



US 20170079620A1

(19) **United States**

(12) **Patent Application Publication**
Xie et al.

(10) **Pub. No.: US 2017/0079620 A1**
(43) **Pub. Date: Mar. 23, 2017**

(54) **AUTOCORRELATION GUIDED
CROSS-CORRELATION IN ULTRASOUND
SHEAR WAVE ELASTOGRAPHY**

(52) **U.S. Cl.**
CPC *A61B 8/5215* (2013.01); *A61B 8/4477*
(2013.01); *A61B 8/485* (2013.01); *A61B*
8/4245 (2013.01); *G01S 7/52022* (2013.01)

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(57) **ABSTRACT**

(21) Appl. No.: **15/311,553**

(22) PCT Filed: **May 11, 2015**

(86) PCT No.: **PCT/IB2015/053441**

§ 371 (c)(1),

(2) Date: **Nov. 16, 2016**

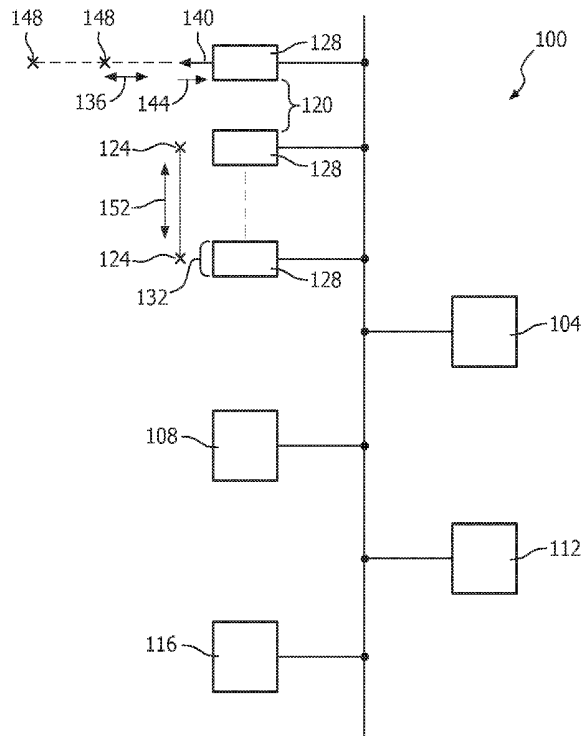
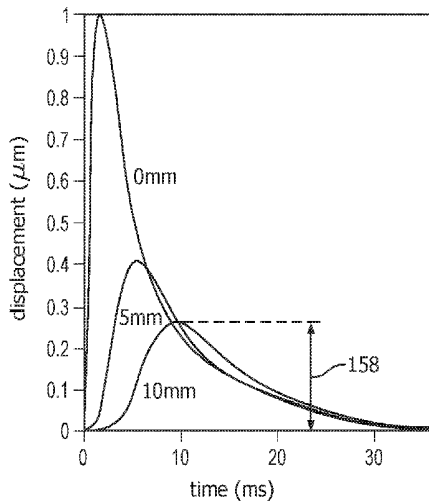
Related U.S. Application Data

(60) Provisional application No. 61/994,370, filed on May
16, 2014.

Publication Classification

(51) **Int. Cl.**
A61B 8/08 (2006.01)
G01S 7/52 (2006.01)
A61B 8/00 (2006.01)

Ultrasound motion-estimation includes issuing multiple ultrasound pulses, spaced apart from each other in a propagation direction of a shear wave, to track axial motion caused by the wave. The wave has been induced by an axially-directed push. Based on the motion, autocorrelation is used to estimate an axial displacement. The estimate is used as a starting point (234) in a time-domain based motion tracking algorithm for modifying the estimate so as to yield a modified displacement. The modification can constitute an improvement upon the estimate. The issuing may correspondingly occur from a number of acoustic windows, multiple ultrasound imaging probes imaging respectively via the windows. The autocorrelation, and algorithm, operate specifically on the imaging acquired via the pulses used in tracking the motion caused by the wave that was induced by the push, the push being a single push. The algorithm may involve cross-correlation over a search area incrementally increased subject to an image matching criterion (S358).



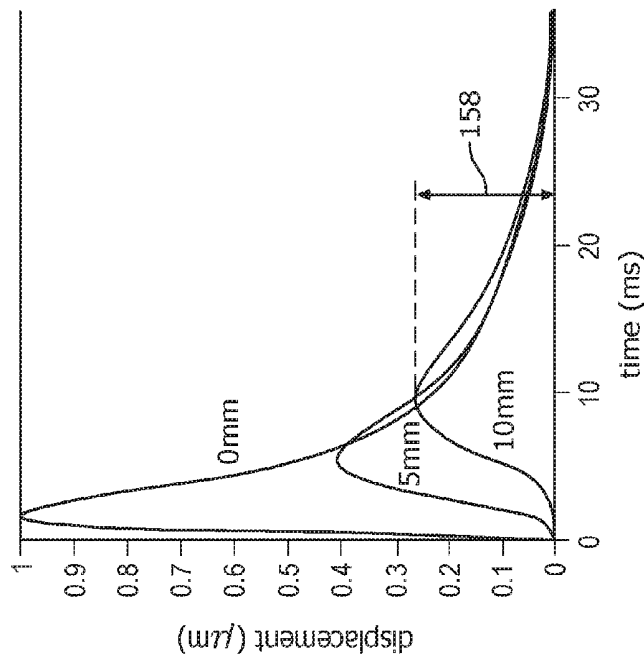
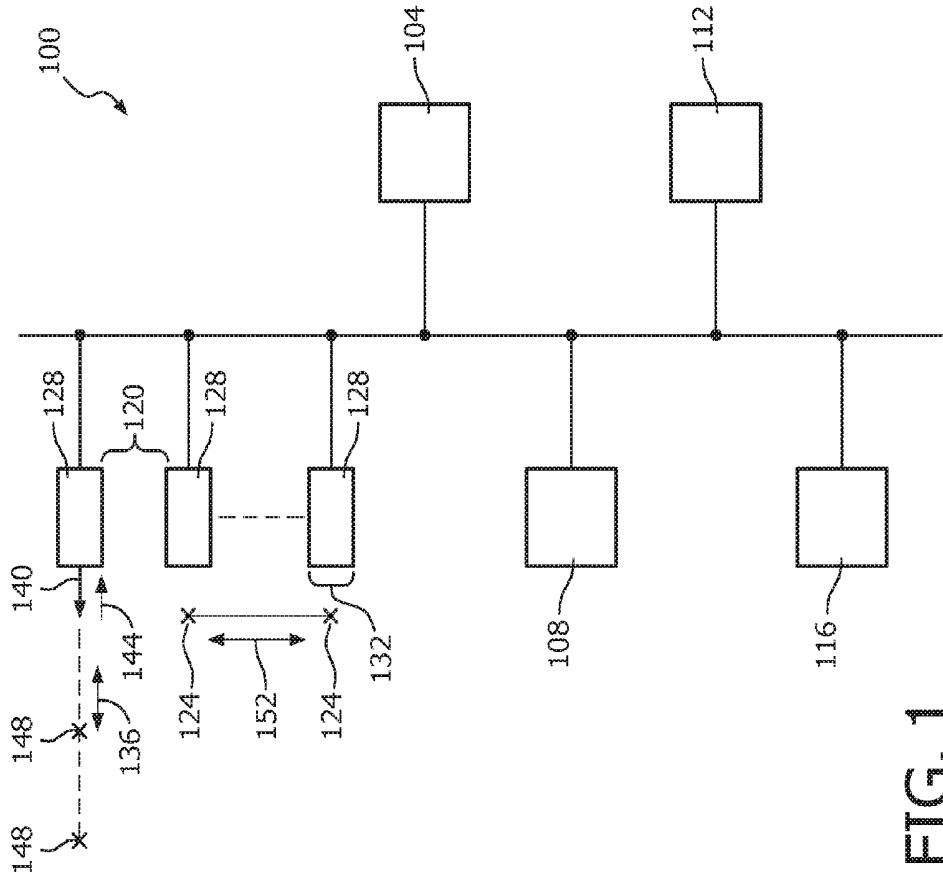


