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(54) **AUTOMATED ULTRASONIC ELASTICITY  
IMAGE FORMATION WITH QUALITY  
MEASURE**

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(52) **U.S. Cl.**  
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**A61B 8/485** (2013.01); **G01N 29/0609**  
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**G01N 2291/02475** (2013.01); **G01N**  
**2291/02827** (2013.01); **G01S 7/5205** (2013.01)

(58) **Field of Classification Search**  
USPC ..... 600/407, 410, 437  
See application file for complete search history.

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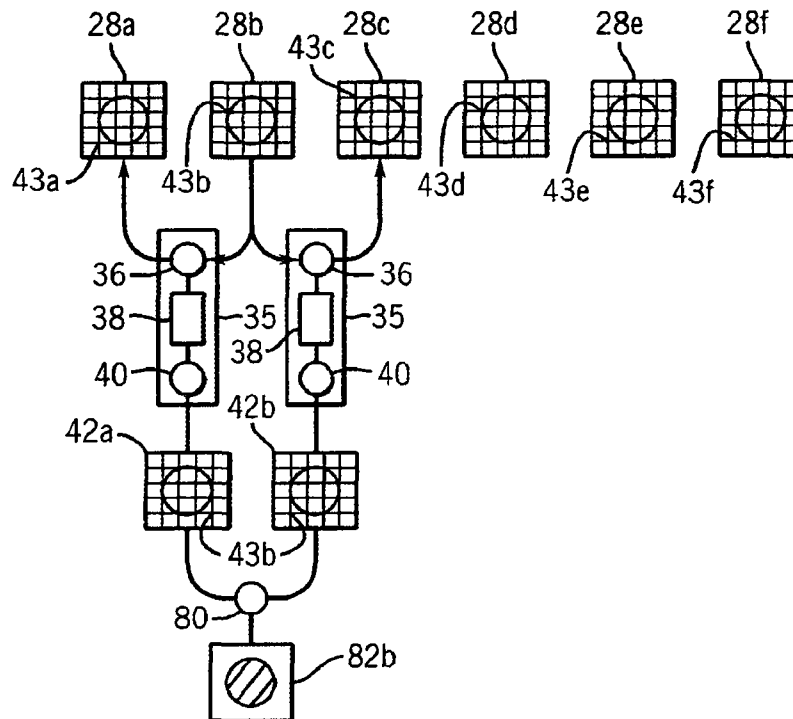
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(57) **ABSTRACT**

Image data and E-mode images used in ultrasonic elasticity  
imaging may be automatically evaluated for quality to pro-  
vide a single value used as operator feedback or for automatic  
selection of images for averaging or animation.

