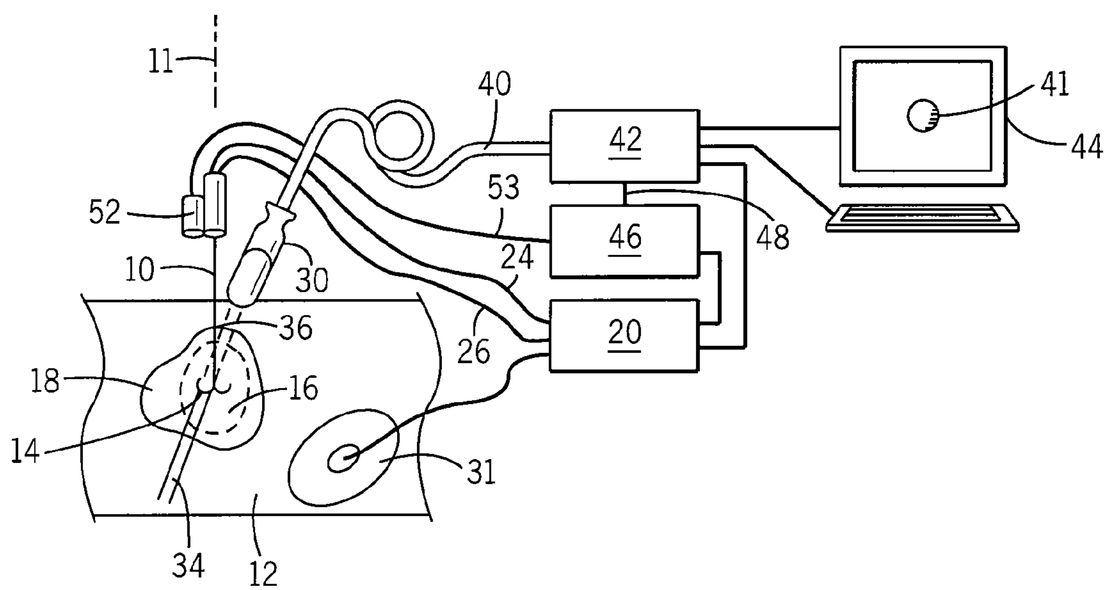
(57) **ABSTRACT**

High-speed three-dimensional reconstruction of elasticity data is obtained by acquiring a sparse set of data in planes sharing a common axis line and angularly arrayed about the axis line. The axis line may be an RF ablation probe and the reconstruction may enforce a circumferential smoothness in the reconstruction about the probe, as is compatible with an ablation volume.



