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(54) ULTRASOUND IMAGING METHOD USING REDUNDANT SYNTHETIC APERTURE CONCEPTS

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(57) **ABSTRACT**

A method for improving the resolution of ultrasound images using synthetic aperture concepts. A two-dimensional image is obtained using ultrasound imaging apparatus located at a first position outside the target area and at a predetermined distance from a center point within the target area. The imaging apparatus is then moved along an arc to a new position and another two-dimensional ultrasound image is obtained. This process is repeated through up to a full 360° around the target area. Image data for each pixel is combined, calculated and transformed for all image positions to produce a highly resolved image of that pixel. The process is repeated for each pixel until all the pixels within the target area are fully resolved, thereby producing a complete, highly resolved over-all image.

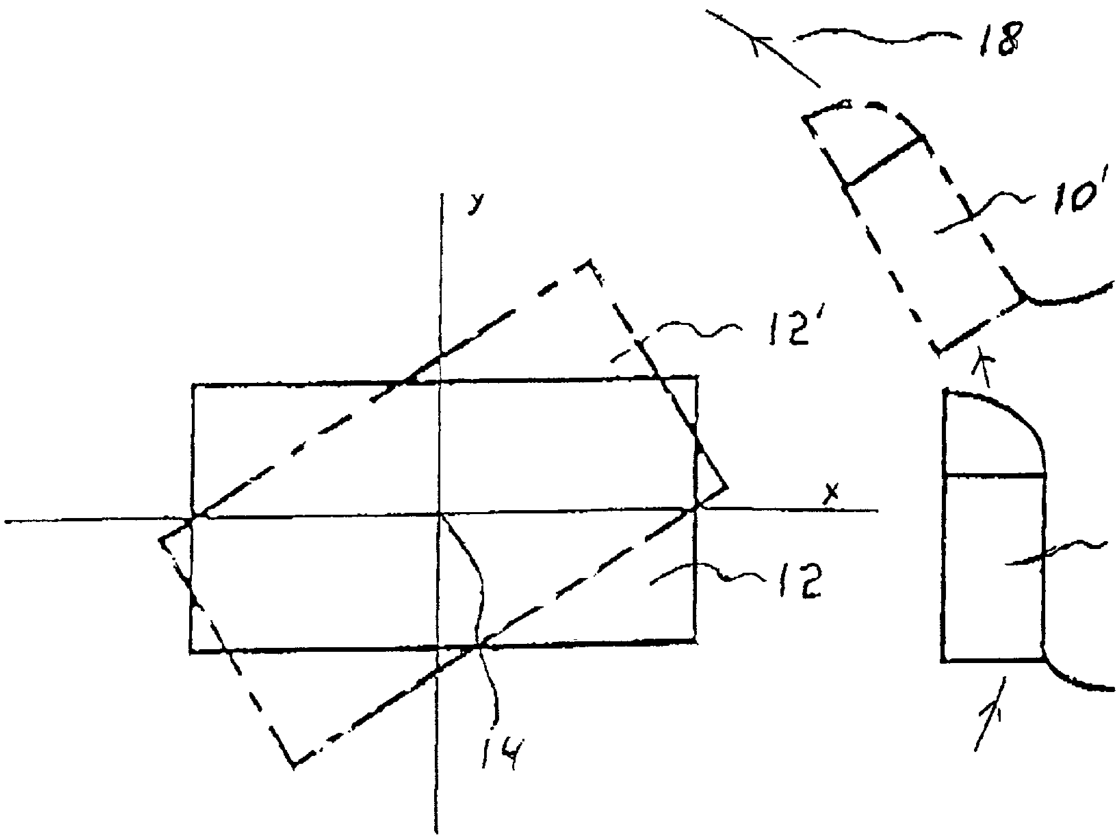


Fig. 1

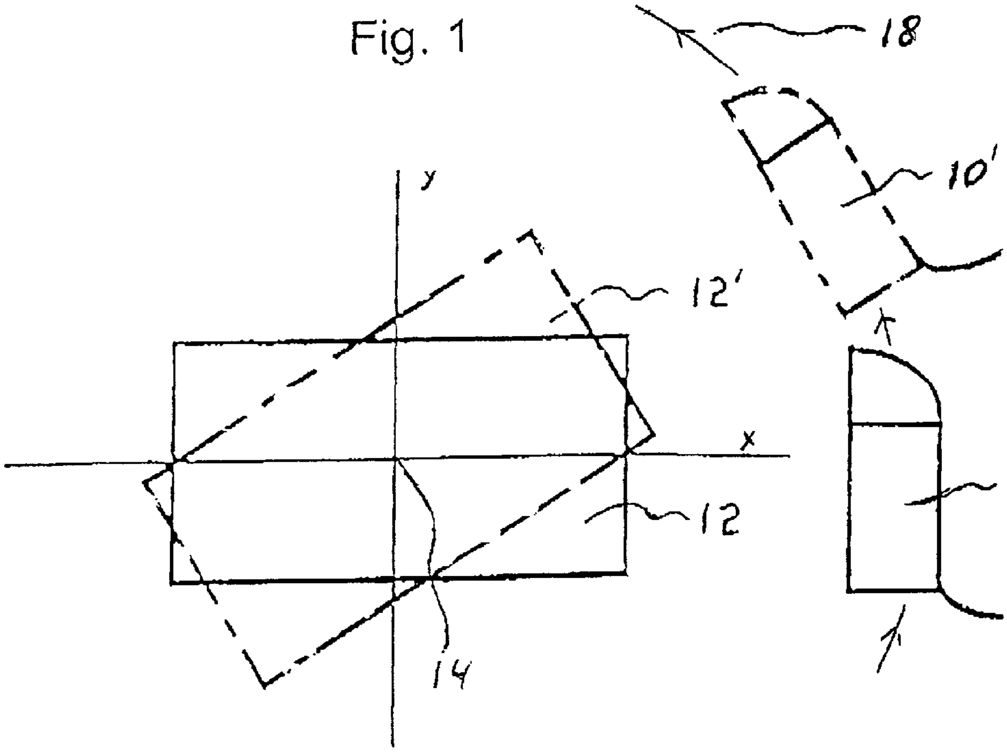
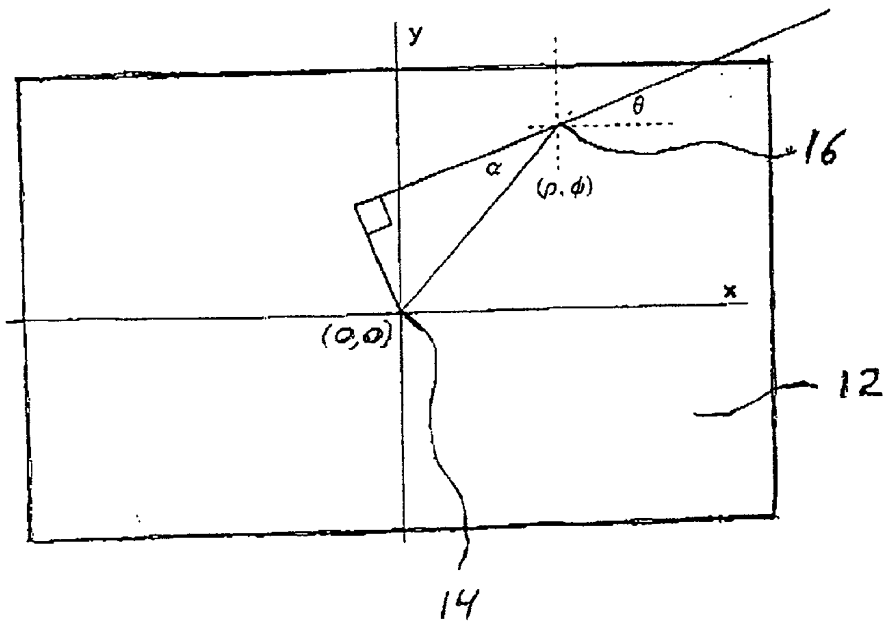