**8 Claims, 3 Drawing Sheets**



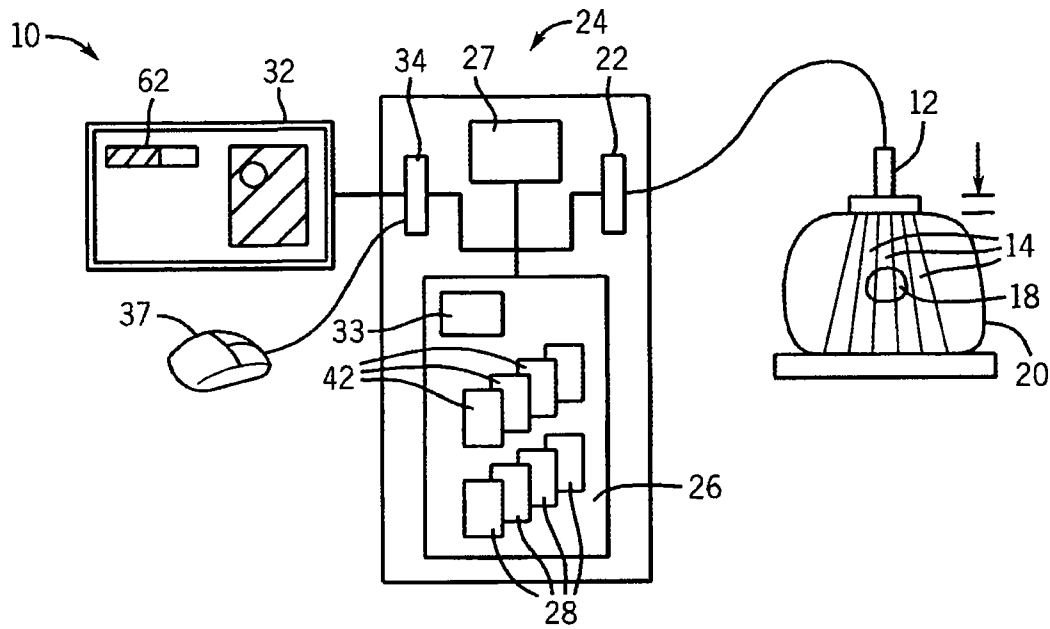


FIG. 1

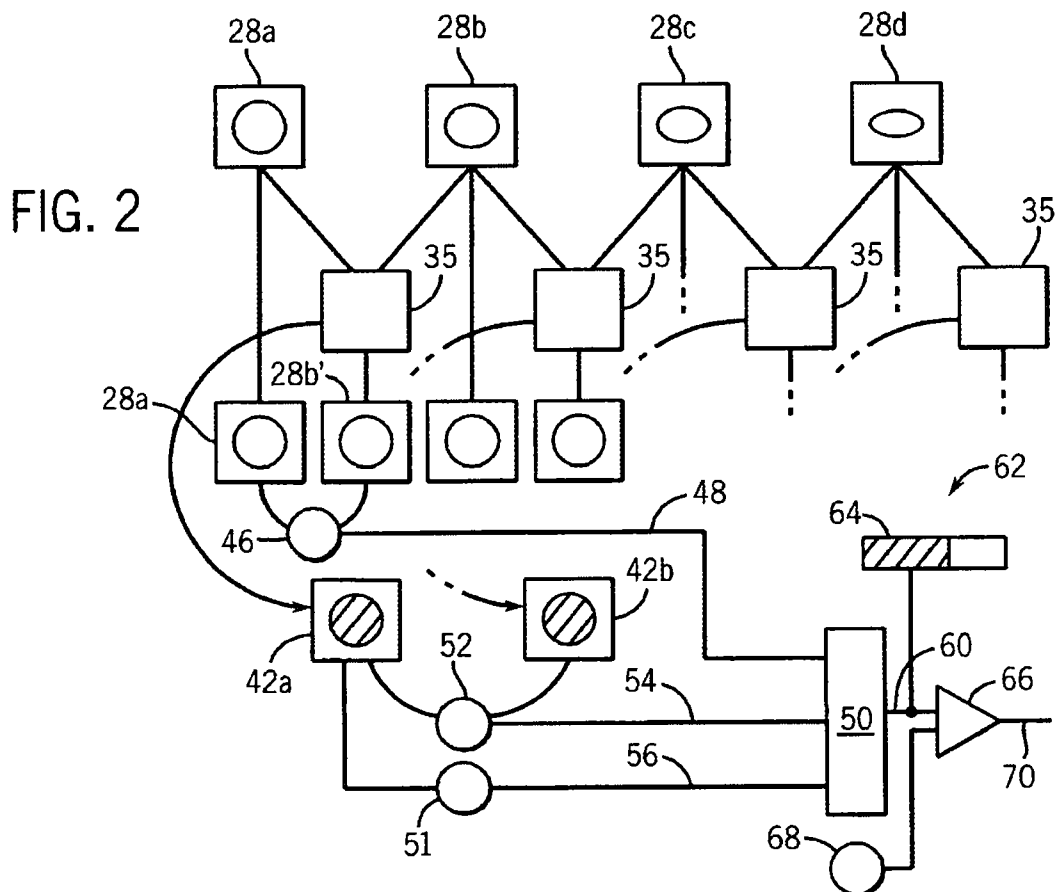


FIG. 2