FIG. 1

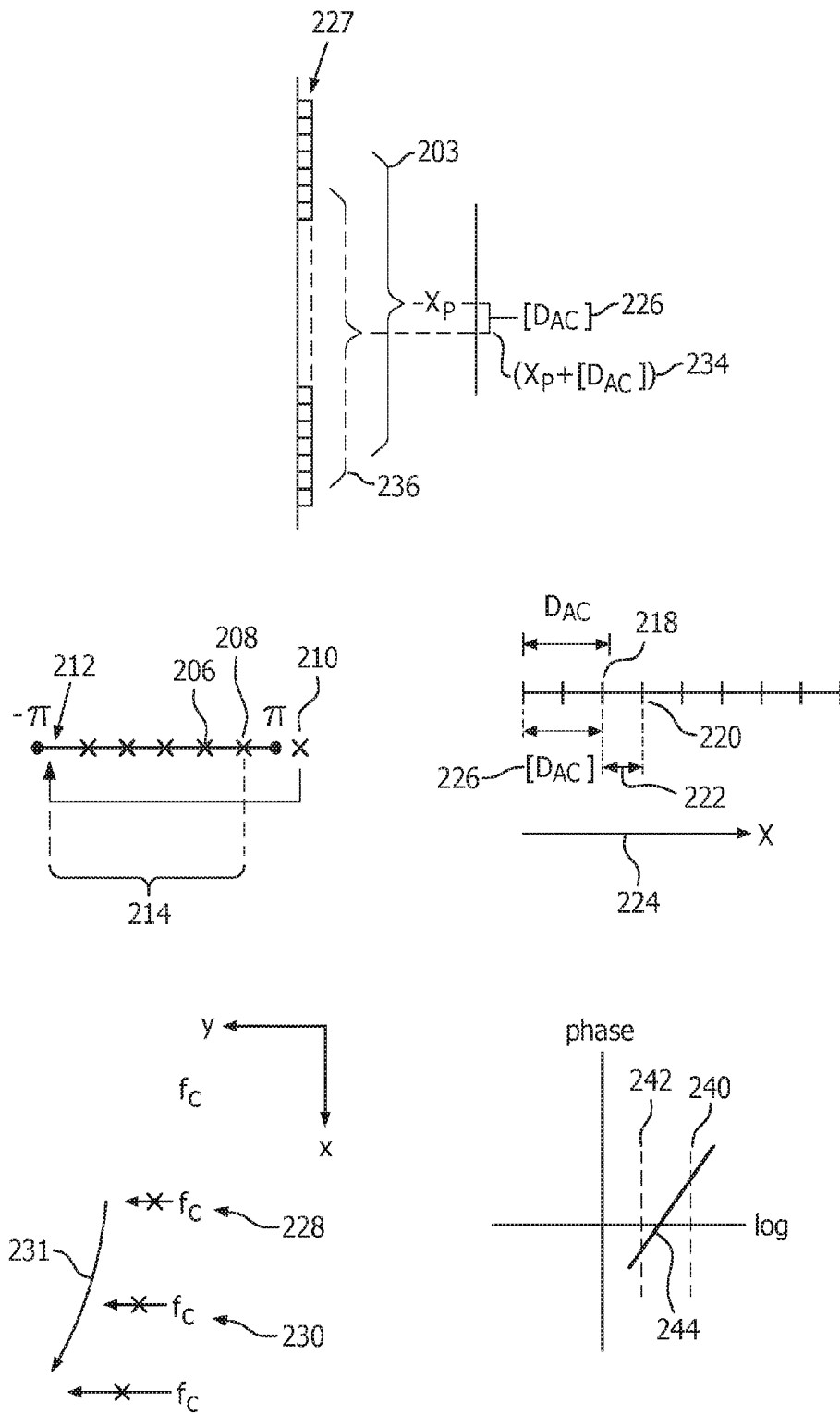


FIG. 2

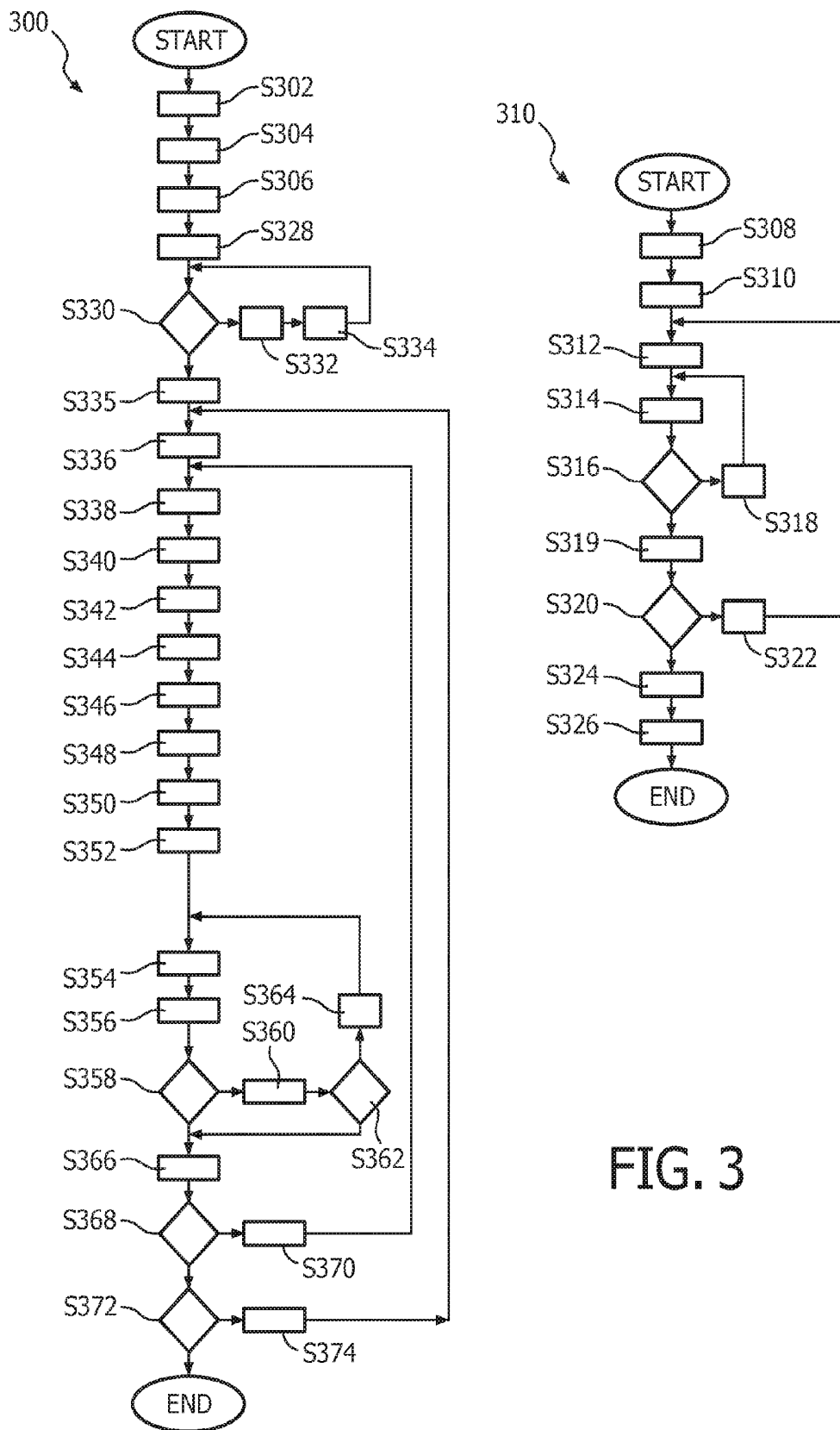


FIG. 3

**AUTOCORRELATION GUIDED
CROSS-CORRELATION IN ULTRASOUND
SHEAR WAVE ELASTOGRAPHY**

FIELD OF THE INVENTION

[0001] The present invention relates to tracking shear-wave-induced motion and, more particularly, to the use of correlation in the motion tracking.

BACKGROUND OF THE INVENTION

[0002] Ultrasound shear wave elastography is a new medical modality that can measure mechanical properties of soft tissue such as shear modulus and shear viscosity. As tissue elasticity is related to pathology, elastography can provide additional clinical information to increase diagnostic confidence. One example is non-invasive liver fibrosis staging by measuring liver stiffness.

[0003] In acoustic-radiation-force based ultrasound shear wave elastography, the dedicated pulse sequence consists of one or more long push pulses (typically hundreds of microseconds long each) and a series of interleaved tracking pulses. Due to the effect of acoustic radiation force, the push pulse causes tissue in the focal area to move away from the probe surface, simultaneously establishing a shear wave propagating away from the focal region in a direction perpendicular to the push beam. For each lateral position along the shear wave pathway at the focal depth, the tissue motion induced by the shear wave will be mainly in the same direction as the push beam. Consequently, the tracking pulses can, for a given position, monitor such dynamic response and translate it into a position-specific displacement waveform representing the magnitude of tissue movement as a function of time. Such waveforms can be computed at multiple positions along the shear wave propagation path. The waveforms can be inputted into a process for calculating the speed of the propagation. For example, Fourier transform can be performed on those shear waveforms to estimate shear wave phase velocity. Alternatively, shear wave