APPROACHES TOWARDS IMPROVED ULTRASONIC STRAIN RATE IMAGING

PACS REFERENCE: 43.35.Yb; 43.80.Vj

Jan D'hooge[1]; Bart Bijnens[2]

[1]Medical Image Computing, Depts. of Electrical Engineering, Cardiology and Physics, Katholieke Universiteit Leuven; Herestraat 49, B-3000 Leuven; BELGIUM; Tel:+32 16 34.75.68; Fax:+32 16 34.34.67; E-mail: jan.dhooge@uz.kuleuven.ac.be [2]Department of Cardiology, Katholieke Universiteit Leuven; Herestraat 49, B-3000 Leuven; BELGIUM; Tel:+32 16 34.75.69; Fax:+32 16 34.34.67; E-mail: bart.bijnens@uz.kuleuven.ac.be;

ABSTRACT: The non-invasive assessment of regional myocardial function is an important goal in clinical cardiology. To this extent, strain rate imaging has been introduced. Current strain rate methodology has been validated and has been shown to be clinically applicable. However, it is associated with some intrinsic limitations. This paper discusses some new approaches towards ultrasonic strain rate estimation based on a discussion of the current implementation of strain rate imaging.

INTRODUCTION

Regional strain and strain rate imaging have been introduced as new clinical tools to quantify regional myocardial function [1,2]. The most widely used method for cardiac strain rate estimation is based on myocardial velocity imaging, i.e. Doppler myocardial imaging [3,4]. This methodology has been validated both in vitro [5] and in vivo [6] and has been shown to be applicable both in the experimental and clinical settings [2,7-11]. Notwithstanding the fact that promising clinical results are obtained, the current methodology has intrinsic limitations. Therefore, ongoing research in ultrasonic strain rate imaging attempts to solve these limitations by looking for alternative approaches towards ultrasonic strain rate estimation. This paper discusses these approaches based on a discussion of the current implementation of strain rate imaging.

VELOCITY ESTIMATION AS A BASIS FOR STRAIN RATE ESTIMATION

As strain rate is nothing but the spatial gradient in velocities [2-4], strain rate estimation simply reduces to velocity estimation with subsequent application of a gradient operator. Ultrasound velocity estimators have been developed for many years and an excellent review was given by Jensen [12]. In general, the assumption is made that the reflected ultrasound signal is a scaled, delayed replica of the transmitted pulse. By transmitting several pulses along each image line at a constant pulse repetition frequency (PRF), the motion of the reflected signal (and thus the scattering object) can be estimated. This motion directly determines the velocity of the object as the time interval between two position estimates is known (and equal to 1/PRF). Two important

methods exist in order to estimate the motion of the reflected signals. Both are briefly discussed below.

Phase shift estimation methods (auto-correlation methods)

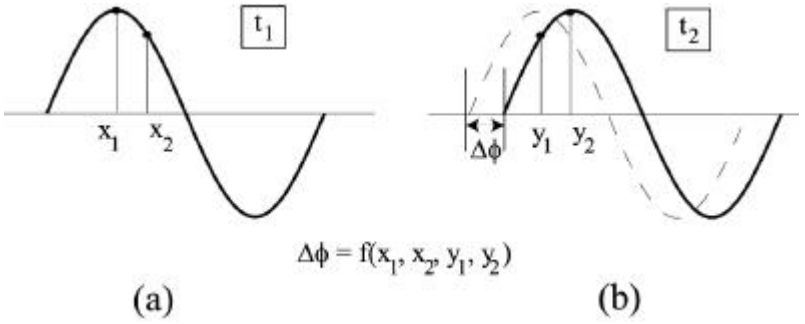

Figure 1: The phase of a signal is completely determined by two samples taken maximally a quarter wavelength apart (a). The phase shift between two signals can thus be estimated based on two samples taken from each of these signals (b).

Phase shift estimators make use of the fact that the phase of a sinusoidal signal is completely determined by two samples taken maximally a quarter wavelength apart (see figure 1(a)). Consequently, two such unique couples of samples are sufficient to completely determine the phase shift $\Delta\phi$ between two subsequent reflections (see figure 1(b)). This phase shift can then be used to calculate the velocity v of the reflecting object as [12]:

$$v = \Delta\phi \, c \, PRF / (4 \, \pi \, f_T)$$

with f_T the frequency of the transmitted ultrasound pulse and c the velocity of sound (which is typically 1530 m/s in soft tissue).