FIG. 3

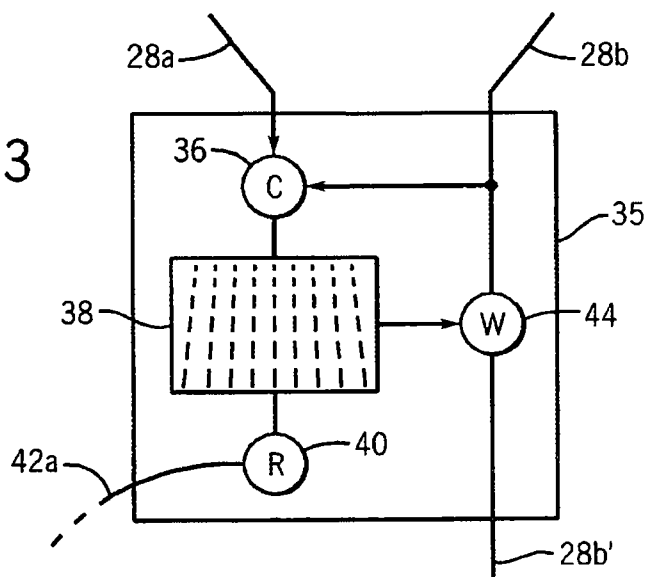


FIG. 4

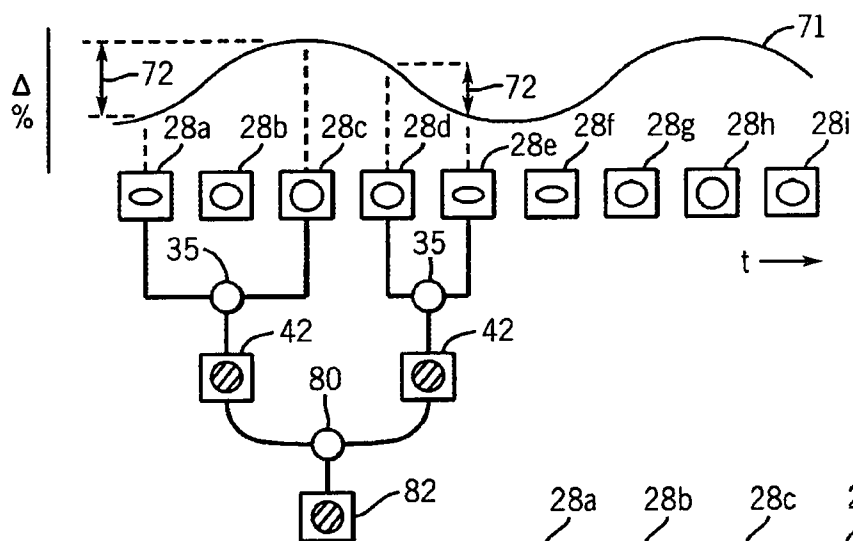
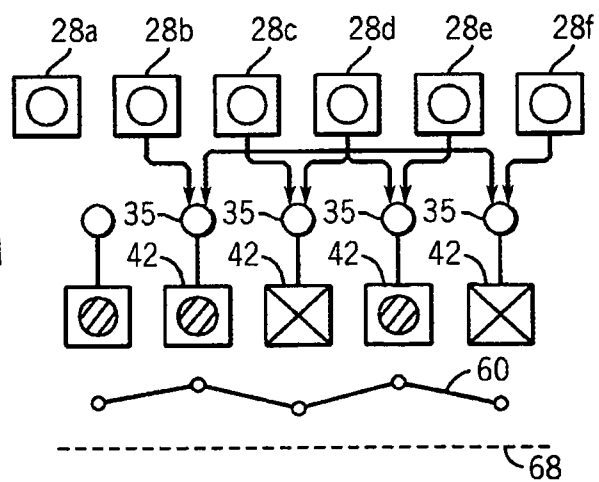