amplitude peak-to-peak spatial and temporal calculations can also yield the shear wave propagation speed. As a result, absolute values of tissue mechanical properties can be determined. In particular and by way of example, the speed at which a shear wave propagates inside the tissue is governed by shear modulus, shear viscosity, tissue density and shear wave frequency through some mechanical models. The stiffer the tissue is, the faster the waves move. A measure of the stiffness can then be used in, for example, liver fibrosis staging.

[0004] Accurate, reliable and efficient motion tracking is a goal in the final estimation of tissue properties in any form of ultrasound shear wave elastography. In general, there are two major motion tracking techniques in ultrasound imaging: 1) phase shift by auto-correlation, and 2) time-shift by cross-correlation (or other alternatives such as sum absolute difference (SAD)).

[0005] In autocorrelation based approaches, the displacement of the structures of interest induces phase shift on successive high frequency ultrasound echoes backscattered by the moving medium. Autocorrelation has been implemented on most commercial ultrasound systems for real-time color flow imaging. As ultrasound waves propagate through soft tissue, the spectrum experiences a downshift due to the frequency dependent attenuation. Therefore,

assuming a constant center frequency in Doppler-based approaches will result in displacement estimation error. It is known to use additional autocorrelation in the fast time domain, i.e., in the axial direction of ultrasound pulses, to estimate the local center frequency and subsequently improve the displacement estimation accuracy. See T. Loupas, J. T. Powers, and R. W. Gill, "An Axial Velocity Estimator for Ultrasound Blood Flow Imaging, Based on a Full Evaluation of the Doppler Equation by Means of Two-Dimensional Autocorrelation Approach," IEEE Trans. Ultrason. Ferroelectr. Freq. Control 42.4., pp. 672-688, 1995.