Calculating the phase shift $\Delta\phi$ for all sampled points along the reflected signals can be done in a very computative efficient manner by use of the auto-correlation function [12].

Time shift estimation methods (cross-correlation methods)

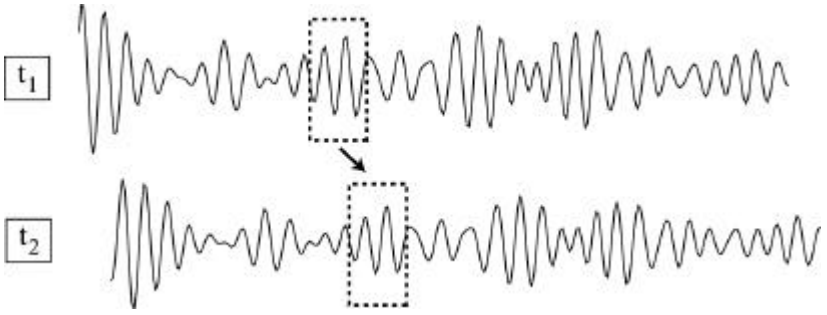

Figure 2: The motion between two signals can be determined by searching for an optimal match of a signal window. Typically, the cross-correlation function is used to find this match.

The phase shift $\Delta\phi$ in the equation above can also be estimated using a cross-correlation approach. Rather than using two samples of a given signal to determine the local phase and hence the phase shift between two signals, a window (of typically 16-32 samples) is used to estimate to motion of a signal pattern between subsequent acquisitions. This principle is illustrated in figure 2. Typically, the cross-correlation or sum-of-absolute differences (SAD) function is used for this purpose. In order to emphasize the difference with the previous method, this type of estimators are called time shift estimator. They offer several advantages over the phase shift (auto-correlation) methodology, i.e. motion between acquisitions of more than half a

wavelength does not result in artefacts such as aliasing [12]. However, this approach shows to be relatively computative intensive.

CHARACTERISTICS OF MOTION ESTIMATORS

Velocity estimation based on a shift in signal phase is one-dimensional

Motion perpendicular to the direction of wave propagation, i.e. the image line, will not result in a phase shift of the reflected signals. As a consequence, using this phase shift as a basis for velocity estimation only provides information on one component (the one along the image line) of the true three-dimensional motion of the scattering object. Since strain rate is calculated as the spatial gradient in velocities, this implies that only one component of the three-dimensional deformation can be assessed.

High acquisition rate

Both the auto- and cross-correlation methods make the assumption that the characteristics of the reflected signals do not change between two acquisitions. This assumption is only valid when the motion/deformation of the object is relatively small (i.e. when the motion/deformation of the object between the reflections of two subsequent acquisitions is small) and if there is only a limited amount of motion/deformation perpendicular to the image line. Thus, in order for these techniques to work, acquisition of data at high temporal resolution is required.

For this reason, strain rate estimation using either auto- or cross-correlation methodology was initially done at high PRF (1-5 kHz) by either sending pulse packages along each image line or by acquiring a single image line [1,2,13,14]. Recent developments showed both methodologies to work at lower PRF (around 300Hz) given the appropriate processing [15-18]. This approach enables conventional two-dimensional grayscale pulsing, given the sector angle of the image is limited.

Although reducing PRF is favorable in terms of field of view (the lower the PRF along an image line, the more lines can be constructed in the same time period), further reducing PRF seems to be unwanted as some of the mechanical events of the myocardium are very short lived. In order for these events to be resolved adequately, some studies indicate that the strain rate curve should be sampled at a rate of about 200-300Hz [1,19].