FIG. 5a



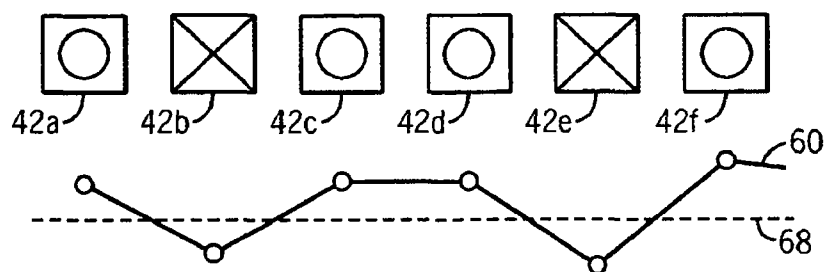


FIG. 5b

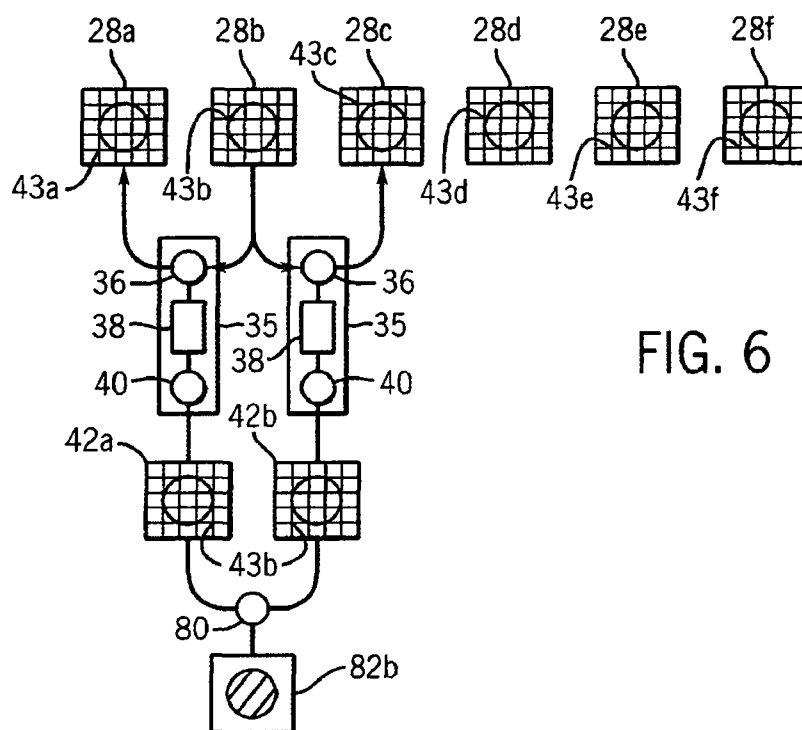


FIG. 6

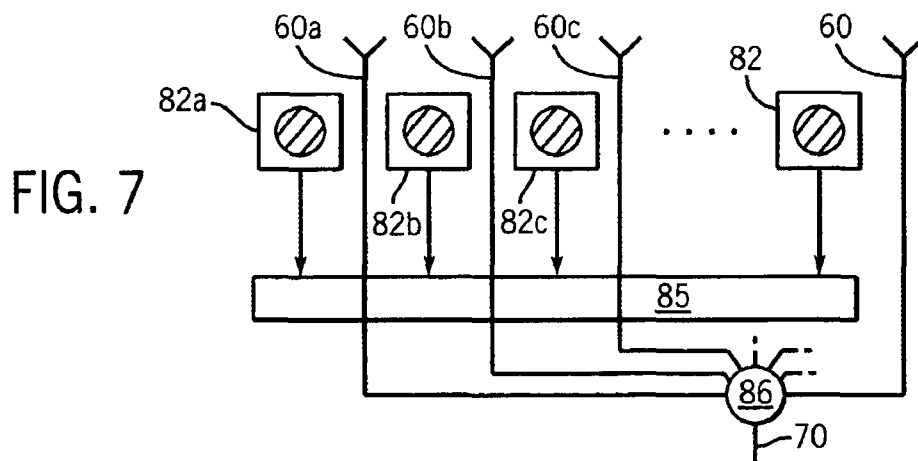


FIG. 7

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# **AUTOMATED ULTRASONIC ELASTICITY IMAGE FORMATION WITH QUALITY MEASURE**

## **CROSS REFERENCE TO RELATED APPLICATION**

This application is a continuation of U.S. patent application Ser. No. 11/155,950 filed Jun. 17, 2005 and hereby incorporated by reference.

## **STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT**

This invention was made with government support under EB002722 awarded by the National Institutes of Health. The government has certain rights in the invention.

## **BACKGROUND OF THE INVENTION**

The present invention relates to ultrasonic medical imaging devices and, in particular, to a method of automatic elasticity image formation in which each elasticity image is accompanied by a quality measure that can be used for the purpose of operator feedback or automatic image selection.

Elasticity (E-mode) imaging reveals the stiffness properties of tissue, for example, strain, Poisson's ratio, and Young's modulus. The stiffness measurements may be collected over an area or volume and then mapped to a gray or color scale to form a two- or three-dimensional E-mode image.

In quasi-static elasticity imaging, images of the tissue in different states of deformation are obtained by ultrasonic or other imaging devices. Strain is deduced from two images by computing a gradient in displacement between the images along any desired direction. Quasi-static elasticity imaging is analogous to a physician's palpation of the tissue during which the physician determines stiffness by pressing the tissue and detecting the amount of tissue yield under this pressure.

The tissue deformation may be obtained manually, for example, by moving the ultrasonic transducer toward and away from the tissue or through a separate compressor mechanism or by physiological movement. Manual deformation of the tissue provides an extremely versatile technique that can be used with standard ultrasonic imaging equipment; however, manual deformation requires considerable operator skill. Ideally, for example, the deformation is at an angle and in an amount to reduce lateral tissue slippage while obtaining appropriate tissue displacement. Too much or too little deformation will not yield consistent E-mode image data.

Often E-mode image data is presented as a time series animation so as to provide an additional dimension of information to the physician. Low quality images incorporated into this animation can create disruptive breaks in the animation obscuring the extra dimension of information hoped to be obtained. Multiple E-mode images may be combined to reduce image noise or provide E-mode measurements along different axes. Again, low quality images incorporated into this combination decrease the quality of the measurement.

## **SUMMARY OF THE INVENTION**

The present invention provides an automatic method of forming E-mode images using quality values that can be employed to provide near real-time operator feedback or an automatic culling of poor images. Importantly, the method operates quickly and may provide a single "quality value"

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that can be evaluated automatically against a threshold and/or unambiguously displayed to an operator to guide the operator's deformation technique and/or to train operators. In the preferred embodiment, the single quality value is derived from different metrics, each having different strengths.

Specifically, the present invention may provide an E-mode imaging apparatus having a tissue compressor adapted to apply a varying deformation to tissue and an image acquisition system collecting a series of images of the tissue during different stages of deformation by the tissue compressor. An electronic computer receives the series of images to generate a quality value singly indicating a quality of E-mode data obtainable from a currently acquired subset of the series of images. An output of the quality value is provided for use in adjusting or varying deformation to improve the quality of E-mode data.