[0006] Time-shift by cross-correlation estimates time delays by cross-correlating, from one pulse to another pulse using radiofrequency (RF) data or complex signals conveyed from RF data. The search area is preset large enough to avoid missing an optimal match.

SUMMARY OF THE INVENTION

[0007] What is proposed herein below addresses one or more of the above concerns.

[0008] Two standard approaches to displacement estimation are autocorrelation and cross-correlation. Autocorrelation is more computationally efficient than cross-correlation. However it is subject to aliasing—the maximum displacement limit is a quarter wavelength (for standard liver image probe with center frequency 3 MHz, the limit is approximately 120 μm).

[0009] In the conventional, i.e., unguided, cross-correlation approach, aliasing limit is eliminated. However it takes more computational time which is proportionally related to the predefined search area. Searching over a large area makes standard cross-correlation computationally expensive. However, if the search area is set too small, the true peak of the cross correlation function will be missed; if it is too large, peak hopping will occur due to noise contained in the signals. In such case, cross-correlation can produce a false correlation peak exceeding the true peak. False peaks will introduce discontinuity and error in displacement estimation. Unfortunately, in practice, the size of a search area needed would be variable. In clinical applications, ultrasound shear wave elastography induced soft tissue motion is on the order of ten-micrometer (10- μm). The upper limit is mainly constrained by a United States Food and Drug Administration (FDA) acoustic output safety limit. The induced shear wave motion is usually observed by ultrasound tracking pulses for a period of 10-20 milliseconds (ms) for one shear wave push pulse. If multiple push pulses are used, the observation can increase to 50-100 ms. Although patients are usually advised to hold breath for a few seconds during shear wave elastography, during the period of time 50-100 ms, patient motion (cardiac motion and breathing) and background motion sometimes can exceed quarter wavelength and reach one order magnitude higher than true shear wave motion to bury the true shear wave signal. In such a case, if conventional cross-correlation alone is utilized, a very large search size has to be used in order to locate the maximum correlation function. This results in longer computational time and potentially in false peak hopping. If auto-correlation alone is used, phase aliasing will likely occur.

[0010] The two-step motion-tracking approach proposed herein is more robust to background motion.

[0011] This new approach uses both auto-correlation, and cross-correlation, for accurate and efficient tracking of shear wave propagation in soft tissue. This is useful, for example, for in vivo applications of ultrasound shear wave elastography. The two-step approach is characterizable as autocorrelation guided cross-correlation. In the first step, phase is derived from autocorrelation of the complex signals and properly un-wrapped. Initial displacement is then calculated from the phase using a constant center frequency. In the second step, the initial displacement is quantized and used as a starting point to feed the cross-correlation with a reduced search window to obtain the final displacement with high precision. By integrating autocorrelation and cross-correlation, the proposed method is well suited for real-time applications. Computation by cross-correlation in the instant proposal is much faster than standard cross-correlation. It also reduces the variance of the displacement estimates and bias, without the need for explicit estimation of the mean frequency of the RF signals.

[0012] Performance improvement of this new method over traditional autocorrelation includes that: 1) aliasing is removed; and 2) there is no need to consider effects of center frequency depth attenuation and frequency random fluctuation. The latter benefit exists because displacement estimation using time-shift based cross-correlation is immune to frequency change. Moreover, the performance improvement of this new method over traditional cross-correlation includes: 1) significantly reduced search size to overcome peak hopping (false maxima or minima) leading to improved estimation accuracy; and 2) much faster computation.

[0013] What is proposed herein combines auto-correlation and cross-correlation estimators in a way that takes advantages of the strength of each to improve overall motion tracking performance. For example, error due to any aliasing not removed by the phase unwrapping in step one is corrected or mitigated by the ensuing cross-correlation. The relatively high computational burden of the cross-correlation, as another example, is relieved by providing the cross-correlation with a search significantly shortened by the autocorrelation-derived starting point. This composite protocol can obtain more accurate and robust displacement estimation for shear wave elastography than either individual protocol.

[0014] In accordance with an aspect of the proposed technology, an ultrasound motion-estimation method includes issuing multiple ultrasound pulses, spaced apart from each other in a propagation direction of a shear wave, to track axial motion caused by the shear wave. The shear wave has been induced by an axially-directed ultrasound, or mechanically-induced, push pulse. Based on the tracking pulse echoes, the method uses autocorrelation to estimate an axial displacement. The method then uses the estimate as a starting point in a time-domain based motion tracking algorithm for modifying the estimate so as to yield a modified displacement. The modification can constitute an improvement upon the estimate in terms of motion tracking accuracy. The issuing may correspondingly occur from a number of acoustic windows, multiple ultrasound imaging probes imaging respectively via the windows. The autocorrelation, and algorithm, can operate specifically on the imaging acquired via the pulses used in tracking the motion caused by the wave that was induced by the push, the push being a single push. The algorithm may involve cross-correlation over a search area incrementally increased subject to an

image matching criterion. The acquisition for the procedure can be extended over multiple pushes.

[0015] Details of the novel, autocorrelation guided time-domain based motion tracking in shear wave elastography are set forth further below, with the aid of the following drawings, which are not drawn to scale.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a schematic diagram of an exemplary ultrasound motion-estimation device and a conceptual depiction of a noise free shear wave, in accordance with the present invention;

[0017] FIG. 2 is a conceptual diagram providing examples of concepts relating to operation of the device of FIG. 1; and

[0018] FIG. 3 is a set of flow charts demonstrating a possible operation for autocorrelation guided time-domain based motion tracking in shear wave elastography, according to the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0019] FIG. 1 depicts, by illustrative and non-limitative example, an ultrasound motion-estimation device 100 usable for shear wave elastography in autocorrelation guided time-domain based motion tracking. The device 100 includes image acquisition circuitry 104, motion tracking circuitry 108, a controller 112, and data storage 116. The image acquisition circuitry is configured for spaced apart 120 image acquisition from respective lateral positions 124. The device 100 further includes multiple ultrasound imaging probes 128. The image acquisition is performed from respective acoustic windows 132. An acoustic window is the area on the imaging surface of the probe 128 that, in contact with the object or patient (human or animal) being examined, exchanges ultrasound used in imaging. In an axial direction 136, ultrasound pulses 140 are emitted, and radio-frequency (RF) data 144 is echoed back from the patient. The pulse 140 is dynamically echoed back from a number of imaging depths 148 being sampled to interrogate the medium within the patient.