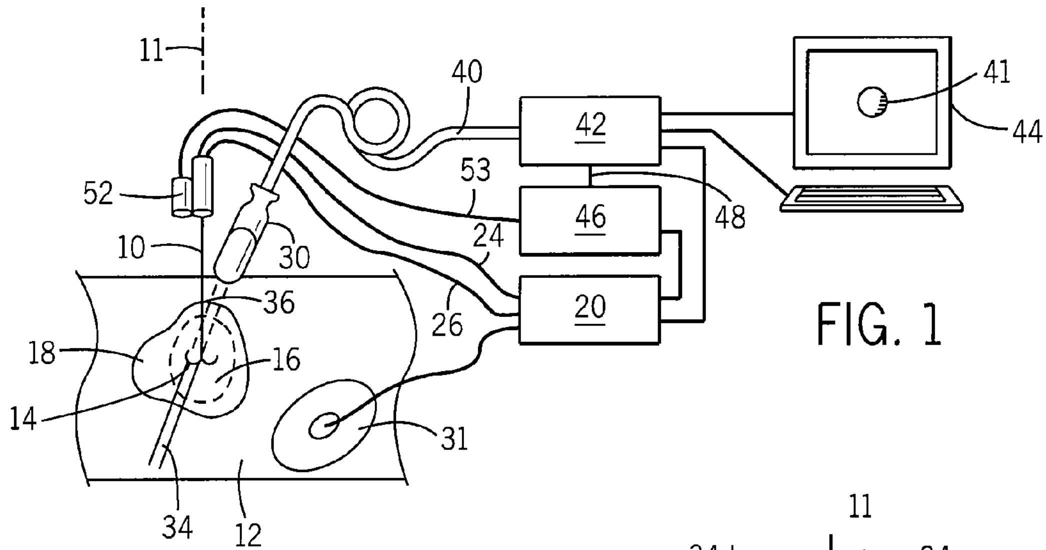


FIG. 1

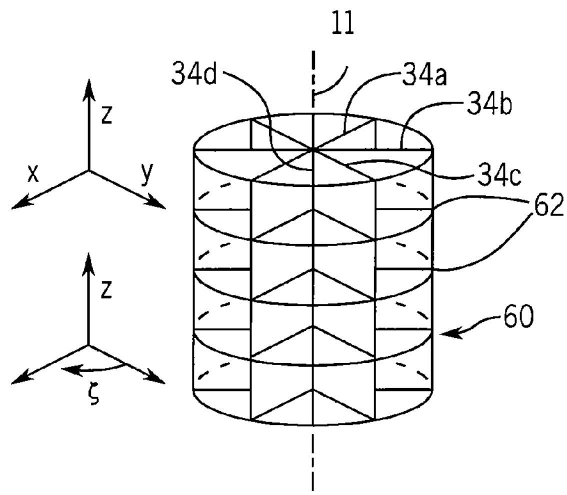


FIG. 2

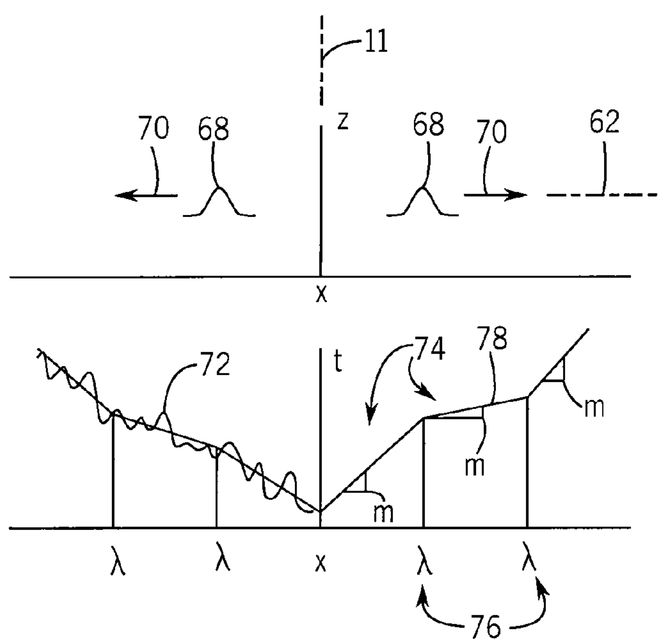


FIG. 3

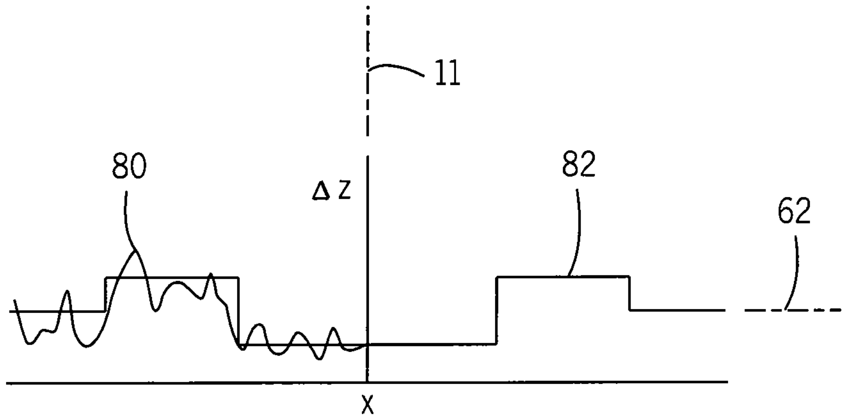


FIG. 4

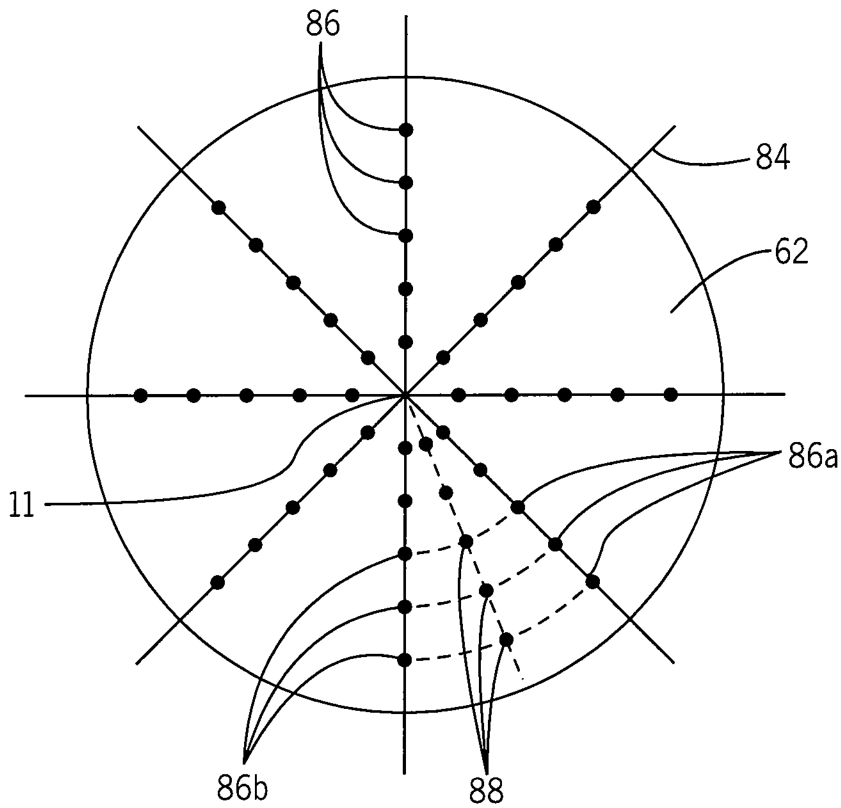


FIG. 5

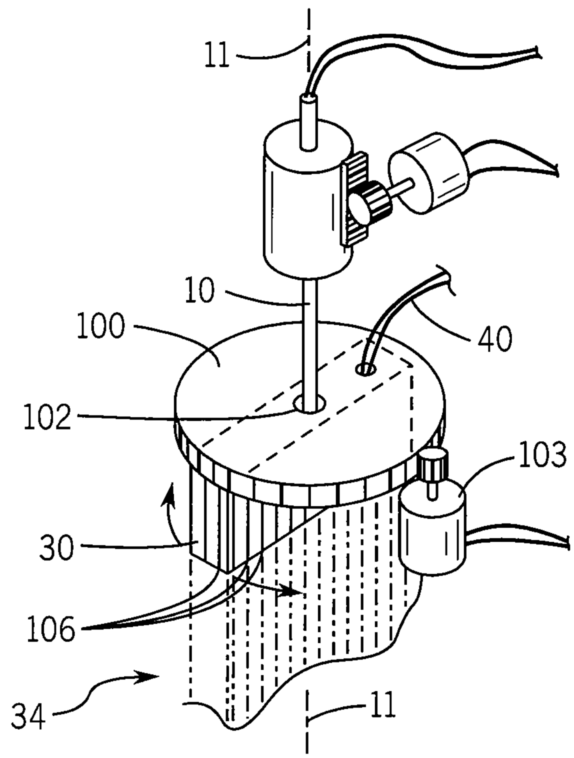


FIG. 6

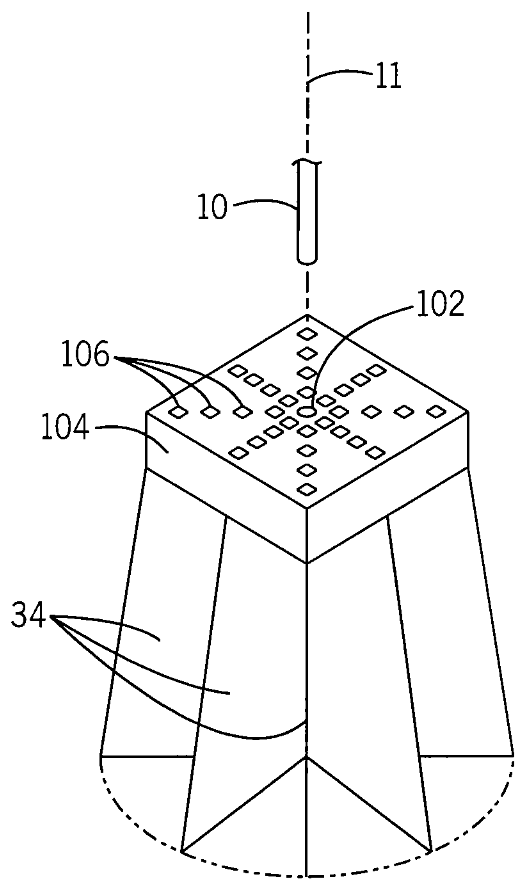
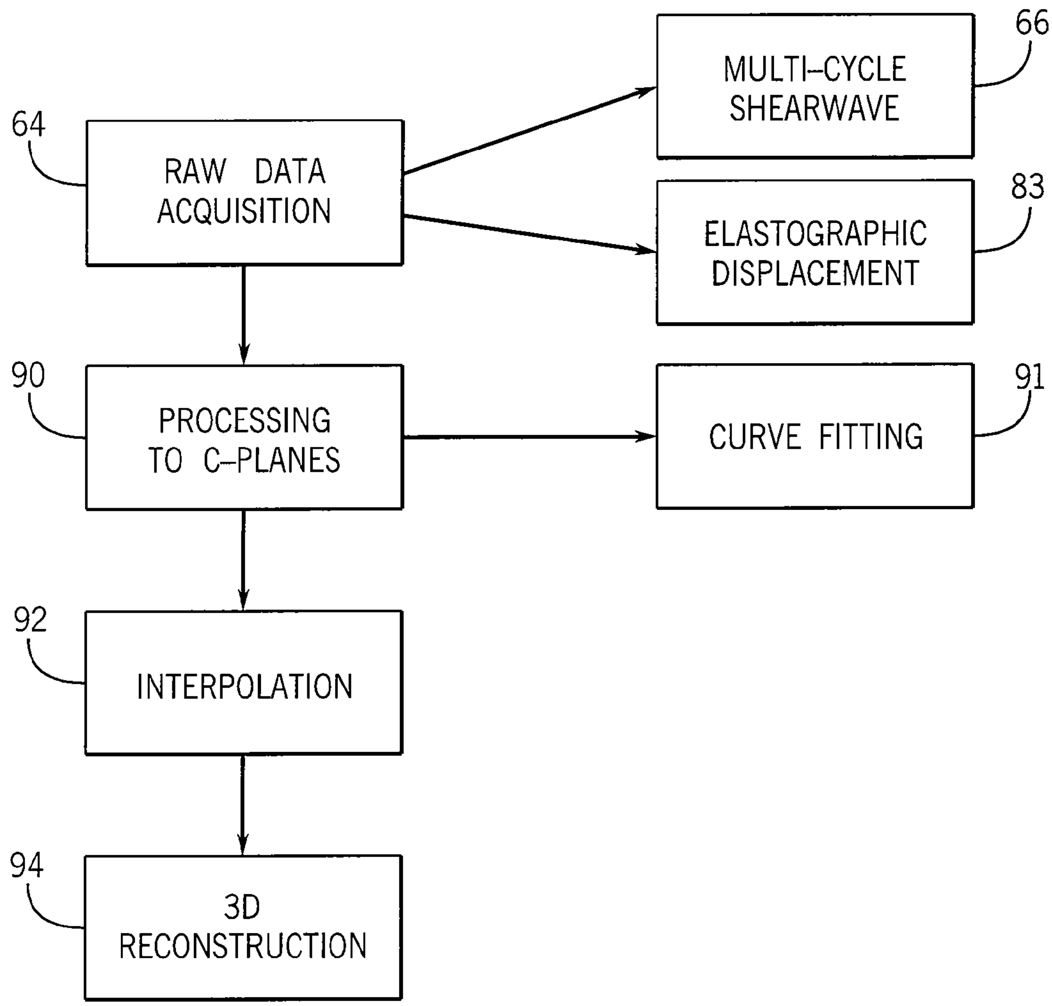


FIG. 7



MULTI–CYCLE SHEARWAVE
66
64
RAW DATA ACQUISITION
ELASTOGRAPHIC DISPLACEMENT
83
90
PROCESSING TO C–PLANES
CURVE FITTING
91
92
INTERPOLATION
94
3D RECONSTRUCTION

FIG. 8

METHOD AND APPARATUS FOR RAPID ACQUISITION OF ELASTICITY DATA IN THREE DIMENSIONS

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0001] This invention was made with government support under CA112192 awarded by the National Institutes of Health. The government has certain rights in the invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] —

BACKGROUND OF THE INVENTION

[0003] The present invention relates to ultrasonic imaging techniques for obtaining information about tissue elasticity and in particular to a method of rapidly acquiring three-dimensional elasticity reconstructions useful, for example, during RF ablation.

[0004] Elastography is an imaging modality that reveals the stiffness properties of tissues, for example axial strain, lateral strain, Poisson's ratio, Young's modulus, or other common stiffness measurements. The stiffness measurements may be output as quantitative values or mapped to a gray or color scale to form a picture over a plane or within a volume.

[0005] Generally, stiffness is deduced by monitoring tissue movement under an applied force or deformation. The monitoring may be done by any medical imaging modality including computed tomography (CT), magnetic resonance imaging (MRI), and ultrasonic imaging. Elastography of this type is analogous to a physician's palpation of tissue in which the physician determines stiffness by pressing the tissue and detecting the amount that the tissue yields under pressure.