Thus it is one object of at least one embodiment of the invention to develop a near real-time E-mode formation method where each E-mode image associates with a single scalar measurement that may be used to assess its quality.

It is another object of at least one embodiment of the invention to provide a real-time single quality measurement that may be used to improve the acquisition of E-mode image data.

The present invention may form E-mode images using multiple image signals (as opposed to derived E-mode images) in such a way that guarantees all E-mode images reside in the same physical grid. Composite E-mode images that may have higher signal-to-noise-ratios (SNRs) can be obtained by averaging these E-mode images located in the same physical grid without losing spatial resolution. These composite E-mode images can be displayed for diagnosis or training.

Thus it is another object of at least one embodiment of the invention to provide a method of E-mode image formation by which averaging E-mode images may provide E-mode images with higher signal to noise ratios for diagnosis or training but are not penalized by the reduction in spatial resolution.

The selection of multiple image signals separated by time (as opposed to the derived E-mode images) in the present invention may be rapidly determined to achieve the highest possible quality in the composite E-mode image.

Thus it is another object of at least one embodiment of the invention to provide a method of selecting image signals (as opposed to the derived E-mode images) under which high quality composite E-mode images can be obtained.

The compressor may be manipulable by an operator and the output may be an operator interface providing a representation of the quality value selected from the group consisting of: a displayed number, a displayed visual gauge, a displayed indicator light, and an audio signal.

Thus it is another object of at least one embodiment of the invention to provide a real-time corrective signal to an operator manually deforming tissue to improve the quality of the data acquired.

The compressor may be an ultrasonic transducer and may also provide echo signals for the image acquisition system.

It is thus another object of at least one embodiment of the invention to provide a system that may be used with standard ultrasonic acquisition systems for elasticity measurements.

The quality value may be derived from a comparison of at least one pair of motion corrected images.

Thus it is another object of at least one embodiment of the invention to provide a measurement that may be made

directly on the image signals (as opposed to the derived E-mode images) to predict the quality of elasticity information to be obtained therefrom.

The comparison may be a correlation of the motion corrected images.

It is another object of at least one embodiment of the invention therefore to provide a simple mathematical technique for evaluating images that can be sensitive to the entire image area.

The electronic computer may further process the images to create E-mode images located in the same physical grid and the quality value may be derived from a comparison of the E-mode images.

Thus it is another object of at least one embodiment of the invention to provide a measurement that looks directly at the E-mode images to deduce their quality.

The comparison of the E-mode images may be an evaluation of cross correlation or mutual information or other correlation providing a mathematical equivalent of these evaluations of the E-mode images.

It is thus another object of at least one embodiment of the invention to provide a measurement of E-mode images analogous to the measurement of the images used to deduce elasticity information.

The comparison of the E-mode images located at the same physical grid using correlation, mutual information or its mathematical equivalence can reveal the signal-to-noise-ratio (SNR) in their corresponding composite E-mode images.

Thus it is another object of at least one embodiment of the invention to measure the signal-to-noise-ratio of the composite E-mode images formed by the current invention.

The quality value, alternatively or in addition, may be derived from an evaluation of information content of at least one E-mode image, for example, by determining entropy.

It is thus another object of at least one embodiment of the invention to provide a measurement of E-mode image quality that may be obtained from a single image for rapid determination.

The quality value may be based on a single quality metric or may be a combination of two or more different types of measurements of the quality of the E-mode image information.

Thus it is another object of at least one embodiment of the invention to provide a single, quality value deriving from the strengths and benefits of different quality measurement techniques.

The present invention also provides a method of processing a stream of image data to produce E-mode measurements including the steps of: evaluating the stream of images to create a set of corresponding quality values indicating a quality of composite E-mode image data obtainable from the stream of images, and generating output E-mode images using only images associated with quality values over a predetermined threshold.

Thus it is another object of at least one embodiment of the invention to provide for the possibility of automatic selection of images for use in generating elasticity data.

The composite E-mode images may generally be used to form an animation or may be further mathematically combined.

Thus it is another object of at least one embodiment of the invention to provide a method suitable for a variety of different E-mode image output techniques.

The evaluation of the stream of images may include evaluation of pairs of images having different time separations and generating for each pair, and for each time separation, a quality value. The generation of the output E-mode images

may then select among the time separations to generate output E-mode images using pairs of images with time separation associated with quality values over a determined threshold.

It is thus another object of at least one embodiment of the invention to provide a method of automatically selecting appropriate time separations to provide improved elasticity data.

The overall evaluation of a stream of E-mode images using quality values may be derived from the quality evaluation for each individual E-mode image to provide additional feedback to operators.

It is thus another object of at least one embodiment of the invention to provide an overall measurement for a sequence of E-mode images obtained from image signals (as opposed to the derived E-mode images) acquired continuously.