Fig. 2



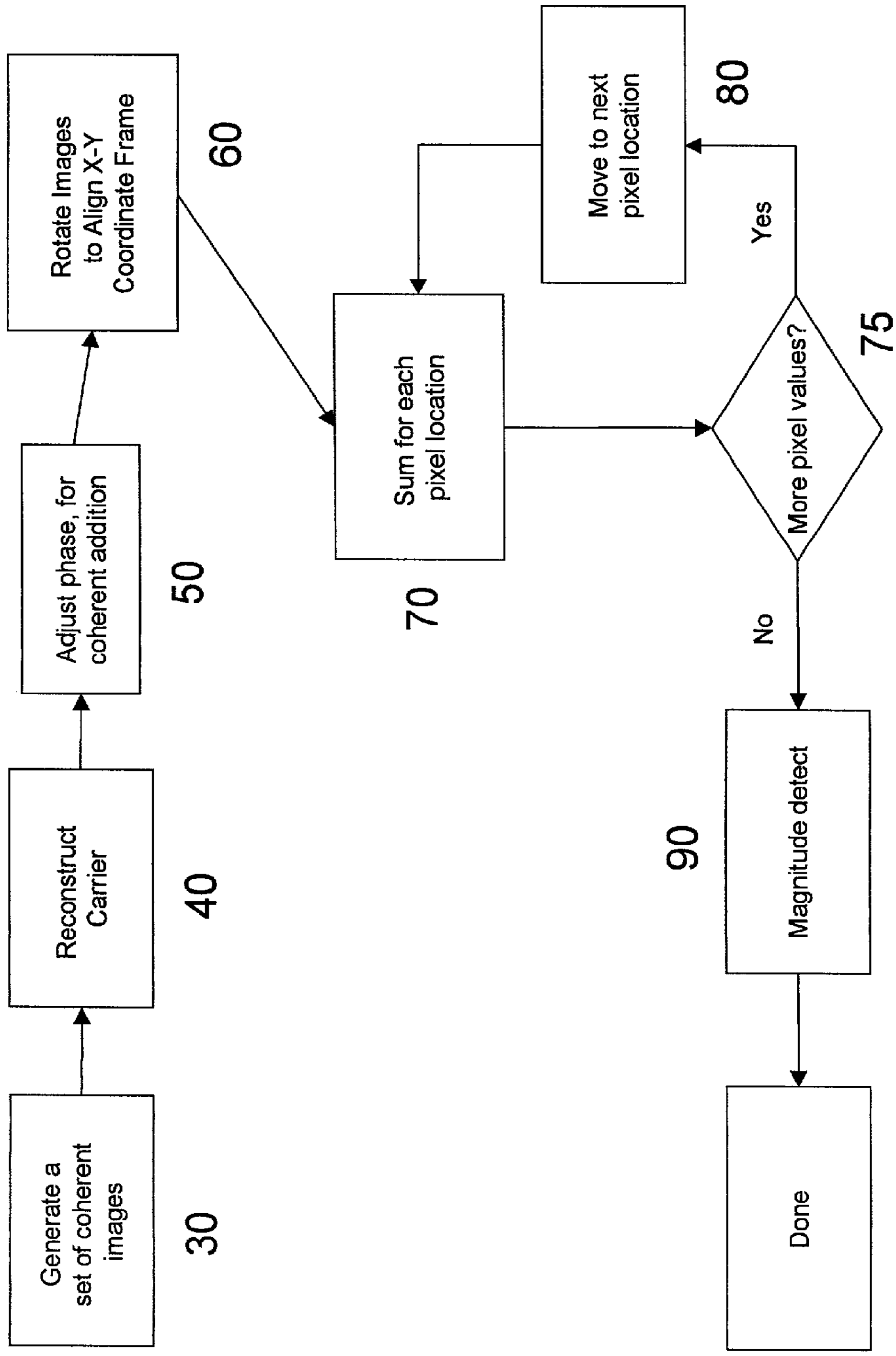


Figure 3: Coherent Images

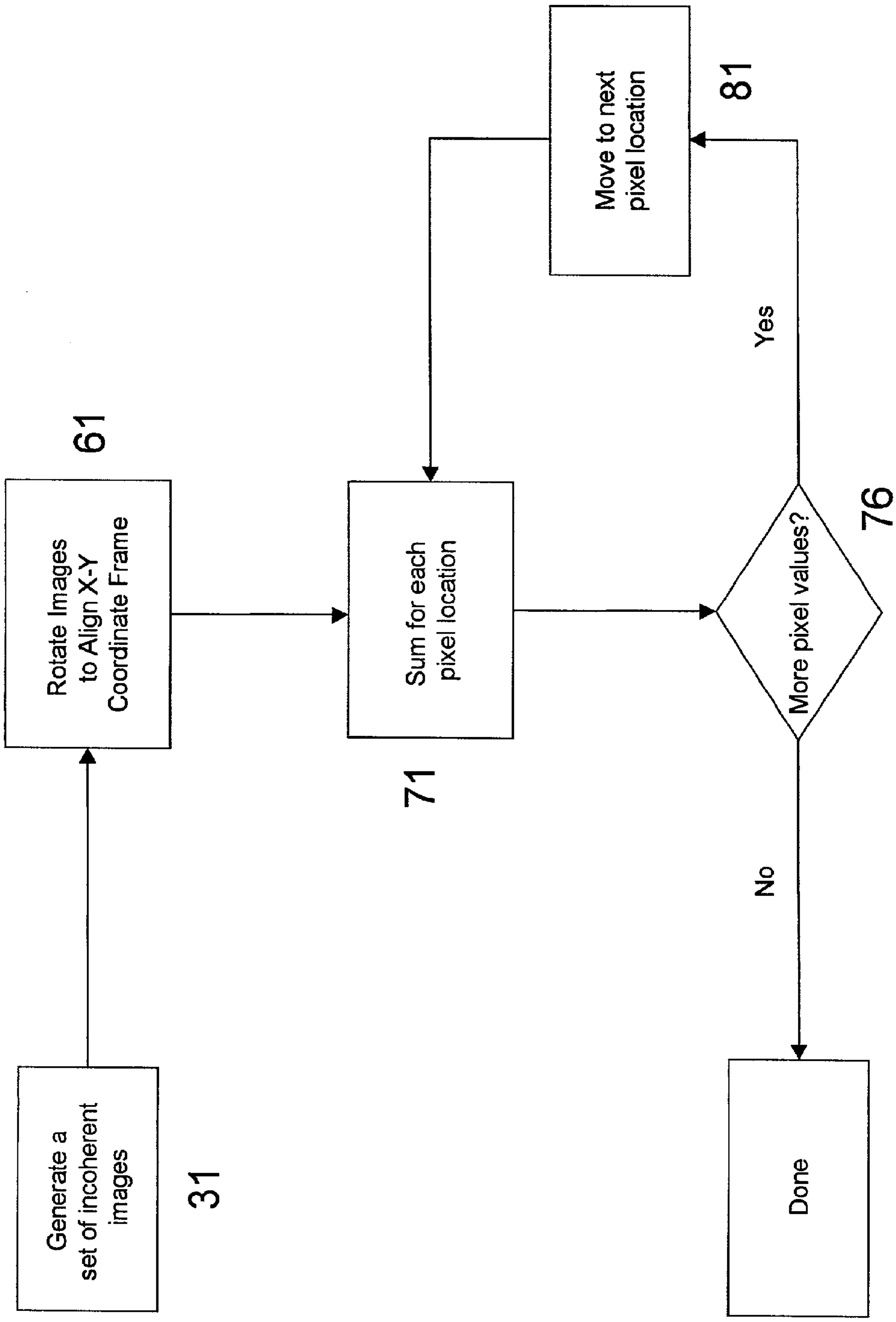


Figure 4: Incoherent Images

ULTRASOUND IMAGING METHOD USING REDUNDANT SYNTHETIC APERTURE CONCEPTS

CONTRACTUAL ORIGIN OF THE INVENTION

[0001] The United States Government has rights in this invention under a contract number DE-AC04-94AL85000 with the Department of Energy.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to ultrasound imaging. More particularly, the invention relates to improved ultrasound imaging using redundant imaging and synthetic aperture concepts.

[0004] 2. Related Art

[0005] There is much interest in improved imaging of fine internal details in a host of technological fields. This is particularly true in the field of medicine. The internal imaging methods used in the medical fields—such as x-ray, CAT scan (an improved x-ray technique), and ultrasound—are capable of providing images of internal organs and have allowed medical professionals to detect, in a non-invasive manner, many afflictions for treatment.

[0006] Ultrasound, one of the most common of these imaging methods, is frequently used in prenatal care because of its safety. Ultrasound allows doctors and other medical professionals to check on the general health of a baby by safely providing an image of the baby before birth, thus enabling early detection of many potential problems.

[0007] Ultrasound methods obtain images of an object by using high frequency sound waves. The sound waves are sent from a transducer to the object to be examined and are reflected by the object back to the transducer. The pattern in which the sound waves "bounce back" to the transducer can be used to calculate a two-dimensional image. The limited resolution of the images obtained by traditional ultrasound machines is, however, such that the images are not useful for certain medical purposes. While a single ultrasound machine is useful in providing a general two-dimensional image, the resolution provided is such that the machine cannot be used for certain delicate applications, e.g., the detection of breast cancer.

