# STRAIN RATE IMAGING BY DOPPLER ULTRASOUND

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ABSTRACT: In cardiology, there is a need for non-invasive assessment of regional myocardial function. Strain is a measure of relative deformation, and is currently being investigated for this purpose, together with its temporal derivative, the strain rate. The strain rate in the beam direction can be estimated from Doppler ultrasound velocity data as the spatial derivative. Finally, the strain can be estimated as the temporal integral of the strain rate data. This paper presents definitions of strain and strain rate, and illustrates how these values may be estimated by Doppler ultrasound. In addition, the current status and limitations of the technique are discussed, together with examples of potential clinical applications.

## INTRODUCTION

Strain is a measure that can be applied to describe the relative deformation of objects, and was proposed for use in cardiology by Mirsky and Parmley [1]. Strain, and the temporal derivative strain rate, has been proposed for assessment of regional myocardial function. Currently, regional cardiac strain and strain rate can be acquired by magnetic resonance imaging [2], computed tomography [3] and gated single-photon emission computed tomography/positron emission tomography (SPECT/PET) [4]. Analysis of M-mode ultrasound data can also provide this information, and at a higher temporal resolution than the previous techniques. Strain by M-mode can however only be acquired for a limited number of regions of the myocardium. Methods to estimate strain and strain rate directly from the received ultrasound signal, using the cross-correlation technique, have also been presented [5-6]. These methods are however computationally intensive and are not yet implemented in commercially available equipment.

Color tissue Doppler imaging is a recent ultrasound technique that provides quantitative information on the velocity of the tissue [7]. Velocity samples from the whole field of view are available simultaneously. This allows for extraction of other parameters through spatial and temporal processing of the velocity data. Strain rate and strain are examples of such parameters. This paper gives an introduction to the physical concepts of these parameters and the signal processing methods involved in estimating them.

## DEFINITION OF STRAIN

*Strain* is a measure of the relative change in size or shape. For a one-dimensional object, the only deformation that is possible is a change in length, as illustrated in Figure 1(a). If the object

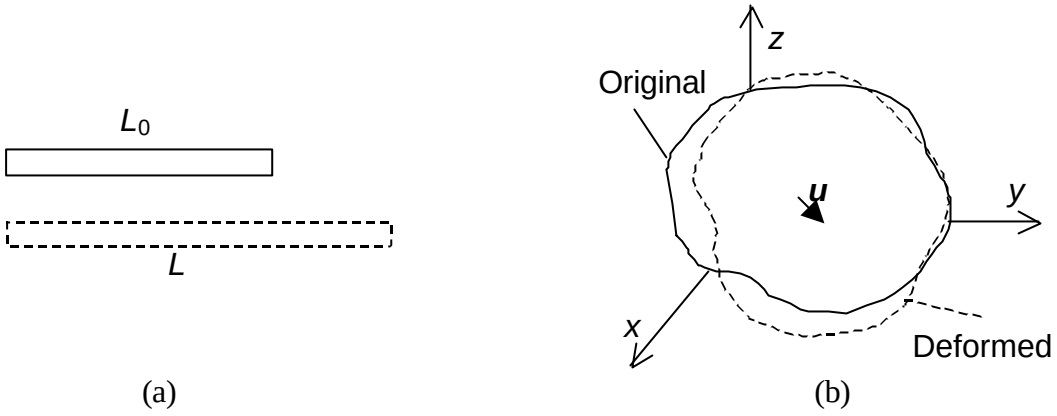


**Figure 1.** Illustration of (a) one-dimensional and (b) three-dimentional deformation. Each point in the object moves according to the displacement vector ***u***.

has an original length of $L_0$ and lengthens or shortens to a new length $L$, the *Lagrangian strain å* (epsilon) is defined as

$$\boldsymbol{e} = \frac{L - L_0}{L_0}. \tag{1}$$

Notice that this is a dimensionless measure. The strain might also be expressed in percent, by multiplying the above equation with 100. Lengthening is represented by positive strain, while shortening is represented by negative strain. For example, a doubling of the length of an object corresponds to a strain of 1 (100%), while a shortening to half the original length corresponds to a strain of -0.5 (-50%).