[0020] While different markings in FIG. 1 annotate different probes 128, this is for explanatory purposes. The probes 128 may be operated generally identically in imaging the medium. They may be operated simultaneously, in parallel, although what is proposed herein is not limited to such operation.

[0021] A lateral direction 152 is a direction of propagation of a shear wave that was generated by an axially-directed push. The push was generated by ultrasound focused to a particular imaging depth to deliver sufficient acoustic radiation force, or may be a mechanically induced push.

[0022] It is mainly in the axial direction 136, at that imaging depth, that the propagating shear wave deforms and displaces the medium. A plot in FIG. 1 shows three waveforms representing displacement of body tissue by a shear wave. The three waveforms correspond to lateral distances of 0 mm, 5 mm and 10 mm away from the focus of the push pulse. The push pulse lasts for a few hundred microseconds, starting at the time corresponding to the origin of the plots. The tissue displacements are tracked for 35 ms. They are normalized to the peak displacement at 0 mm, for illustration purposes. The shear wave induced displacements or deformations 158 at the different lateral distances (i.e., 0 mm, 5 mm, 10 mm) manifest the displacing effect of the propagat-

ing shear wave. Their waveforms vary as a function of tissue mechanical properties and the lateral propagation distance from the shear wave origin (i.e., push pulse focus location).

[0023] Autocorrelation is, as mentioned herein above, the first step in the two-step approach to tracking axial displacement. The displacement of structures of interest in the moving medium induces phase shift on successive high frequency ultrasound echoes backscattered by the moving medium.

[0024] The phase shift is estimated by 1-D autocorrelation of the complex signals (complex analytic or baseband signals) in the slow time. Baseband data consists of in-phase (I) and quadrature (Q) component derivable post-receive-beamforming by demodulating to remove the carrier frequency. The derivation of complex analytic signals from RF data is also well-known, and described in U.S. Pat. No. 7,873,686 to Elfataoui et al.

[0025] In shear wave tracking, $G_0(x,y)$ is the complex image acquired as the reference signal before the excitation of the push pulse. The reference pulses by which the reference image $G_0(x,y)$ was acquired are an initial part of the motion tracking. The axial direction **136** is along the x-axis, and the lateral direction **152** is along the y-axis. Each point, or “pixel”, (x_p, y_q) represents an image sample at an imaging depth **148** corresponding to x_p and at a lateral position **124** corresponding to y_q .

[0026] $G_n(x,y)$ is the n^{th} image acquisition, post-push, during shear wave tracking. The image acquisitions can be repeated, e.g., in parallel via the probes **128**, with n ranging up to, for example, $N=30$ or more following a single push (N is determined by the tracking pulse repetition frequency and the tracking duration). Although, it is within the intended scope of what is proposed herein that tracking may extend past a second or even subsequent push.

[0027] The generalized formula to calculate 1-D correlation $R_{k,n}$ at pixel (x,y) is expressed as below for a complex baseband signal or a complex analytic signal

$$R_{k,n}(x, y) = \frac{1}{2M+1} \sum_{i=-M}^M G_{g_0}(x+i, y) G_n^*(x+i+k, y) \quad (1)$$

where $(2M+1)$ is the size, in the axial direction **136**, of the correlation kernel **203** as seen in FIG. 2; and $R_{k,n}$ is the correlation coefficient at k -lag in fast time (axial direction) and n -lag in the slow time (tracking time). G_n^* is the complex conjugate of G_n .

[0028] The displacement D at (x,y) for the n^{th} shear wave tracking acquisition is initially computed to be

$$D_n(x, y) = \frac{c}{4\pi} \left(\frac{\angle R_{0,n}(x, y)}{f_c} \right), \quad (2)$$

where c is the speed of sound, $\angle R_{0,n}(x,y)$ is the angle of the 1-D autocorrelation coefficient at zero-lag in fast time and n -lag in the slow time, and f_c is the center frequency. Thus, $D_n(x_p, y_q)$, after quantization which is discussed below, serves as an estimate of axial displacement of the medium, the estimate being specific for the current pixel (x_p, y_q) . The angle, or “phase”, is derivable from the formula

$$\angle R_n(x,y) = \tan^{-1}(\text{Im}[R_n(x,y)]/\text{Re}[R_n(x,y)]) \quad (3)$$

and, before substitution into equation (2), subjected to phase unwrapping to mitigate or avoid aliasing. The functions Re and Im respectively extract the real and imaginary components of the complex-valued autocorrelation coefficient R_n . With regard to phase unwrapping, the unwrapped phase shift in slow time (i.e., between n and $n+1$, where $n=1, \dots, N-1$) is expected to be smooth without disruption. Referring to FIG. 2, a wrapped phase **206** for acquisition n is followed by a wrapped phase **208** of acquisition $n+1$. A phase **210** for acquisition $n+2$ wraps back, modulo 2π , within the confining interval $[\pi, -\pi]$. This results in a wrapped phase **212**, and a phase discontinuity **214** close to 2π (in magnitude and unrepresentative of the actual axial motion in the medium. Phase unwrapping resolves this, yielding the unwrapped phase **210**. If, despite the phase unwrapping, disruption occurs, it usually indicates significant externally-caused motion, i.e., originating from out of the plane of the shear wave.

[0029] Equation (1) has $2M+1$ sampling depths used in the kernel of auto-correlation for a specific value of “ x ”. For any given acquisition n , samples are acquired from each of the $2M+1$ sampling depths, and additional sampling depths. The additional sampling depths allow equation (1) to be executed multiples times, each time for a different value of “ x .” For example, in one execution, $D_n(x_p, y_q)$ is to be determined for a pixel (x_p, y_q) ; in the next execution, $D_n(x_{p-1}, y_q)$ is to be determined for a pixel (x_{p-1}, y_q) , with x_p and x_{p-1} being at correspondingly different sampling depths.