[0008] To date, other imaging technologies, such as standard x-ray and CAT scan, have been used to produce the higher resolution images necessary for breast cancer detection and for other medical purposes requiring high-resolution imaging. However, x-rays can be cancer causing in and of themselves. The danger is minimal for an individual x-ray procedure, but x-rays suffer from the disadvantage that there is only a limited number of times per day that x-rays can be used before there is an unacceptable risk to the patient. CAT scans, in addition to suffering from the same limitations as standard x-ray techniques, are extremely expensive and have limited applications.

[0009] One alternative approach for creating high-resolution images would be to surround a patient with ultrasound machines. A large number of ultrasound machines providing images of the same two-dimensional area from a multitude of angles would increase the resolution of each pixel within that two-dimensional area to a level where very fine or small abnormalities, such as breast cancer, could be detected. However, such an apparatus would suffer from some limitations similar to those of a CAT scan. Providing a ring of ultrasound machines surrounding a patient would obviously be bulky and prohibitively expensive.

[0010] As such, there remains a need for an inexpensive method to generate high-resolution ultrasound images.

SUMMARY OF THE INVENTION

[0011] In accordance with the invention, a method is provided for improving the resolution of images produced by ultrasound machines, wherein an ultrasound image is obtained of a target area using an ultrasound imaging apparatus located at a first position outside the target area and at a predetermined distance from a center point within the target area. The ultrasound imaging apparatus is moved along an arc spaced from the center point of the target area to a new position and a further ultrasound image of the target area is obtained. This process is repeated for a plurality of further positions along the arc, as desired. The phase of sound waves returning from a pixel within the target area to the ultrasound apparatus is calculated for all the imaging positions until complete image data for the pixel is obtained. The image data for the pixel are combined and calculated for all of the positions of the apparatus to produce a higher resolution image of the pixel. This is repeated for each pixel within the target area.

[0012] Preferably, the ultrasound transducer would be moved about 2-5° around the arc between positions, but the imaging method of this invention will function with any angle of change between individual imaging positions.

[0013] Advantageously, the method can be used whether the ultrasound images are coherent images or incoherent images. If the ultrasound images are incoherent images, they are combined, using a synthetic aperture algorithm, into a much higher resolution set of incoherent images.

[0014] Advantageously, the method will be used in the medical field and, more particularly, in the detection of cancer.

[0015] More specifically, the method can be used for the safe, effective detection of breast cancer.

[0016] Other features of this invention will be set forth in, or will be apparent from, the detailed description of the embodiments that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] **FIG. 1** is a schematic diagram showing a single ultrasound apparatus in use about a center point.

[0018] **FIG. 2** is a schematic diagram showing the mathematical extrapolation and resolution of a single pixel.

[0019] **FIG. 3** is a flow diagram of the imaging process as shown in **FIGS. 1 and 2**, as applied to ultrasound machines that store coherent images.

[0020] **FIG. 4** is a flow diagram of the imaging process as shown in **FIGS. 1 and 2**, as applied to ultrasound machines that do not store coherent images.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] As indicated above, according to the present invention, an inexpensive method is provided for obtaining highly resolved ultrasound images. In general, the invention uses a synthetic aperture concept to simulate the resolution that would be provided by using multiple surrounding ultrasound devices. Synthetic receiver aperture imaging is discussed, e.g., in Nock et al., "Synthetic Receive Aperture Imaging with Phase Connection for Motion and for Tissue Inhomogneities—Part I; Basic Principles," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39, No. 4, 489-495, July 1992; and Trahey et al., "Synthetic Receive Aperture Imaging for Motion and for Tissue Inhomogneities—Part II: Effects of and Connection for Motion," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39, No. 4, 496-501, July 1992. The term synthetic aperture concept refers, in brief, to the simulation of the use of multiple devices, so as to obtain the superior resolution provided thereby, by the repeated use of a single mobile imaging apparatus, together with a mathematical combining of the images from the single mobile imaging apparatus to produce a highly resolved image.

[0022] Referring to **FIG. 1**, there is shown a movable ultrasound transducer **10** positioned directly above a target area **12**. Within this target area **12** is a center point **14**. The ultrasound transducer **10** captures a two-dimensional ultrasound image of the target area **12** and the image is recorded. This two-dimensional to ultrasound image captured by transducer **10** in the position thereof shown in solid lines is of a low definition because the sound waves returning to the transducer **10** are from one angle only. To increase the number of angles of surveillance and, hence, improve the resolution, the transducer **10** is moved 2-5° along a circular arc **18** to a new position indicated at **10'**. The transducer **10'** captures a second two-dimensional image of target area **12'** from the new angle corresponding to its position in the circular arc **18**. The sound waves return to the transducer **10** and the second image is recorded. The resolution is increased because sound waves from these two angles provide a more complete picture than sound waves from the first, single angle shown in solid lines in **FIG. 1**.