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

FIG. 1 is a simplified block diagram of an ultrasonic scanner suitable for use with the present invention;

FIG. 2 is a flow diagram showing processing of a series of ultrasonic images obtained from the scanner of FIG. 1 to produce a quality value;

FIG. 3 is a detailed block diagram of a motion correction block of FIG. 2 for making motion correction comparison of the image data;

FIG. 4 is a diagrammatic representation of an application of the present invention to automatically select pairs of images using deformation values to obtain high quality E-mode images;

FIG. 5a is a diagrammatic representation of the selection of particular pairs of images based on quality values to obtain high quality E-mode images;

FIG. 5b is a pictorial representation of the selection of particular E-mode images in a time series by use of a quality value obtained by the present invention;

FIG. 6 is a figure similar to that of FIG. 2 showing the preservation of a single physical grid in the combination of image data; and

FIG. 7 is a diagrammatic representation of the collection of quality data for a measure of a combined sequence of E-mode images.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1 in a preferred embodiment, an E-mode imaging system 10 suitable for use with the present invention provides an ultrasonic transducer 12 which may transmit multiple ultrasonic beams 14 toward a region of interest 18 within a patient 20. The ultrasonic beams 14 produce echoes along different measurement rays passing through volume elements within the region of interest 18.

The echoes are received by the transducer 12 and converted to electrical signals acquired by interface circuitry 22 of a main processor unit 24. The interface circuitry 22 may perform amplification, digitization, and other signal processing on the echo signals as is understood in the art. These digitized echo signals may then be transmitted to a memory 26 for storage and subsequent processing by a processor 27 as will be described. The processor 27 is preferably an electronic computer, a term which, as used herein, encompasses all numeric processing machines providing equivalent function

including analog and digital computers as well as specially designed signal processing circuitry.

According to the techniques well known in the art, the stored echo fields **28** may each provide a B-mode image and thus will be referred to generally as image data. Two or more of the echo fields **28** used to form B-mode images are processed to produce an E-mode image **42** according to a stored program **33** held in memory. The B-mode images and the E-mode images **42**, both derived from the echo fields **28**, may be displayed on an operator display **32** connected with the processor unit **24** by graphic interface **34**. The operator display **32** may provide a color monitor and/or a sound output according to techniques well known in the art. The graphic interface **34** may also accept inputs from the keyboard and/or cursor control device **37**.

These features are generally available in commercial ultrasound machines such as the Elegra scanner available from the Siemens Medical Solutions, Inc., having a 7.2 MHz linear array transducer operating at 36 MHz in sampling frequency.

Referring now to FIGS. **1** and **2**, the present invention may be implemented in software of the stored program **33** as a series of functional blocks to now be described.

Initially, sequential echo fields **28a** through **28d** are analyzed in a pairwise fashion (e.g. echo fields **28a** and **28b**, **28b** and **28c**, etc.) to estimate displacements, derive E-mode images and to perform an initial E-mode image quality assessment. At a first step in the E-mode image quality assessment, each echo field of the pair, for example, echo fields **28a** and **28b** are first received by a data warping block **35** which warps the later echo field, in this case, echo field **28b** to produce a warped echo field **28b'** matching as closely as possible the earlier echo field **28a**. Generally each of the echo fields will have been acquired with a different tissue deformation.

Referring also to FIG. **3**, the warping block **35** first compares the two echo fields **28a** and **28b**, as indicated by comparison block **36**, to determine a displacement map **38** indicating relative motion between the tissue of the two echo fields **28a** and **28b**. Calculating such a displacement map **38** is well understood in the art of E-mode imaging and may, for example, be done by making local correlations of the echo fields **28a** and **28b** within a series of predefined windows over the surface, or volume, of the data to determine local displacement. As will be understood to those of skill in the art, the invention may operate on two or three dimensional echo field acquisitions.

The displacement map **38** is then further processed by the E-mode estimation block **40** to produce an E-mode image **42a**. E-mode image formation is well understood in the art of elasticity imaging and may, for example, form strain images by computing the spatial gradient of the displacement field or compute Poisson's ratio or elastic moduli with additional processing, as will be discussed further below.

The displacement map **38** is also received by warped **44** which uses the displacements indicated in the displacement map **38** to warp echo field **28b** to approximate the echo field **28a** thereby producing motion corrected or warped echo field **28b'**.

Referring again to FIG. **2**, the unwarped echo field **28a** and warped echo field **28b'** may then be compared by correlator **46** and the correlation value provides a first quality parameter **48** to be received by combiner **50** to be discussed below. Correlation, as is well understood in the art may measure the sum of the magnitude of the differences between the images on a point-by-point basis over the entire images. Generally this first quality parameter **48** will be sensitive to errors in the displacement map caused by a variety of problems including

excessive deformation that moves corresponding tissue outside the analyses window, or by poorly resolved correlation maxima caused by noise or lack of strong echo features in the echo field **28**.