[0030] Equation (1) is not only executed repeatedly, each time for a given pixel whose displacement estimate is being calculated; this set of executions is repeated, each time for a different acquisition n ($1 \leq n \leq N$).

[0031] Furthermore, all of the above-described executions of equation (1) are repeated each time for a different lateral position. Each lateral position **124** corresponds to a value of “ y .” Thus, y_q has a lateral position **124** different than that of y_{q+1} .

[0032] In FIG. 2, two consecutive ones of the sampling depths, at a given lateral position **124**, are denoted **218**, **220**.

[0033] In a given acquisition n at a given lateral position **124**, data is acquired sampling depth **218** by sampling depth **220** for all sampling depths, during the receive window. This is all redone acquisition by acquisition. In turn, the repeated acquisitions (i.e., each being sampling depth **218** by sampling depth **220**) are all redone lateral position by lateral position.

[0034] The entire set of acquisitions is done once and recorded in data storage **116**, that data then being drawn on repeatedly in steps one and two.

[0035] The axial displacement D , (or “ D_{AC} ”) in equation (2) is indicative of a starting point for the second step in the two-step approach.

[0036] D_{AC} in equation (2), as an axial offset from the current pixel (x_p, y_q) , will generally have an endpoint disposed in between sampling locations.

[0037] Instead of using D_{AC} itself as the starting point, D_{AC} is quantized based on consecutive sampling depths **218**, **220** separated by a pixel spacing unit **222** in the axial direction shown in FIG. 2 by the arrow **224**. The same pixel spacing or further refined spacing (by upsampling the RF or complex signal) could be used in the second step. In the latter case, D_{AC} should be adjusted using the ratio of the pixel spacing before and after upsampling.

[0038] The quantization, which may be up or down, and by rounding based on proximity or by default, results in a quantized displacement $[D_{AC}]$ **226**.

[0039] This serves as the pixel-specific, i.e., specific to (x_p, y_q) , estimate of axial displacement of body tissue.

[0040] The pixel (x_p, y_q) , offset by $[D_{AC}]$, is the starting point for step two. It is this second step that fine tunes the estimate **226** from the first step—this is done via image to image matching, followed by peak searching, and polynomial fitting or phase zero crossing detection, for the fine tuning.

[0041] Since the image to image matching in step two is time-domain based, there is no need for taking into account, in step one, center frequency attenuation of ultrasound issued for the acquisitions, and there is no need in step one to correct the estimate **226** for center frequency attenuation. Advantageously, center frequency attenuation correction overhead is avoided. The attenuation accumulates **231** sampling depth **228** to sampling depth **230**. The “x’s” crossing arrows in FIG. 2 represent the lack of need for accounting for center frequency attenuation that occurs during propagation of the tracking pulse **140**.

[0042] For a cross-correlation which is part of the time-domain based motion tracking algorithm, the starting point **234** is provided as an offset **226** from the axial position, denoted “x,” in FIG. 2, of the currently considered pixel (x_p, y_q) . The offset, or “positioning”, **226** corresponds to a shift, with respect to a reference image **227**, of the correlation kernel **203** that was utilized in the autocorrelation. The shifted kernel **236** is used in the cross-correlation.

[0043] Time domain based cross-correlation estimates time delays by cross-correlating received RF echoes (or complex analytic or baseband signals) from one pulse to another pulse.

[0044] A two-dimensional cross-correlation is described immediately herein below, because steps one and two may be used to determine a two-dimensional offset. This would be for greater accuracy, in tradeoff for extra computation.

[0045] In two-dimensional ultrasound imaging, two components of a displacement vector (u,v) can be estimated using the 2-D speckle tracking procedure. Thus, “u” is in the axial direction **136** and “v” is in the lateral direction **152**. In particular, at every pixel (x,y) in the initial phase-sensitive signals or images that make up the reference image $G_0(x,y)$ (i.e., RF signal, complex baseband or complex analytic signal), a 2-D correlation kernel of spatial extent equaling approximately one speckle is defined around the pixel. A speckle, corresponding in size to M and J in formula (4) below, is defined as the full-width at half maximum in both dimensions of the two-dimensional autocorrelation function of the initial complex image $G_0(x,y)$. This kernel is then cross-correlated with the complex image $G_n(x,y)$ following deformation, i.e., post-push. The resultant 2-D weighted cross-correlation coefficient $\rho'_{k,l}$ at pixel (x,y) at n^{th} acquisition as a function of 2-D lags (k,l) is calculated :

$$\rho'_{k,l,n}(x, y) = \frac{\sum_{i=-M}^{i=M} \sum_{j=-J}^{j=J} W_{ij} [G_0(x+i, y+j) G_n^*(x+k+i, y+l+j)]}{\left[\sum_{i=-M}^{i=M} \sum_{j=-J}^{j=J} W_{ij} |G_0(x+i, y+j)|^2 \right]^{1/2} \left[\sum_{i=-M}^{i=M} \sum_{j=-J}^{j=J} W_{ij} |G_n(x+k+i, y+l+j)|^2 \right]^{1/2}} \quad (4)$$

[0046] In this expression, W_{ij} is a simple two-dimensional weighting function over the $(2M+1) \times (2J+1)$ point correlation kernel. The weighting, by weights of a weighted average, reduces the likelihood of peak hopping, and overall error, in the search for the optimal (or “maximum”) lag. High frequency noise can be reduced by use of a weighting function that smoothly decreases to zero at the tails, such as a Hanning window.

[0047] The correlation coefficient is a unit-normalized, complex function of lags (k,l) with a range of $\pm K$ and $\pm L$.