[0023] To continue the process, the transducer **10** is moved a further 2-5° about the circular arc **18** and the imaging process is repeated. The overall process can be repeated until the transducer **10** has moved up to a full 360° through the circular arc **18**.

[0024] It will be appreciated that the transducer **10** moves in the circular arc **18** around, and at a constant distance from, the center point **14**. Referring to **FIG. 2**, the center point **14** is positioned at the intersection of a pair of X and Y coordinates, this intersection being denoted in **FIG. 2** as **(0, 0)**. The transducer **10** moves within the XY plane and relative to the X and Y coordinates of the plane. In this embodiment, the ultrasound transducer **10** is always the same distance from the center point **14** as it moves around arc. This arc may be up to 360°. Residual body motion and movement that would otherwise diminish resolution quality can be mitigated using autofocus techniques.

[0025] After all the multiple images are captured and recorded, a redundant imaging method is employed to improve image definition. The images taken about the arc **18** are combined to form a composite image. The images can be is combined to form a composite image whether the images are coherent (i.e., both magnitude and phase information are recorded or incoherent (i.e., magnitude information only is recorded). Commonly, the redundant images are incoherent and are thus combined as a weighted average of the magnitudes only. The imaging system processes the combined image at each pixel and calculates the ideal resolution obtainable. The image of the representative pixel **16** within the target area **12** will be in the form of a set of plane waves returned to the transducer **10** from the representative pixel **16**. The phase of the returning waves is determined by the location of the representative pixel **16** relative to the location of the transducer **10**. The combination of sound waves from the representative pixel **16** returned to the transducer **10** for various positions of the transducer **10** around the arc **18**, and the varying phases of the sound waves which are returned, when processed in accordance with this invention provide a complete, high resolution, final image of the representative pixel **16**.

[0026] Improved resolution can also be obtained if coherent images are combined, that is, if the waves from the separate images are in phase with each other. Coherent image addition requires the use of a coherent imaging system. Coherent imaging systems are linear and preserve both signal amplitude and phase. The General Electric LOGIQ 700 ultrasound system provides this capability. To achieve improved resolution, each coherent image is processed by adding a phase term prior to combination.

[0027] As shown in **FIG. 2**, the representative pixel **16** is located in the target area **12** with respect to the center of rotation **14** at coordinates ($\rho\phi$). A representative plane wave will return from this pixel back to the transducer **10**. The position of the pixel **16** relative to the transducer **10** is a function of the phase of the wave upon return.

[0028] Various phases of waves from the representative pixel **16**, resulting from the different positions of the transducer **10** are calculated, and multiplied by a phase factor. This is repeated for each pixel in the sub-images until a more clearly resolved picture of all of the pixels appears.

[0029] The phase of the scattered wave relative to the center of rotation, and as a function of the transducer angle data, is given by:

$$s(x,y)=e^{-ik(x\cos\theta+y\sin\theta)}e^{i2k\Delta}. \qquad \text{Eq. (1)}$$

[0030] Where 2Δ is determined by noting that

$$\alpha=\pi/4-(\pi/4)-\phi+\theta=\theta-\phi.$$

[0031] Giving

$$\Delta=\rho\cos(\phi-\theta). \qquad \text{Eq. (2)}$$

[0032] Eq. (1) then becomes

$$s(x,y)=e^{-ik(x\cos\theta+y\sin\theta-2\rho\cos(\phi-\theta))}. \qquad \text{Eq. (3)}$$

[0033] The field at (r, β) with respect to the point scattered is obtained by substituting,

$$x=\rho\, cos\,\phi+r\, cos\,\beta,$$

$$y=\rho\, cos\,\phi+r\, sin\,\beta.$$

[0034] This gives,

$$s(r,\beta)=e^{-ik(\beta\cos\phi\cos\theta+r\cos\beta\cos\theta+\rho\sin\phi\sin\theta+r\sin\beta\sin\theta)}e^{-i2k\rho\cos(\phi-\theta)}=e^{ik\rho\cos(\phi-\theta)}e^{-ikr\cos(\beta-\theta)}. \qquad \text{Eq. (4)}$$