CURRENT IMPLEMENTATION OF ULTRASONIC STRAIN RATE IMAGING AND ITS LIMITATIONS

Commercially available ultrasonic scanners have typically implemented phase shift estimators as current computer technology does not allow to run time shift estimators in real time at appropriate frame rates. As a consequence, most of the clinical results presented in the literature, if not all, are based on phase shift estimator based strain rate imaging. Although time shift estimator based methods can be made to work succesfully, their application in clinical cardiology has so far been limited. In contrast, in non-cardiac applications such as intravascular imaging and mammography, where temporal resolution is less of an issue, time shift estimators have typically been the estimator of choice [20,21].

The major limitation of the existing approaches is that they are limited to making only a one-dimensional measurement. Indeed, as explained above, only the strain rate along the image line can be assessed. This limitation causes the technique to be angle dependent, i.e. the measured strain rate value depends on the exact position of the region under investigation

within the image [22]. This problem can be avoided by making sure the image line is either perpendicular or parallel to the principal motion of the muscle [3,4]. Unfortunately, this cannot always be achieved for every myocardial segment over the complete cardiac cycle. Moreover, the one-dimensional character of the current measurements implies that the ultrasound-based cardiac deformation data sets are incomplete. This could limit their application in quantifying cardiac function.

Finally, it can be shown that phase shift estimators show a trade-off between velocity and spatial resolution [12]. In other words, good velocity estimates can only be obtained at relatively low spatial resolution. Time shift estimators do not show this trade-off.

ALTERNATIVE APPROACHES TOWARDS MYOCARDIAL STRAIN RATE IMAGING

One-dimensional strain rate estimation

A straight forward improvement of the current one-dimensional strain rate imaging methodology would replace the phase shift estimator by a time shift estimator. Although these estimators can be made to operate in real time [13,23], only limited experimental results in cardiac imaging have been presented using this methodology. As time shift estimators operate accurately using broadband transmission pulses, the advantage of this approach is that it potentially improves spatial resolution without compromising the velocity resolution. This might allow the assessment of differences in strain rate characteristics across the cardiac wall [14].

Multi-dimensional strain rate estimation

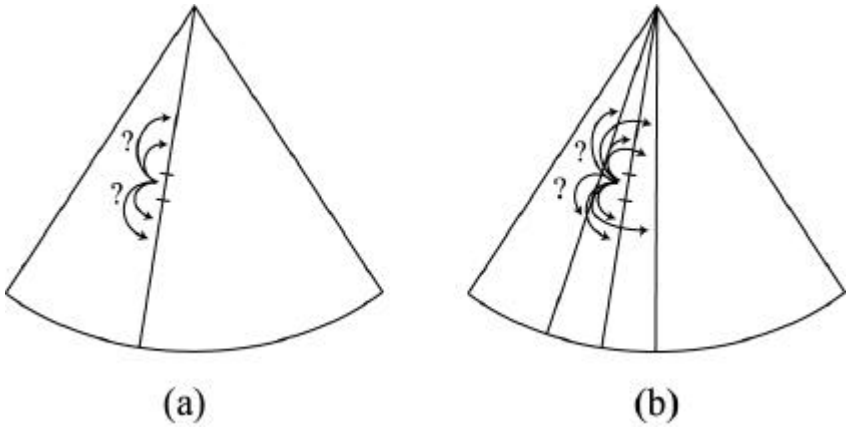

Figure 3: Tracking of a signal pattern along the image line provides an estimate of the velocity along the image line (a). Extending the search region to neighbouring lines enables to estimate the in-plane velocity vector (b).

Both the angle dependency and the incomplete assessment of three-dimensional deformation properties could be solved if strain rate could be estimated in multiple dimensions, i.e. not only along the image line but also perpendicular to the image line. Hereto, the time shift estimator, i.e. cross-correlation methodology, has been extended not only to define the motion of a specific signal window along the image line but also in neighbouring image lines [24]. This principle is illustrated in figure 3. A similar, but slightly different, approach has been used by looking for the optimal match of a two-dimensional window in the subsequent image [25]. As these methods allow to measure both in-plane components of the velocity vector, all in-plane strain rate components can be obtained (both normal and shear strain rates). Recently, this approach has been shown to be feasible for two-dimensional strain rate imaging of the human heart in vivo [17]. This is illustrated in figure 4.