[0048] When, as in equations (1) through (3), only 1-D correlation and 1-D searching are used for tracking the axial motion, the above formula is simplified to $L=0$ and $J=0$ thereby reducing to:

$$\rho'_{k,n}(x, y) = \frac{\sum_{i=-M}^{i=M} W_i [G_0(x+i, y) G_n^*(x+k+i, y)]}{\left[\sum_{i=-M}^{i=M} W_i |G_0(x+i, y)|^2 \right]^{1/2} \left[\sum_{i=-M}^{i=M} W_i |G_n(x+k+i, y)|^2 \right]^{1/2}} \quad (5)$$

[0049] The corresponding correlation kernel **236** is of size $2M+1$. The value “x” on the right side of equation (5) is replaced by the starting point **234**, i.e., $(x_p + [D_{AC}], y_q)$ for $G_n(x,y)$ ($0 < n \leq N$). The lag k , and thus the range $[-K, K]$, is incremented over iterative executions of equation (5). Thus, the extent of the search area is $M+k$ pixel spacing units **222** on either axial side of the center of the correlation kernel **236**. The lag k associated with what turns out to be the maximum value of the correlation coefficient $\rho'_{k,n}(x,y)$ is used in an interpolation to find a peak of a correlation coefficient curve and the corresponding, or “maximum”, lag k_{max} . Since lag k_{max} is in the axial direction **136**, it is a vector. The estimate $[D_{AC}]$ **226** from step one is likewise a vector in the same direction **136**. The two vectors (or equivalently scalars in the 1-D case) are added to derive a modified displacement, i.e., an improved measurement of the displacement, for pixel (x_p, y_q) . In the 2-D case, both of the vectors added are two-dimensional. As an alternative to using the starting point **234** as a replacement for the value of “x” for $G_n(x,y)$ ($0 < n \leq N$), $(x_p - [D_{AC}], y_q)$ may be used as a replacement for “x” in $G_0(x,y)$.

[0050] Operationally and with reference to the exemplary procedure **300** in FIG. 3, an acquisition counter is initialized to zero (step **S302**).

[0051] The probes **128** are positioned spaced apart **120** and in contact with the patient or subject (step **S304**).

[0052] The reference image **227** is acquired, i.e., an imaging acquisition is made (step **S306**).

[0053] In particular, in executing step **S306**, an image-acquiring sub-procedure **310** is invoked, and is executed as follows. A lateral position counter is initialized to zero (step **S308**). An imaging depth counter is likewise initialized to zero (step **S310**). An ultrasound pulse **140** is emitted by the probe **128** in the current lateral position **124** (step **S312**). An RF signal **144** is acquired from an ultrasound echo originating from the current imaging depth **148** (step **S314**). If it is not the last depth (step **S316**), the depth counter is incremented (step **S318**) and return is made to the sample receive step **S314**. If, instead, it is the last depth (step **S316**), the depth counter is cleared (step **S319**). If the current

position 124 is not the last position (step S320), the position counter is incremented (step S322) and processing branches back to the pulse emitting step S312. If, on the other hand, the current position is the last position (step S320), complex analytic signals are derived from the RF data acquired (step S324). The derived analytic signals are stored in correspondence with the stored RF signals (step S326). Alternatively, complex analytic data may not be generated or needed if, for example, correlation lag interpolation is done via a polynomial fitting technique. Likewise, complex baseband data may serve the role of RF data in steps one and two.

[0054] With reference again to the main procedure 300, the push pulse is emitted (step S328). Here, it is assumed that a single push pulse is emitted for the entire procedure 300, although there alternatively could be, later on, an additional one or more push pulses to allow for extra tracking at the possible expense of more global background noise from patient motion during the time period needed for the extra tracking. If, currently, image acquisition is still to continue (step S330), the acquisition counter is incremented (step S332), the image acquisition sub-procedure 310 is invoked for tracking (step S334), and return is made to step S330. If, however, image acquisition is no longer to continue (step S330), processing points to the first lateral position 124 in the acquired data for which displacement is to be measured (step S335). Processing points to the first pixel (x_p, y_q) at the current lateral position 124 (step S336). Autocorrelation according to equation (1) is performed at zero lag (step S338). Equation (3) is used to extract the phase of the complex-valued autocorrelation coefficient R_n (step S340). The phase is unwrapped based on the phase determination of the prior acquisition (step S342). Equation (2) is used to estimate the axial displacement D_{AC} for the current pixel (step S344). D_{AC} is quantized to yield the quantized displacement $[D_{AC}]$ 226 (step S346). The correlation kernel 203 used in the autocorrelation is now shifted, resulting in a shifted kernel 236 for subsequent cross-correlation (step S348). The absolute value of a correlation lag k is initialized, based, for example, on what is expected to be the smallest search needed to correct the estimate 226 from step one (step S350). For example, a typical 100 μm predefined cross-correlation search area can be reduced to 30 μm , which is a benefit of the proposed two-step method. Cross-correlation in accordance with equation (5) draws on complex analytic signals, iteration by iteration as the lag k varies between $-K$ and K (step S352). This is not a limitation on step one any combination of RF, complex analytic or complex baseband signals may have been used. From the set of coefficients $\rho_{k,n}^i(x,y)$ generated in the iterations, a maximum coefficient ρ_{max} is selected, and its phase 240 is determined, as was done for the autocorrelation coefficient (step S354). The iterative-wise closest neighboring coefficient with a phase 242 of opposite polarity is selected, and interpolation is used to determine, from a zero crossing 244, an interpolated correlation lag lag_{maxI} and the corresponding interpolated maximum cross-correlation coefficient ρ_{maxI} (step S356). If ρ_{maxI} does not meet an image-matching threshold, or “criterion”, T_{IM} (step S358), the lag k is increased (step S360). Query is made as to whether the lag k now is greater than a maximum lag threshold T_{ML} (step S362). If the lag k is not greater than T_{ML} (step S362), the cross-correlation of equation (5) is repeated for each of the intervening values of k introduced by the just-previous instance of step S360 (step S364). Return is then made to step S354. If, on the other hand, ρ_{maxI}

does meet T_{IM} (step S358) or the lag k exceeds T_{ML} (step S362), a vector addition is performed, summing the quantized displacement $[D_{AC}]$ 226 with the interpolated correlation lag lag_{maxI} (step S366). If more pixels (x_p, y_q) remain to be processed (step S368), the pixel pointer is incremented (step S370) and return is made to the autocorrelation step S338. Otherwise, if no more pixels remain to be processed (step S368), but more spatial positions are to be processed (step S372), the position pointer is incremented (step S374) and processing returns to step S336.

[0055] The method proposed herein above has been validated using in vivo clinical data. Improved motion tracking success was found for the two-step method, in the post-processing of data, in comparison to other algorithms. Higher motion tracking success rate means more valid clinical data for better diagnostic performance under the same examination time.

[0056] Although methodology of the present invention can advantageously be applied in providing medical diagnosis for a human or animal subject, the scope of the present invention is not so limited. More broadly, techniques disclosed herein are directed to improved shear-wave-based motion tracking, in vivo or ex vivo.