This process of determining the first quality parameter **48** is repeated for each sequential pair of echo fields **28** to provide a series of first quality parameters **48** associated with each pair of echo fields **28**.

As mentioned above, the E-mode estimation block **40** of the warping block **35** also provides the E-mode image **42a** according to techniques well known in the art. Each pair of echo fields **28** processed in this manner will produce one of a series of E-mode images **42a**, **42b**, etc.

Referring now to FIG. **6**, each pair of E-mode images **42**, for example, E-mode images **42a** and **42b** are estimated at the same physical grid **43b**. One way to accomplish this goal is to use three echo fields, for instance, echo fields **28a**, **28b** and **28c**. The warping block **35** first compares two echo fields **28a** and **28b** at comparison block **36** to determine a displacement map **38**. The echo fields **28a** and **28b** are used as target and reference echo fields, respectively. That is, the displacement map **38** indicates a relative motion from the echo fields **28b** and its physical grid **43b** to the echo fields **28a**. Then the E-mode estimation block **40** is used to extract the E-mode image **42a** that is mapped into the physical grid **43b** of the echo field **28b**. As will be understood to those of ordinary skill in the art, this use of the same physical grid is not essential for all embodiments of the invention.

The E-mode image **42b** is obtained from the echo fields **28b** and **28c** following a similar procedure where the echo fields **28b** and **28c** are the reference and target echo fields respectively to assure that the E-mode image **42b** also located at the physical grid **43b** of the echo field **28b**. The E-mode images **42a** and **42b** can be combined using the combiner **80** to produce a composite E-mode image **82b** by weighted averaging. The composite E-mode image **82b** is then on the same physical grid **43b** as the reference echo field **28b**. The combination procedure is intended to reduce noise and will not degrade spatial resolution in E-mode images (as opposed to temporal smoothing where E-mode images separated by time and referenced to different physical grids are averaged directly).

Referring again to FIG. **2**, each pair of these E-mode images **42**, for example, E-mode images **42a** and **42b**, are next compared to determine their similarity by cross correlation (or mutual information or other functionally equivalent comparison) comparison block **52**. Mutual information is a well known mathematical technique described, for example, in Introduction to Statistical Communication Theory, by D. Middleton, New York, John Wiley & Sons, 1991, hereby incorporated by reference. The similarity of the two E-mode images **42a** and **42b** is provided as second quality parameter **54** for each pair of echo fields **28** to be received by combiner **50**. The similarity between the two E-mode images **42a** and **42b** strongly correlates to the E-mode image signal-to-noise-ratio (SNR) of the composite E-mode image **82b** (FIG. **6**) and the E-mode image SNR can also be used as a second quality parameter **54**.

Each E-mode image **42** is also evaluated individually for its information content by means of an entropy measurement, for example, Shannon's entropy also defined in the above-referenced book to provide a third quality parameter **56**. Generally, maximum entropy is obtained when all gray (or color) values of the image are equally represented while minimum entropy occurs when the image is of a single brightness. The entropy of the first E-mode image **42a** of each image pair is determined by entropy block **51** as third quality parameter **56**.

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received by combiner **50**. The third quality parameter **56** may be normalized to a quantity between zero and one.

Each of these quantitative quality parameters **48**, **54** and **56** may be combined by combiner **50** which combines the quality parameters **48**, **54** and **56** together by an empirically determined equation to produce a single quality value **60**.

One realization may be the products of quality parameters **48**, **54** and **56**.

This single quality value **60** may be displayed by the processor **27** on the operator display **32**, for example, in the form of a bar display **62** having a shaded portion **64** that increases to fill the bar of the bar display **62** as the quality value **60** increases. In this way, the operator may be presented with a real-time display of quality value **60** to adjust his or her technique in compressing the tissue using the ultrasonic transducer **12**.

Alternative forms of representation including numeric displays, for example, from zero to **100**, color displays, tones, or the like may also be used.

Referring now to FIG. **5a**, one way of selecting three echo fields, for example, echo fields **28a**, **28d** and **28f**, may be done by using measurements of quality value **60** obtained as described above. For example, a reference echo field **28d** may first be selected. Two series of E-mode images can be generated by going backward (for instance, echo fields **28d** to **28c**, and echo fields **28d** to **28b**) and forward (for instance, echo fields **28d** to **28e**, and echo fields **28d** to **28f**) in time. Then the composite E-mode images **82** can be accepted or rejected depending on the quality value **60** of that triplet of echo fields **28** and their consequent E-mode images **42**. Among these echo fields **28** having a quality value **60** greater than the pre-determined threshold **68** for its corresponding composite E-mode image **82**, the triplet that has the highest quality value **60** will be eventually selected.