[0006] In "dynamic" elastography, a low frequency vibration is induced in the tissue and the velocity of the resulting compression/shear waves is measured, for example, using ultrasonic Doppler detection. In "quasi-static" elastography, two images of the tissue are obtained at different states of compression, typically using the ultrasonic transducer as a compression paddle. Displacement of the tissue between the two images is used to deduce the stiffness of the tissue.

[0007] U.S. Pat. No. 7,166,072, assigned to the same assignee as the present invention and incorporated by reference, describes a novel technique for monitoring a radiofrequency ablation using quasi-static elastography. Radiofrequency or microwave ablation is a process for treating tumors or the like which employs one or more electrodes inserted percutaneously to the site of a tumor. Ionic heating of the tissue induced by radiofrequency fields in the tissue kills tumor cells and produces a hardened lesion. This lesion, being much stiffer than the surrounding tissue, may be monitored by quasi-static elastography using the ablation electrode as the compression device. Adhesion between the ablated tissue and the electrode allows the source of the compression to be at the site of the tumor (as opposed to external compression to the patient) providing a more accurate characterization of the stress field near the tumor and, accordingly, substantially improved elastographic measurement.

[0008] The present inventors have also developed a method of evaluating tissue elasticity by monitoring the propagation of shear waves extending generally perpendicularly to an axis of the ultrasound. The shear waves may be induced, for example, by reciprocation of an ablation probe. The speed of the shear wave is dependent on tissue elasticity, and may be extracted from the ultrasound image to reveal information about the size and growth of an ablated region. This process is described in U.S. Pat. No. 8,328,726 issued Dec. 11, 2012, assigned to the assignee of the present invention and hereby incorporated by reference.

[0009] Generally, these techniques may be used to produce three-dimensional elasticity data and images, for example, by sliding or rocking the ultrasound transducer to obtain multiple image planes within a volume. The data of these planes may be collected to produce a three-dimensional image. Substantial time is required to acquire the necessary data for these three-dimensional techniques limiting their usefulness for monitoring a real-time process such as RF ablation. Acquiring three-dimensional data sets is particularly time consuming when multiple registered images need to be obtained at each location as is often the case with elastography. Although data volumes can also be acquired directly using 2D ultrasound array transducers, the use of such technology is currently limited due to the high cost of manufacturing such sensor arrays.

SUMMARY OF THE INVENTION

[0010] The present invention provides a way of rapidly acquiring three-dimensional elasticity images by acquiring a limited number of planes of data extending along and arrayed angularly about a central axis. This acquisition technique allows, for example, monitoring of ablation on a real-time basis but may also be used for other 3-D imaging purposes. The radial acquisition pattern provides a good trade-off between reducing the required data acquisition while still providing the resolution necessary to identify ablation region boundaries or other similar volume edges.

[0011] Specifically then, the present invention may provide an apparatus for acquiring three-dimensional elasticity data having an ultrasonic probe assembly adapted to direct an ultrasound beam into an elastic material and receive ultrasonic echoes generally along an axis to acquire a set of planes of ultrasound data such that the axis lies substantially within each plane, and the planes are angularly spaced around the axis. An electronic computer receives the ultrasound data to compute measures of material elasticity at multiple points within each plane and reconstruct the multiple points of material elasticity of multiple planes into a three-dimensional representation of elasticity of the material.

[0012] It is thus a feature of at least one embodiment of the invention to provide a rapid 3-D acquisition and reconstruction system suitable, for example, for real-time monitoring of operations such as ablation. It is further a feature of at least one embodiment of the invention to provide an acquisition and 3-D reconstruction technique generally applicable to quantitative ultrasound imaging.

[0013] The set of planes may be between 4 and 6 in number.

[0014] It is thus a feature of at least one embodiment of the invention to reconstruct useful three-dimensional reconstructions with extremely sparse data.

[0015] The reconstruction of the multiple points of material elasticity of multiple planes may enforce a circumferential smoothness in the reconstruction.

[0016] It is thus a feature of at least one embodiment of the invention to provide an acquisition and reconstruction system well suited for structures that tend to be radially uniform about a known axis.

[0017] The reconstruction may employ a multidimensional interpolation (e.g., bilinear, trilinear or multilinear interpolation) along cylindrical coordinates centered on the axis.

[0018] It is thus a feature of at least one embodiment of the invention to provide a simple reconstruction algorithm providing one way to enforce circumferential smoothness.

[0019] The measures of material elasticity may evaluate speed of a shear wave extending perpendicularly through the material from the axis.

[0020] It is thus a feature of at least one embodiment of the invention to provide an acquisition and reconstruction system compatible with wave speed analyses of radially propagating shear waves.

[0021] The apparatus may further include an electrical probe adapted for percutaneous insertion into tissue at a tumor site communicating with a high-frequency power source to ablate tissue at the tumor site.

[0022] It is thus a feature of at least one embodiment of the invention to provide an ultrasound system for rapidly evaluating an ablated tumor volume on a real-time basis.

[0023] The electrical probe may include an actuator communicating with the electrical probe to provide reciprocation of the electrical probe along the axis.

[0024] It is thus a feature of at least one embodiment of the invention to provide a simple method of generating elasticity data well suited for the radial data acquisition pattern of the present invention.

[0025] The electronic computer may communicate with the actuator to time acquisitions of echoes to obtain multiple acquisitions of echoes at each of successive phase offsets with respect to a phase of the reciprocation of the electrode.

[0026] It is thus a feature of at least one embodiment of the invention to provide a method of evaluating shear wave propagation using B-mode data acquisition that would normally be too slow for such acquisition.

[0027] The measures of material elasticity may evaluate displacement of the material in response to a quasi-static periodic compression of the material.

[0028] It is thus a feature of at least one embodiment of the invention to provide an acquisition and 3-D reconstruction technique generally applicable to quasi-static elastography.

[0029] The ultrasonic probe assembly may be adapted to direct a tissue-stimulating beam of ultrasonic energy into the tissue to promote a displacement of the tissue measurable by the ultrasonic echoes, and wherein the measures of material elasticity evaluate the promoted displacement.