[0057] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

[0058] For example, an example of an alternative time-domain based motion tracking algorithm is the block-matching minimum difference method.

[0059] Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. Any reference signs in the claims should not be construed as limiting the scope.

[0060] A computer program can be stored momentarily, temporarily or for a longer period of time on a suitable computer-readable medium, such as an optical storage medium or a solid-state medium. Such a medium is non-transitory only in the sense of not being a transitory, propagating signal, but includes other forms of computer-readable media such as register memory, processor cache and RAM.

[0061] A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

1. An ultrasound motion-estimation device comprising:
 - image acquisition circuitry configured for issuing, via multiple acoustic windows spaced laterally apart in a propagation direction of a shear wave, a respective plurality of ultrasound pulses to track axial motion caused by said wave, said wave having been induced by an axially-directed push; and
 - motion tracking circuitry configured for, based on said motion, using autocorrelation to estimate an axial displacement and for using the estimate as a starting point in a time-domain based motion tracking algorithm for modifying said estimate so as to yield a modified displacement.

2. The device of claim 1, said algorithm comprising cross-correlation, said using said estimate comprising using said estimate for positioning a kernel of said cross-correlation.

3. The device of claim 1, said issuing comprising issuing initial respective pulses via said windows to acquire a reference image.

4. The device of claim 3, said issuing further comprising issuing, for the tracking, respective tracking pulses subsequent to the issuing of pulses to acquire the reference image.

5. The device of claim 4, configured for, based on acquisition from said tracking pulses, forming an image that reflects deformation caused by said motion, said autocorrelation being based, in part, on said image that reflects said deformation.

6. The device of claim 5, said algorithm operating on said image that reflects said deformation.

7. The device of claim 3, said algorithm comprising cross-correlation, said using said estimate comprising using said estimate for positioning a kernel of said cross-correlation relative to the acquired reference image.

8. The device of claim 7, said reference image comprising pixels, said using autocorrelation being repeated for different ones of said pixels, thereby generating different positionings and corresponding different estimates, said positioning being among said positionings, said estimate being among said estimates.

9. The device of claim 1, said motion tracking circuitry being further configured for, with respect to performance of said autocorrelation, and of said algorithm, operating specifically on imaging acquired via said pulses used in tracking said motion caused by said wave that was induced by said push, said push being a single push.

10. The device of claim 1, said autocorrelation operating on complex signals derived from radiofrequency data acquired via said pulses.

11. The device of claim 10, said motion tracking circuitry being further configured for deriving, from said autocorrelation, a phase.

12. The device of claim 11, said motion tracking circuitry being further configured for unwrapping said phase, to resolve phase discontinuities.

13. The device of claim 12, said motion tracking circuitry being further configured for making said estimate based on the unwrapped phase.

14. The device of claim 1, configured for making said estimate without need for taking into account center frequency attenuation of ultrasound issued in said issuing.

15. The device of claim 1, said autocorrelation being based on image samples at correspondingly different imaging depths.

16. The device of claim 1, said algorithm, in the yielding of said modified displacement, alternating searching with evaluating a result of said searching.

17. The device of claim 1, said modifying comprising quantizing said estimate based on a pixel spacing unit corresponding to a difference between consecutive sampling depths for a pulse from among said pulses.

18. The device of claim 1, the estimating comprising deriving a first vector, said modifying comprising deriving a second vector and adding, to said second vector, said first vector.

19. The device of claim 1, said image acquisition circuitry being further configured for said issuing for a series of acquisitions, the spacing apart serving to space apart positions in said direction, said motion tracking circuitry being further configured, in order to calculate respective ones of said modified displacement, performing both the estimating, and said modifying, position-by-position, sampling depth by sampling depth, and acquisition by acquisition.

20. The device of claim 1, configured for deriving complex analytic signals from ultrasound echoed back from said pulses, said algorithm comprising cross-correlating said signals to yield a cross-correlation coefficient and further comprising estimating where a phase of said coefficient crosses zero.

21. The device of claim 1, said algorithm including cross-correlation over a search area that, subject to an image matching criterion, is incrementally increased.

22. The device of claim 1, further comprising multiple ultrasound imaging probes for respective imaging via said multiple acoustic windows.

23. An ultrasound motion-estimation method comprising: issuing multiple ultrasound pulses, spaced apart from each other in a propagation direction of a shear wave, to track axial motion caused by said wave, said shear wave having been induced by an axially-directed push; based on said motion, using autocorrelation to estimate an axial displacement; and using the estimate as a starting point in a time-domain based motion tracking algorithm for modifying said estimate so as to yield a modified displacement.

24. A computer readable medium for ultrasound motion-estimation, said medium embodying a program having instructions executable by a processor for performing a plurality of acts, among said plurality there being the acts of: issuing multiple ultrasound pulses, spaced apart from each other in a propagation direction of a shear wave, to track axial motion caused by said wave, said shear wave having been induced by an axially-directed push; based on said motion, using autocorrelation to estimate an axial displacement; and using the estimate as a starting point in a time-domain based motion tracking algorithm for modifying said estimate so as to yield a modified displacement.

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专利名称(译)	自相关引导超声剪切波弹性成像中的互相关		
公开(公告)号	US20170079620A1	公开(公告)日	2017-03-23
申请号	US15/311553	申请日	2015-05-11
[标]申请(专利权)人(译)	皇家飞利浦电子股份有限公司		
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IPC分类号	A61B8/08 G01S7/52 A61B8/00		
CPC分类号	A61B8/5215 A61B8/4477 G01S7/52022 A61B8/4245 A61B8/485		
优先权	61/994370 2014-05-16 US		
其他公开文献	US10588604		
外部链接	Espacenet USPTO		

摘要(译)

超声运动估计包括发出在剪切波的传播方向上彼此间隔开的多个超声脉冲，以跟踪由波引起的轴向运动。这种波是由轴向推动引起的。基于运动，自相关用于估计轴向位移。该估计被用作基于时域的运动跟踪算法中的起点 (234)，用于修改估计以产生修改的位移。修改可以构成对估计的改进。发布可以相应地从多个声窗口发生，多个超声成像探头分别通过窗口成像。自相关和算法特别针对通过用于跟踪由推动引起的波引起的运动的脉冲而获得的成像，该推动是单次推动。该算法可以涉及在受到图像匹配标准 (S) 的情况下逐渐增加的搜索区域上的互相关。