[0035] For each (discrete θ) θ_n one obtains a scattered field of the form

$$s_n(r, \beta)=e^{-ik\rho\cos(\phi-\theta n)}e^{-ikr\cos(\beta-\theta n)}. \qquad \text{Eq. (5)}$$

[0036] Each image can be multiplied by

$$e^{-ik\rho\cos(\phi-\theta n)}$$

[0037] and the total phases of the resulting images are summed to give

$$|(r, \beta)=\Sigma e^{-ikr\cos(\beta-\theta n)}. \qquad \text{Eq. (6)}$$

[0038] In the continuous case the summation becomes an integral resulting in an image of the form:

$$|(r, \beta)={}_0\int^{2\pi}e^{-ikr\cos(\beta-\theta)}d\theta. \qquad \text{Eq. (7)}$$

[0039] This result defines the limiting resolution for such systems.

[0040] It is noted that Eq. (1) and subsequent equations should be multiplied by an amplitude function (δfunction), and, if this is done, the resulting image is a convolution of the above impulse response with the input. Further, this analysis can be extended to include diffraction and system image impulse response.

[0041] For coherent processing it is more convenient to describe the algorithm in rectangular coordinates using discrete pixels as variables. If we let $\sigma\cos\theta=x_o$ and $\sigma\sin\phi=y_o$, Eq. (3) can be written in the form

$$s(x, y)=e^{-ik((Xi-Xo)\cos\theta+(Yj-Yo)\sin\theta)}e^{ik(Xo\cos\theta+Yo\sin\theta)} \qquad \text{Eq. (8)}$$

[0042] where the subscripts (i, j) denote discrete pixel locations (not shown).

[0043] Based on Equation (8), the steps of the algorithm will now be described with reference to **FIG. 3**.

[0044] Referring to **FIG. 3**, for ultrasound machines that generate and store coherent images, as described herein above, the first step, denoted **30**, is the generation of a set of images by moving the ultrasound transducer **10** in a circular arc **18** about a center point **14**. The next step, denoted **40**, is reconstructing the carrier frequency by multiplying each image by a function of the form,

$$e^{-ik(Xi\cos\theta+Yj\sin\theta)}. \qquad \text{Eq. (9)}$$

[0045] This step may not be necessary if the stored data already contains the carrier information within it. It should be noted that Eq. (8) describes data already containing the carrier function. The intent is to render the data in a manner consistent with the expression of Eq. (8). The next step, denoted **50**, is multiplying the image pixel at position (x_i, y_j) by a phase factor,

$$e^{-ik(Xo\cos\theta+Yo\sin\theta)}. \qquad \text{Eq. (10)}$$

[0046] The phase function in Eq. (10) is just the conjugate of the second factor in Eq. (8) for a point target at point (x_i, y_j).

[0047] The next step, denoted **60**, is the rotation of all images to align the common x-y coordinate system to gain a more complete picture of the entire pixel range within the target area **12**.

[0048] The next step, denoted **70**, is to sum the value of that pixel for each θ-dependent image as in Eq. (6). After producing a highly resolved image of a single pixel through mathematical imaging using the mathematical process described above, the process is repeated with the next pixel, as indicated by decision diamond **75** and block **80**. Thus, step **70** is repeated until all of the pixels have been processed.

[0049] The summation of the coherent images from step **70** will generally result in an image for which each pixel has both magnitude and phase components. While such a pixel image can be stored as a coherent-sum image, for viewing, however, the information of interest is merely the magnitude of each pixel. Therefore, it is necessary to strip the phase component from the image prior to submission to a display device. This operation, denoted as step **90**, is typically referred to as magnitude detection.

[0050] The process is far less complex for ultrasound machines that do not store coherent images. Referring to **FIG. 4**, for ultrasound machines that do not store coherent images, the first step, denoted **31**, is the generation of a set of images by moving the ultrasound transducer **10** in a circular arc **18** about a center point **14**.

[0051] The next step, here denoted **61**, is the rotation of all images to align the common x-y coordinate system to gain a more complete picture of the entire pixel range within the target area **12**.

[0052] The next step, denoted **71**, is to sum the value of that pixel for each □-dependent image as in Eq. (6), above. After producing a highly resolved image of a single pixel through mathematical imaging using the mathematical process described above, the process is repeated with the next pixel, as indicated by decision diamond **76** and block **81**. Thus, step **71** is repeated until all of the pixels have been processed—producing a highly resolved, final image.