[0030] It is thus a feature of at least one embodiment of the invention to provide an acquisition and 3-D reconstruction technique generally applicable to dynamic elastography, for example acoustic radiation force impulse imaging (ARFI), Supersonic Shear Imaging (SSI), Electrode Vibration Elastography (EVE) and similar techniques.

[0031] The ultrasonic probe assembly may provide a substantially one-dimensional array of transducer elements extending perpendicularly to the axis and may provide a mechanism for rotating the one-dimensional array about the axis to acquire the multiple planes.

[0032] It is thus a feature of at least one embodiment of the invention to provide a simple acquisition system that may rotate a standard probe used for two-dimensional acquisitions.

[0033] Alternatively, the ultrasonic probe assembly may provide a two-dimensional array of transducer elements arrayed preferentially along lines of diameter extending perpendicular to the axis.

[0034] It is thus a feature of at least one embodiment of the invention to provide a specialized array for acquisition along multiple planes without necessary movement and compatible with limited acquisition bandwidth available in most ultrasound systems.

[0035] These particular objects and advantages may apply to only some embodiments falling within the claims, and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0036] FIG. **1** is a simplified block diagram of an ultrasound imaging system for use with the present invention using a standard 2-D array ultrasound transducer as used with an optional RF ablation system providing an ablation probe for introduction into a tumor site of an in vivo organ and including a control system for applying a controlled reciprocation RF ablation probe for shear wave or quasi-static elastography imaging;

[0037] FIG. **2** is a simplified depiction of a geometry of a pattern of data acquisition employed in the present invention showing an example with four angularly separated planes of data acquisition sharing a common axis;

[0038] FIG. **3** is a graph of the shear wave propagation along an x-axis as fit to a set of constant slope segments by preprocessing/filtering/smoothing technique for noise reduction;

[0039] FIG. **4** is a graph similar to that of FIG. **3** showing tissue displacement at different points along the x-axis associated with quasi-static elastography;

[0040] FIG. **5** is a top plan view of the data acquisition geometry of FIG. **2** showing bilinear cylindrical interpolation used in one embodiment of the invention;

[0041] FIG. **6** is a simplified representation of an ultrasonic transducer for automatically acquiring data in the geometry shown in FIG. **2** by rotation of a 2-D ultrasound probe;

[0042] FIG. **7** is a figure similar to that of FIG. **6** showing a sparse 3-D ultrasonic probe for obtaining data in the geometry of FIG. **2**; and

[0043] FIG. **8** is the principal steps of the present invention in several embodiments.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0044] General Description of the Hardware

[0045] Referring now to FIG. **1**, an RF ablation probe **10** may be inserted percutaneously into a patient **12** along an axis **11** to have its tip located at an ablation region **16** within an organ **18**, such as the liver. Extensible electrode tines **14**, at the tip of the probe **10**, may grip the tissue of the ablation region and provide a greater area of electrical contact to conduct ablative current from a radiofrequency (RF) source **20**.

[0046] In this regard, electrical energy from the RF source **20** is conducted through an insulated shaft of the probe **10** to the conductive tines **14** where ionic heating of the tissue kills tumor tissue. A large-area grounding pad **31** placed on the patient's skin provides a return path for this current. The tines **14** may optionally include thermocouples for temperature measurements used to control the electrical energy to minimize the formation of a layer of high impedance charred tissue between the tines **14** and the tissue.

[0047] RF ablation probes **10** suitable for this purpose may include a single 17-gauge electrode, with a 2-3 cm long electrically active region at the tip embedded in tissue.

[0048] These electrodes also offer the option of internally circulating chilled water during the ablation procedure to minimize the charring of tissue adjacent to the electrically active region of the electrode. RF ablation probes **10** of this kind having extensible tines and thermocouple sensors are known in the art and commercially available, for example, under the tradename Valleylab Cool-tip™ ablation electrode manufactured by Valleylab, Colo., USA, or from other companies. The RF source **20** may be a Rita Model **30** electrosurgical device manufactured by Rita Medical Systems, Inc., Mountain View, Calif., or another similar device.

[0049] During the ablation process, electrical current is conducted from the RF source **20** along line **26** to the ablation probe **10**. The temperature signal is returned along line **24** to be received by the RF source **20** and used to limit the temperature of ablation according to techniques well understood in the art.

[0050] Imaging of the tissue and the tip of the probe **10** may be done using standard ultrasonic imaging system hardware, for example the Siemens 52000 Real Time Scanner manufactured by Siemens, Inc. of California. The ultrasonic imaging system hardware may include an ultrasonic transducer **30** communicating with ultrasound processing circuitry **42**. The ultrasonic transducer **30** may be, for example, a one-dimensional ultrasonic transducer **30** (meaning that it has a one-dimensional array of individual transducer elements to acquire data over two dimensions) in the form of a linear array transducer approximately forty millimeters wide, operating with dynamic focus over a forty percent bandwidth and producing signals at a center frequency of five megahertz.

[0051] During insertion of the probe **10**, the ultrasound transducer **30** is placed against the skin of the patient **12** to emit a beam **36** of ultrasound directed into the patient **12** to acquire echo data along an imaging or data plane **34** extending from the ultrasound transducer **30** (seen edgewise in FIG. **1**). After insertion of the probe **10**, the ultrasound transducer **30** may be used to monitor the ablation using elastographic imaging as will be described. During this monitoring and the subsequent Alaska graphic imaging, the axis of the ultrasound transducer along which the ultrasound beam **36** propagates is aligned as closely as possible to the axis **11** along which the probe **10** extends. The probe **10** stabilizes the organ **18** and prevents lateral shifting along an axis perpendicular to axis **11**.

[0052] During both insertion of the probe **10** and the ablation process, an ultrasound beam **36** generated by the ultrasound transducer **30** travels into the tissue of the patient **12** and is reflected at various tissue structures and boundaries. These echoes are detected by the ultrasound transducer **30** and conducted by cable **40** to the ultrasound processing circuitry **42**. The received signals are digitized at a sampling rate of approximately **50** megahertz, and then processed according to techniques well known in the art, to produce a sequence of two-dimensional images, for example, providing a constantly refreshed B-mode image on display terminal **44**.