Referring now to FIG. **4**, in another application of the present invention, a series of echo fields **28a** through **28i** may be obtained at different degrees of tissue deformation as indicated by deformation curve **71** providing field averaged strain of the echo fields **28**. The processor **27** executing the stored program **33** receiving echo fields **28** may evaluate pairs of echo fields **28** having different time separations. Thus, for example, echo fields **28a** and **28c** may be compared as well as echo fields **28d** and **28e**. Generally, each pair of echo fields will provide between them a tissue strain value **72** representing the difference between the values of the deformation curve **71** at the time of the acquisition of the particular echo field **28**.

The selection of the particular pairs of echo fields **28a** and **28c**, for example, may be done by finding comparable tissue strain values **72** or may be done by using a combination of tissue strain and measurements of quality value **60** obtained as described above. For example, pairs of echo fields **28** may first be selected by tissue strain values **72** and then accepted or rejected depending on the quality value **60** of that pair of echo fields **28**.

Referring now to FIG. **5b**, the quality value **60** may further be used to select only those E-mode images **42** having greater than a pre-determined quality value **60** to be combined by combiner **80** to produce a composite E-mode image **82**. The composite E-mode image may produce a superior signal-to-noise ratio when constructed of similar E-mode images **42** or may provide additional dimensions of E-mode measurement, for example, for deformations along different angles or of different amounts.

In this latter regard, referring to FIG. **2**, the quality value **60** may be provided to a comparator **66** which may compare the quality value **60** against a threshold **68** to produce a binary

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acceptance value **70** that may be used for eliminating low quality images on an automatic basis.

Referring now to FIG. **5**, this same technique may be applied to a series of E-mode images **42a** through **42f** as shown in FIG. **5** such as may be output as composite E-mode images in the form of an animation. In this case, the quality value **60** is compared against the threshold **68** and where the quality value **60** drops below the threshold **68** for a particular E-mode image **42b** and **42e** in this example, those E-mode images are eliminated from the animation.

Referring now to FIG. **7**, the quality value **60** associated with each E-mode image **42** may further be used by a sequence combiner **85** (combining the quality values **60** of the E-mode images **42**) to accumulate the overall quality **86** for a sequence of echo fields **28** acquired continuously. The overall quality **86** provides additional feedback to operators or can be used for training purposes.

These techniques are not limited to use with data acquired with ultrasound machines, but can be used with other image modalities as will be understood to those of ordinary skill in the art. 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.

What we claim is:

1. An E-mode imaging apparatus comprising:

- (a) a probe containing an ultrasound transducer for (i) transmitting ultrasonic beams toward a material to be imaged and (ii) receiving ultrasound echo signals produced by the ultrasonic beams to provide electrical echo signals;
- (b) an interface circuitry programmed to receive and process the electrical echo signals to provide digital values;
- (c) a processor for receiving the digital values and producing a series of echo images imaged during different stages of deformation of the material to be imaged, each image comprised of multiple image values;
- (d) a memory for storing the image values of the series of echo images and a stored operating program; and
- (e) an operator interface communicating with the processor to communicate a quality value of the image values to an operator manipulating the probe;

wherein the processor receives the image values of the series of echo images and executes the stored operating program held in a non-transient medium to calculate:

- (i) E-mode data indicating a stiffness of the material determined from displacement of corresponding elements of the material represented in image values between different images;
  - (ii) a quality value indicating a quality of E-mode data wherein the quality value is a combination of two different evaluations of the image values of two images, a first evaluation indicating a similarity of corresponding image values in the two images providing a higher first evaluation value when the similarity increases and a second evaluation indicating a degree of variation in values of an E-mode image formed of the image values of the two images provides a higher second evaluation value when the degree of variation increases;
- wherein the quality value increases as the first evaluation value increases and as the second evaluation value increases.

2. The E-mode imaging apparatus of claim **1** further including an operator interface providing a representation of



the quality value selected from the group consisting of: a displayed number, a displayed visual gauge, a displayed indicator light, an audio signal.

3. The E-mode imaging apparatus of claim 2 wherein the first evaluation is a correlation. 5

4. The E-mode imaging apparatus of claim 3 wherein the correlation is between a first image and a warping of a second image according to displacements used to determine the E-mode images from the image data.

5. The E-mode imaging apparatus of claim 4 wherein the second evaluation is an evaluation indicating an information content of an E-mode image formed of the two images. 10

6. The E-mode imaging apparatus of claim 5 wherein the information content is determined from an entropy of an E-mode image formed of the two images. 15

7. The E-mode imaging apparatus of claim 6 wherein the quality value is a combination of three different evaluations of the image values of three images, wherein the third evaluation indicates a similarity of corresponding image values in two &mode images formed from the three images. 20

8. The E-mode imaging apparatus of claim 7 wherein the third evaluation is selected from the group consisting of correlation and mutual information of the image values of the two E-mode images. 25

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