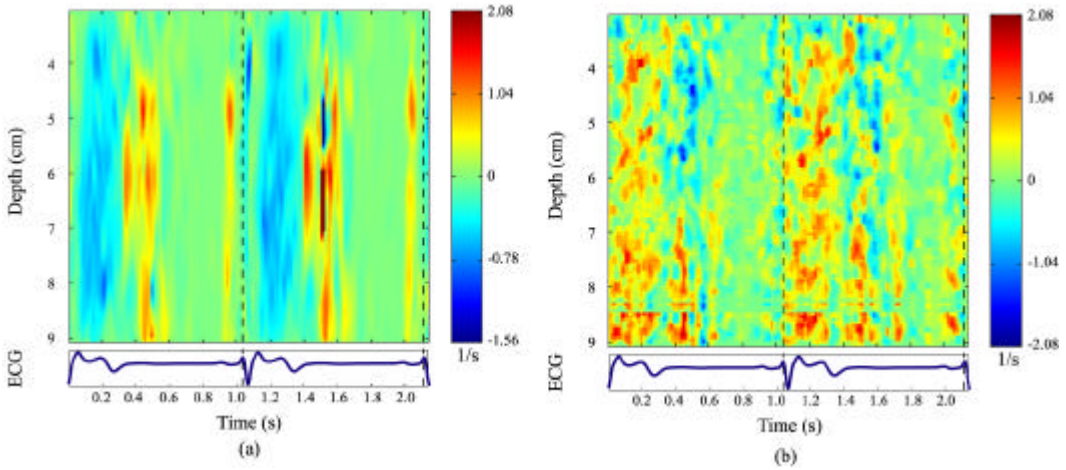

Figure 4: Axial (a) and lateral (b) strain rate estimates of the septal wall in a young volunteer.

The same "tracking" principle can be used if three-dimensional data sets could be acquired at sufficient frame rate in order to obtain all components of the three-dimensional strain rate tensor. As three-dimensional echocardiography becomes feasible with the use of fastly rotating phased arrays or by using full 2D array transducers, three-dimensional ultrasonic strain rate imaging should become possible in the relatively near future.

DISCUSSION AND CONCLUSION

Ultrasound strain rate imaging is a new imaging modality that can be used to quantify local myocardial deformation at high temporal resolution. The method offers new possibilities to study regional myocardial function which should give new insights into changes in local deformation over a wide range of cardiac pathologies and which could also provide a new quantitative tool to monitor the benefits of therapy. Current methodology towards strain rate imaging is merely phase shift estimation based. This results in the technique having a relatively low spatial resolution. Moreover, it intrinsically implies the measurements to be angle dependent and not to represent the true three-dimensional deformation characteristics of the heart. Both limitations can be overcome using the cross-correlation methodology. This estimator is thus likely to become more popular in future cardiac strain rate imaging.

ACKNOWLEDGMENTS

This work was supported by the Fund for Scientific Research - Flanders (FWO).

REFERENCES

[1] Noninvasive evaluation of local myocardial thickening and its color-coded imaging Kanai H, Hasegawa H, Chubachi N et al. *IEEE Transactions on Ultrasonics, Ferro-electrics and Frequency Control*, **44**(4):752-768,1997

[2] Real-time strain rate imaging of the left ventricle by ultrasound Heimdal A, Stoylen A, Torp H et al. *Journal of the American Society of Echocardiography*, **11**(11):1013-1019,1998

[3] Regional strain and strain rate measurements by cardiac ultrasound: principles, implementation and limitations D'hooge J, Heimdal A, Jamal F et al. *European Journal of Echocardiography*, **1**(3):154--170,2000

[4] Strain rate imaging by Doppler ultrasound Heimdal A, D'hooge J *Proceedings Forum Acusticum*,2002