[0053] A controller **46**, which may be a computer or logic controller programmed as described below, may also provide output lines **53** connected to a motorized carriage **52**, for example, using a motor and a lead screw (not shown) to provide motion of the probe **10** along its insertion axis **11** to reciprocate the probe **10** in a controlled manner according to signals on output line **53** as will also be described. Other mechanisms for implementing the motorized carriage **52**, including those which apply a predetermined compressive force or low frequency oscillation, are also contemplated, for example, using an eccentric weight. In some embodiments, the controller **46** may also communicate with ultrasound processing circuitry **42** (or the display terminal **44** directly) for displaying images and receiving user input commands.

[0054] The digitized echo signals from the ultrasound transducer **30** are further processed either within the ultrasound processing circuitry **42**, or within controller **46**, to produce an elastographic image **41**. In the former case, line **48** communicates signals from the controller **46** to the ultrasound processing circuitry **42** to coordinate generation of the elastographic image; in the latter case, line **48** carries the control signals and digitized echo signals from the ultrasound processing circuitry **42** to the controller **46** for processing by the controller **46**.

Operation

[0055] Referring now to FIGS. **1** and **2**, in a first embodiment, the ultrasound transducer **30** may be rotated about the probe **10** so as to rotate the data plane **34** about axis **11** while maintaining the plane **34** substantially aligned with axis **11**. This rotation allows the acquisition of echo data along multiple planes. In this example four planes **34***a-d* are shown spaced from each other by 45 degrees. Other numbers of planes, for example five and six equally or unequally spaced planes **34**, are also practical and there is generally no upper limit to the number of planes based on a trade-off between data acquisition and speed of reconstruction. Each of these planes **34** will provide multiple points of echo data over the surface of the plane **34**, each point of echo data described, for example, by a z-axis coordinate value (where the z-axis is aligned with axis **11**) and an x-axis coordinate value perpendicular to the z-axis and lying within the plane **34**. Together the planes **34***a-d* are circumscribed within a cylindrical volume **60** that holds multiple C-planes **62** generally normal to axis **11** and spaced regularly along the z-axis. Generally, these planes may be acquired by beam steering or other techniques.

[0056] Referring momentarily to FIG. **8**, in a first step of the invention, echo data of each plane **34** is processed to extract raw data necessary for elasticity measurements as indicated by process block **64**. The deduced elasticity may indicate absolute or relative elasticity of the tissue, and the raw data may be obtained using various different techniques. In a first technique, indicated by sub process block **66**, the data of the planes **34** may be processed to acquire multi-cycle shear wave data as will now be described.

[0057] Referring to FIGS. **1** and **3**, a reciprocating motion of the probe **10**, or other stimulation techniques such as ARFI, SSI and EVE and the like, may generate shear waves **68** propagating perpendicularly to axis **11**, for example radially away from that axis **11** as indicated by arrows **70**. Detection of the shear waves at each C-plane **62** may be performed by direct analysis of the radiofrequency ultrasonic signal or through the analysis of B-mode images to detect the displacement between successive images incident to the deformation of the shear wave **68**, for example, as described in U.S. Pat. No. 8,328,726 cited above. Generally the generation of B-mode imaging will not occur rapidly enough to track movement of the shear waves **68** along arrows **70** in real time but an effective reconstruction of that motion may be obtained by coordination between ultrasound processing circuitry **42** and the controller **46** reciprocating the probe **10** to obtain data of the data plane **34** capturing the shear waves **68** at multiple times, each time having a different phase delay with respect to the reciprocation of the probe **10**. Under the assumption that the shear waves **68** will be identical for each cycle of the reciprocation, this allows a piecewise reconstruction of the motion of the shear wave **68**. Alternatively, the entire image plane can be scanned using a plane acoustic wave to bypass the low imaging speed of B-mode acquisitions. Such plane acoustic wave acquisitions image the complete imaging plane in a single sweep, unlike the sequential focused technique used in B-mode acquisitions.

[0058] As indicated by process block **90** of FIG. **8**, propagation of the shear wave **68** in terms of arrival time at various locations along the x-axis may be plotted in a measurement curve **72** for each C-plane against different positions along the x-axis. The reciprocal of the slope of the measurement curve **72** will generally indicate the velocity of the shear wave **68** providing information about elasticity of the propagating medium. The substantial noise component in the measurement curve **72** presents a problem with respect to differentiating this measurement curve **72** in order to obtain velocity. Accordingly, the present invention first fits the measurement curve **72** to an a priori model of the tissue per process sub block **91**. One such model postulates radially extending regions **74** of constant of propagation velocity having slopes m separated by breakpoints **76**, for example, representing boundary lines between ablated tissue and unablated tissue within the organ or between unablated tissue within the organ and tissue outside of the organ, for example. By fitting this model **78** to the actual data of the measurement curve **72**, velocities may be readily extracted as the values m with reduced noise. These velocities 1/m provide elasticity data for points in the data plane **34**.

[0059] It will be appreciated that other methods of extracting data from the measurement curve **72** may be used, for example a stochastic hidden Markov model, wherein the hidden states of slopes and breakpoints are determined, for example, using a particle filter algorithm. See, for example, Arulampalam, M. S., Maskell, S., Gordon, N., Clapp, T., "A Tutorial on Particle Filters for Online Nonlinear/Non-Gaussian Bayesian Tracking,"Signal Processing, IEEE Transactions on, Volume 50, Number Two, Pages 174-188 (February 2002).

[0060] This process of fitting the measurement curve **72** to a model **78**, for example, may provide a least square fit between the model **78** and the measurement curve **72** using standard numerical optimization routines such as sequential quadratic programming, interior point optimization, log-barrier algorithms, or stochastic optimization methods such as simulated annealing.