[0053] Additionally, it can be appreciated that this technique can be extended to produce 3-dimensional, highly resolved images if the individual images are taken from adjacent non-planar arcs or from a longitudinal spiral pattern.

[0054] As indicated above, one important application of the present invention is in breast cancer detection and treatment. Currently, breast cancer is the number one cause of cancer-related deaths in women. With higher resolution imaging, breast cancer could be detected earlier and more accurately, and diagnoses could be more precise. In comparison to the other techniques described above, ultrasound has the advantage of being a non-ionizing modality that has not been shown to cause cancer, and can be used in real time in combination with fine needle aspiration in biopsy procedures. Ultrasound equipment is relatively inexpensive and portable, particularly as compared with techniques such as computer axial tomography (CAT) and magnetic resonance imaging (MRI). Moreover, patients can be imaged without the painful compression of breast tissue that is currently required in x-ray mammography.

[0055] The high-resolution ultrasound imaging herein can overcome a serious disadvantage with current ultrasound techniques—the lack of image resolution. Tests have shown that a substantial enhancement in resolution can be provided with the method of the invention. Moreover, it is projected that the method of the invention will provide an improvement in resolution from 0.5 mm to 0.3 mm at low frequencies and even higher resolution at higher frequencies.

[0056] Although the invention has been described above in relation to preferred embodiments thereof, it will be understood by those skilled in the art that variations and modifications can be effected to the preferred embodiments without departing from the scope and spirit of the invention.

We claim:

1. A method of improving the resolution of ultrasound images, said method comprising the steps of:

(a) obtaining an ultrasound image of a target area using an ultrasound imaging apparatus located at a first position outside said target area and at a predetermined distance from a center point within said target area;

(b) moving said ultrasound imaging apparatus along an arc spaced from the center point of the target area by said predetermined distance to a new position and obtaining a further ultrasound image of the target area;

(c) repeating step (b) for a plurality of further positions along said arc until the ultrasound apparatus has been moved up to 360° along said arc;

(d) calculating the phase of sound waves returned from a pixel within said target area to said ultrasound imaging apparatus for all of said positions of said ultrasound imaging apparatus so as to obtain image data for the pixel;

(e) combining the image data for the pixel calculated for all of said positions of said ultrasound imaging apparatus to produce a resolved image of the pixel; and

(f) repeating steps (d) and (e) for each pixel within said target area until all pixels within said target area are resolved.

2. A method according to claim 1, wherein said ultrasound apparatus is moved between 2° and 5° around said arc between each of said further positions.

3. A method according to claim 1, wherein the ultrasound images comprise incoherent images, and wherein said incoherent images are combined, using a synthetic aperture algorithm, into an improved-resolution incoherent image.

4. A method according to claim 1, wherein the ultrasound images from the ultrasound apparatus are coherent images, and wherein the coherent images are combined into an improved-resolution coherent image.

* * * * *

专利名称(译)	使用冗余合成孔径概念的超声成像方法		
公开(公告)号	[US20020138004A1](US20020138004A1)	公开(公告)日	2002-09-26
申请号	US09/814103	申请日	2001-03-22
[标]申请(专利权)人(译)	DICKEY FRED中号 DOERRY ARMINW 森本ALANķ		
申请(专利权)人(译)	DICKEY FRED M. DOERRY ARMIN W. 森本ALAN K.		
当前申请(专利权)人(译)	DICKEY FRED M. DOERRY ARMIN W. 森本ALAN K.		
[标]发明人	DICKEY FRED M DOERRY ARMIN W MORIMOTO ALAN K		
发明人	DICKEY, FRED M. DOERRY, ARMIN W. MORIMOTO, ALAN K.		
IPC分类号	A61B8/00 G01S15/89		
CPC分类号	A61B8/00 G01S15/8997		
外部链接	Espacenet USPTO		

摘要(译)

一种使用合成孔径概念来改善超声图像分辨率的方法。使用位于目标区域外的第一位置并且距目标区域内的中心点预定距离的超声成像设备获得二维图像。然后将成像设备沿弧移动到新位置，并获得另一个二维超声图像。该过程在目标区域周围重复达到整个360°。针对所有图像位置组合，计算和变换每个像素的图像数据，以产生该像素的高分辨率图像。对每个像素重复该过程，直到目标区域内的所有像素被完全分辨，从而产生完整的，高度分辨的整体图像。