[5] Real-time strain rate imaging: validation of peak compression and expansion rates by a tissue-mimicking phantom Belohlavek M, Bartleson VB and Zobitz ME *Echocardiography* **18**(7):565-71,2001
[6] Myocardial strain by Doppler echocardiography. Validation of a new method to quantify regional myocardial function Urheim S, Edvardsen T, Torp H et al. *Circulation*, **102**:1158--1164,2000
[7] Quantitative systolic and diastolic transmyocardial velocity gradients assessed by M-mode colour Doppler tissue imaging as reliable indicators of regional left ventricular function after acute myocardial infarction Garot J, Derumeaux G.A, Monin J.L et al. *European Heart Journal*, **20**:593--603,1999
[8] Differentiation between restrictive cardiomyopathy and constrictive pericarditis by early diastolic doppler myocardial velocity gradient at the posterior wall Palka P, Lange A, Donnelly J.E et al. *Circulation*, **102**:655--662,2000
[9] Regional myocardial systolic function during acute myocardial ischemia assessed by strain Doppler echocardiography Edvardsen T, Skulstad H, Aakhus S et al. *Journal of the American College of Cardiology*, **37**(3):726--730,2001
[10] Non-Invasive Quantitation of the Contractile Reserve of Stunned Myocardium by Ultrasonic Strain Rate and Strain Jamal F, Strotmann J, Weidemann F et al. *Circulation*, **104**:1059-1065,2001
[11] Time to Onset of Regional Relaxation: Feasibility, Variability and Utility of a Novel Index of Regional Myocardial Function by Strain Rate Imaging Abraham T.P, Belohlavek M, Thomson H.L et al. *Journal of the American College of Cardiology*, **39**(9):1531-1537,2002
[12] Estimation of blood velocities using ultrasound Jensen, J.A Cambridge University Press, Cambridge,1996
[13] Real-time measurements of local myocardium motion and arterial wall thickening Kanai H, Koiwa Y, Zhang J *IEEE Transactions on Ultrasonics, Ferro-electrics and Frequency Control*, **46**(5):1229--1241,1999
[14] Evaluation of transmural myocardial deformation and reflectivity characteristics D'hooge J, Schlegel J, Claus P et al. *Proceedings IEEE International Ultrasonics Symposium*, Atlanta, p. 1185-1188,2001
[15] High frame rate tissue Doppler imaging Bjaerum S, Torp H, Kristoffersen K *Proceedings of the IEEE International Ultrasonics Symposium*, p.1417-1421,2001
[16] High frame rate strain rate imaging of the interventricular septum in healthy subjects Slordahl S.A, Bjaerum S, Amundsen B.H et al. *European Journal of Ultrasound* **14**(2-3):149--155,2001
[17] Two-dimensional ultrasonic strain rate measurement of the human heart in vivo D'hooge J, Konofagou E, Jamal F et al. *IEEE Transactions on Ultrasonics, Ferro-electrics and Frequency Controle*, **49**(2):p.281-286,2002
[18] Myocardial elastography -- A feasibility study Konofagou E, D'hooge J, Ophir J *Ultrasound in Medicine and Biology*,2002 (In Press)
[19] Calculation of strain values from strain rate curves: how should this be done ? D'hooge J, Jamal F, Bijnens B et al. *Proceedings of the IEEE International Ultrasonics Symposium*, p.1269--1272,2000
[20] Elastography: a method for imaging the elasticity in biological tissues Ophir J, Cespedes I, Ponnekanti H et al. *Ultrasonic Imaging*, **13**:111--134,1991
[21] Intravascular ultrasound elastography in human arteries: initial experience in vitro de Korte CL, van der Steen AF, Cespedes EI et al. *Ultrasound in Medicine and Biology*, **24**(3):401-408,1998
[22] Potential pitfalls of strain rate imaging: angle dependency Castro P.L, Greenberg N.L, Drinko J et al. *Biomedical sciences instrumentation*, **36**:197--202,2000
[23] A system for realtime elastography Pesavento A, Lorenz A, Siebers S et al. *IEEE Transactions on Ultrasonics, Ferro-electrics and Frequency Controle*, **35**(11):941-942,1999
[24] A new method for estimation and imaging of lateral strains and Poisson's ratios in tissues Konofagou E.E, Ophir J *Ultrasound in Medicine & Biology*, **24**:1183--1199,1998
[25] Strain rate imaging using two-dimensional speckle tracking Kaluzynksi K, Chen X, Emelianov S.Y et al. *IEEE Transactions on Ultrasonics, Ferro-electrics and Frequency Controle*, **48**(4):1111-1123,2001