[0061] Referring now to FIGS. **4** and **8**, in an alternative technique, the acquired ultrasound data at process block **64** may be used to determine, at process block **90**, z-axis displacement of the tissue with reciprocation of the probe along axis **11** or other stimulation of the tissue along axis **11**; for example, ultrasonic stimulation, may be used to deduce tissue movement within a cycle of stimulation according to standard dynamic or quasi-static elastography. Again, a measurement curve **80** providing a measure along the x-axis for each C-plane **62** may be obtained and averaged or otherwise fit to a model **82** (e.g., multiple regions of constant elasticity) to obtain low noise signal from model **82** reflecting tissue elasticity per process sub block **83** of FIG. **8**.

[0062] Referring now to FIGS. **5** and **8**, the data of model **78** or **82** acquired at process block **90** will lie along intersection lines **84** between the planes **34** and each C-plane **62** to provide for multiple elasticity data points **86** spaced along each of the lines **84** within each C-plane **62**. This relatively sparse data may be interpolated, per process block **92** of FIG. **8**, for example, to develop additional interpolated data points **88** between corresponding data points **86*a*** and **86*b*** of adjacent lines **84**. This interpolation may use a bilinear or trilinear cylindrical interpolation (multidimensional or multilinear interpolation) where points **88** lie at a same radial distance from axis **11** as the corresponding points **86*a*** and **86*b*** from which they are interpolated. The trilinear interpolation operates between C-planes on corresponding points in each C-plane which may in turn be the result of bilinear interpolation. Additional interpolation between points **88** or between points **86*a*** and **86*b*** may also be performed. For convenience interpolated points **88** may be selected to lie on a rectilinear grid. It will be understood that normal Cartesian coordinates may also be used for interpolation in some embodiments.

[0063] It will be appreciated that this cylindrical interpolation enforces a circumferential smoothness to the data, that is, data that varies relatively smoothly as one moves in circumference about axis **11** at a given radius from axis **11**. More generally, such circumferential smoothness may be implemented by using general numerical optimization techniques. For example, a nearest neighbor interpolation scheme may determine data values of unknown data for a vector x to be reasonably close to known data represented by vector b. The interpolator may be a matrix operator A which is a sparse matrix with very few nonzero values per row. In order to enforce circumferential and axial smoothness, it is assumed that the size of the gradient of the unknown vector x is small. This is enforced by adding the norm of the gradient into an objective function to be minimized by standard numerical optimization techniques such as those described above. Since the gradient for discrete data may be calculated by finite differencing, it can be expressed as Bx where B is the finite differencing matrix. A least squares optimization routine can then be used to solve for values of x to minimize:

$$\|Ax-b\|^2+\|Bx\|^2.$$

[0064] It will be appreciated that data can be acquired in multiple passes where the interpolated visualization from an earlier pass provide feedback for sampling interesting locations in the volume for subsequent passes to provide an adaptive sampling. In this respect, it will be further appreciated that data can also be acquired over beam planes **34** that are not angularly, uniformly spaced in order to derive better quality measurements from certain regions of the volume for finer interpolation reconstructions. Knowledge of earlier reconstructions can be easily incorporated in the interpolation procedure, for example, by reconstructing only a specific part of the volume that is known to contain an interesting feature or changed.

[0065] Upon filling in of the data of each C-plane **62** per the interpolation of process block **92**, the data of each of the C-planes may be collected together to create a 3-D data set and to display an image **41** of the 3-D ablation zone, for example, as indicated by process block **94**. This reconstruction may use conventional 3-D reconstruction and display techniques. For example, view of the ablation region **16** isolated from other surrounding tissue, for example of the organ **18**, may be created by a sorting of the data by an elasticity threshold and creating a polygon defined surface from outermost points within that threshold.

[0066] Referring now to FIG. **6**, in one embodiment, movement of the ultrasonic transducer **30** may be automated by mounting a one-dimensional or 1.5 D ultrasonic transducer **30** on an axially reciprocating carriage **100**, for example, driven by electric actuator **103** under the control of controller **46** (shown in FIG. **1**). The transducer **30** may provide, for example, one (for a one-D probe) or a small number such as three rows of ultrasonic elements **106** (for a 1.5-D probe) each that may be separately actuated for phased array or other imaging modes to transmit portions of the ultrasound beam **36** and to be independently readable to receive echo signals in return. The multiple rows of ultrasonic elements help provide for focusing of the ultrasound into a substantially planar ultrasound beam **36**. The reciprocating carriage **100** may rotate the ultrasonic transducer **30** about axis **11** substantially mimicking the motion described above with respect to FIG. **1** while providing improved orientation of the resulting ultrasound beam **36** along the axis **11**. The reciprocating action, for example, may move the ultrasonic transducer **30** by 180 degrees in one direction and then backward to its initial starting position to obtain the sheaf of data planes **34** described with respect to FIG. **2**. A center of the ultrasonic transducer **30** may provide for an opening **102** through which the probe **10** may pass to permit for this improved orientation of the ultrasound beams **36** with the axis **11** while sacrificing only one center ultrasonic element **106** of the ultrasonic transducer **30** in an area which is generally oversampled. A simplified motorized carriage **52** is shown providing for vertical reciprocation along axis **11** of the probe **10** also under control of controller **46**.

[0067] Referring now to FIG. **7**, in an alternative embodiment, a modified two-dimensional array **104** may be created having scattered ultrasonic elements **106** positioned as needed for the acquisition of the multiple planes **34** without movement of the two-dimensional array **104**. For example, the ultrasonic elements **106** may be placed along diagonal lines arrayed radially from axis **11** with a 45-degree spacing. This sparse ultrasound array reduces the number of channels necessary for data acquisition while still providing the rapid 3-D reconstruction of the present invention.

[0068] It will be appreciated that the spacing of the ultrasonic elements **106** along the lines perpendicular to the axis **11** of the ultrasonic elements **106** may be varied, for example, to reduce the element density toward the center of the array in favor of those ultrasonic elements **106** further outward for improved imaging resolution away from the center. The array **104** may be combined with the reciprocating carriage **100** to create a hybrid system.

[0069] It will be appreciated that the present invention may be combined with techniques to measure temperature of an ablated region, for example, as described in U.S. Pat. No. 7,166,075 hereby incorporated by reference.

[0070] It will be appreciated that the present invention may be used advantageously with parametric imaging techniques on radiofrequency, or B-mode data for 3-D quantitative ultrasound imaging. In addition, the invention can be used with color/power Doppler systems, for example, to produce a three-dimensional representation of blood flow.

[0071] It will be further appreciated that the present invention may be used advantageously with standard imaging techniques such as B-mode, color and power Doppler imaging and the like for ablation techniques in which the simplification of the imaging acquisition provides for good reconstruction of ablation masses and for other high-speed 3-D visualization such as blood flow for 3-D vascular imaging.

[0072] It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein, but include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims.

We claim:

1. An apparatus for acquiring three-dimensional elasticity data comprising:

an ultrasonic probe assembly adapted to direct an ultrasound beam into an elastic material and receive ultrasonic echoes generally along an axis to acquire a set of planes of such that the axis lies substantially within each plane, and the planes are angularly spaced around the axis; and

an electronic computer receiving the ultrasound data and executing a stored program held in non-transitive medium to:

(a) compute measures of material elasticity at multiple points within each plane; and

(b) reconstruct the multiple points of material elasticity of multiple planes into a three-dimensional representation of elasticity of the material.

2. The apparatus of claim **1** wherein the set of planes is between four and six in number.

3. The apparatus of claim **1** wherein the reconstruction of the multiple points of material elasticity of multiple planes enforces a circumferential smoothness in the reconstruction.

4. The apparatus of claim **3** wherein the reconstruction employs a multidimensional interpolation along cylindrical coordinates centered on the axis.

5. The apparatus of claim **1** wherein the measures of material elasticity evaluate speed of a shear wave extending perpendicularly through the material from the axis.

6. The apparatus of claim **5** further including:

an electrical probe adapted for percutaneous insertion into tissue at a tumor site;

a high-frequency power source communicating with an electrode of the electrical probe to ablate tissue at the tumor site.

7. The apparatus of claim **6** further including an actuator communicating with the electrical probe to provide reciprocation of the electrical probe along the axis.

8. The apparatus of claim **7** wherein the electronic computer communicates with the actuator to time acquisitions of echoes to obtain multiple acquisitions of echoes at each of successive phase offsets with respect to a phase of the reciprocation of the electrode.

9. The apparatus of claim **1** wherein the measures of material elasticity evaluate displacement of the material in response to a quasi-static periodic compression of the material.

10. The apparatus of claim **1** wherein the ultrasonic probe assembly is further adapted to direct a material-stimulating beam of ultrasonic energy into the material to promote a displacement of the tissue measurable by the ultrasonic echoes and wherein the measures of material elasticity evaluate the promoted displacement.

11. The apparatus of claim **1** wherein the ultrasonic probe assembly provides a substantially one-dimensional array of transducer elements extending perpendicular to the axis and providing a mechanism for rotating the one-dimensional array about the axis to acquire the multiple planes.

12. The apparatus of claim **1** wherein the ultrasonic probe assembly provides a two-dimensional array of transducer elements arrayed preferentially along lines of a diameter extending perpendicular to the axis.

13. The apparatus of claim **1** wherein the electronic computer further executes the stored program to display a three-dimensional rendering of elasticity of the material.

14. A method of acquiring three-dimensional elasticity data comprising the steps of:

(a) using an ultrasonic probe to direct an ultrasound beam into an elastic material and receive ultrasonic echoes generally along an axis to acquire a set of planes of ultrasound data such that the axis lies substantially within each plane, and the planes are angularly spaced around the axis;

(b) computing measures of material elasticity at multiple points within each plane from the ultrasound data; and

(c) reconstructing the multiple points of material elasticity of multiple planes into a three-dimensional representation of elasticity of the material.

15. The method of claim **14** wherein the set of planes is between 4 and 6 in number.

16. The method of claim **14** wherein the reconstruction of the multiple points of material elasticity of multiple planes enforces a circumferential smoothness in the reconstruction.

17. The method of claim **16** wherein the reconstruction employs a multidimensional interpolation along cylindrical coordinates centered on the axis.

18. The method of claim **14** wherein the measures of material elasticity evaluate at least one of a speed of a shear wave extending perpendicularly through the material from the axis and a quasi-static periodic compression of the material.

19. The method of claim **14** further including the steps:

inserting an electrical probe into tissue at a tumor site; and

applying a high-frequency power source communicating with the electrical probe to ablate tissue at the tumor site.

20. The method of claim **14** further including the step of displaying a three-dimensional rendering of elasticity of the material.

21. The method of claim **14** further including the step of applying a quasi-static compression to the material and wherein the measures of elasticity are computed from a determination of material displacement between different quasi-static compressions.

22. A method of acquiring three-dimensional elasticity data comprising the steps of:

(a) inserting an electrical probe into tissue at a tumor site along an axis;

(b) applying a high-frequency power source communicating with the electrical probe to ablate tissue at the tumor site.

(c) using an ultrasonic probe to direct an ultrasound beam into an elastic material and receive ultrasonic echoes generally along the axis to acquire a set of planes of ultrasound data such that the axis lies substantially within each plane, and the planes are angularly spaced around the axis;

(d) computing measures of material elasticity at multiple points within each plane from the ultrasound data; and

(e) reconstructing the multiple points of material elasticity of multiple planes into a three-dimensional representation of elasticity of the material of the tumor site.

23. An apparatus for acquiring three-dimensional Doppler images comprising:

an ultrasonic probe adapted to direct an ultrasound beam into a vascularized tissue and receive ultrasonic echoes generally along the axis to acquire a set of planes of ultrasound data such that the axis lies substantially within each plane, and the planes are angularly spaced around the axis; an electronic computer receiving the ultrasound data and executing a stored program held in non-transitive medium to:

(a) compute Doppler frequency shifts at multiple points within each plane; and

(b) reconstruct the multiple planes into a three-dimensional representation of blood flow of the material

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