The strain definition in equation (1) depends only on the initial and final states. There is an infinite variety of ways to get from the initial to the final state. To model the strain history, one can write the Lagrangian strain as a function of time as

$$\boldsymbol{e}(t) = \frac{L(t) - L(t_0)}{L(t_0)}, \tag{2}$$

where $L(t)$ is the instantaneous length at time $t$, and $L(t_0) = L_0$ is the initial length. Another way to model the strain history is to use the *strain increment*, defined as

$$d\boldsymbol{e}_N(t) = \frac{L(t + dt) - L(t)}{L(t)}, \tag{3}$$

where *dt* is an infinitesimal time increment. By integrating these strain increments from the initial time $t_0$, the *natural strain* $\boldsymbol{å}_N$ is found as

$$\boldsymbol{e}_N(t) = \int_{t_0}^{t} d\boldsymbol{e}_N(t) = \ln\left(\frac{L(t)}{L(t_0)}\right). \tag{4}$$

By comparing equations (2) and (4), one can see that the Lagrangian and natural strains have a fixed nonlinear relationship given by:

$$\boldsymbol{e}_N(t) = \ln(\boldsymbol{e}(t) + 1) \quad \text{or} \quad \boldsymbol{e}(t) = \exp(\boldsymbol{e}_N(t)) - 1. \tag{5}$$

Strain can also be defined for a three-dimensional object. In this case, each point within the object can move in any spatial direction as illustrated in Figure 1(b). The Green or Lagrangian strain can then be defined using the displacement vector $\boldsymbol{u} = (u_x, u_y, u_z)$ defined for each point in the original object as

$$\boldsymbol{e}_{ij} = \frac{1}{2}\left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_k}{\partial x_i}\frac{\partial u_k}{\partial x_j} \right), \tag{6}$$

where the indices $i$, $j$ and $k$ can range over the values {x, y, z} representing the three-dimensional space, and $(x_x, x_y, x_z)$ are the coordinates $(x, y, z)$.

For infinitesimal strains, the last term in equation (6) can be ignored. Expanding the equation for each coordinate then gives

$$\begin{aligned} \boldsymbol{e}_{xx} &= \frac{\partial u_x}{\partial x} \quad \boldsymbol{e}_{xy} = \frac{1}{2}\left( \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) = \boldsymbol{e}_{yx} \\ \boldsymbol{e}_{yy} &= \frac{\partial u_y}{\partial y} \quad \boldsymbol{e}_{yz} = \frac{1}{2}\left( \frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} \right) = \boldsymbol{e}_{zy} \\ \boldsymbol{e}_{zz} &= \frac{\partial u_z}{\partial z} \quad \boldsymbol{e}_{zx} = \frac{1}{2}\left( \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right) = \boldsymbol{e}_{xz} \end{aligned} \tag{7}$$

where the strains in the left column are termed normal strains and the strains in the right column are termed *shear strains*[*] since they involve spatial deformations that vary along another spatial direction.

## DEFINITION OF STRAIN RATE

*Strain rate* is the speed of deformation, and is defined as the temporal derivative of strain. It is denoted $\dot{\boldsymbol{e}}$ (epsilon dot):

$$\dot{\boldsymbol{e}} = \frac{d\boldsymbol{e}}{dt}. \tag{8}$$

The unit of strain rate is $s^{-1}$ or equivalently $1/s$[†]. Consider, for example, an object that is deformed to a strain of 1 (100%) and that the deformation requires 10 seconds. The average strain rate is then 1 divided by 10 seconds, resulting in 0.1 $s^{-1}$, indicating that, on average, the object lengthens 10% every second. Notice that a positive strain rate means that the object is becoming longer, while a negative strain rate means that it is becoming shorter.

Since the strain can be defined in various ways, as described earlier, the strain rate has a corresponding range of definitions. In particular, by taking the temporal derivative on each side of equation (4), the *natural strain rate* can be expressed as

$$\dot{\boldsymbol{e}}_N(t) = \frac{L(t_0)}{L(t)} \cdot \frac{L'(t)}{L(t_0)} = \frac{L'(t)}{L(t)}, \tag{9}$$

where $L'(t)$ is the temporal derivative of the instantaneous length $L(t)$. This is the strain rate that will be discussed in the rest of this paper. Notice that the strain rate is independent of the initial length $L(t_0)$.

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[*] The value inside the parentheses is termed *engineering shear strain*.

[†] Note that the unit Hz is not used, since the deformation does not necessarily have a cyclic nature.

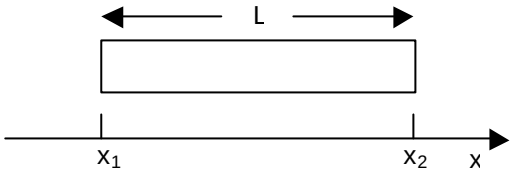


**Figure 2.** Illustration of a tissue segment at a specific time instant.

## ESTIMATION OF STRAIN RATE AND STRAIN

The motion of the tissue is available at a high temporal resolution using tissue Doppler imaging. It is the mean velocity component along each ultrasound beam that is measured. A non-deforming (stiff) region, moving in the beam direction, will have equal velocity in every point. If the velocities vary along the beam, it must mean that the region is being deformed.

### Relation between Strain Rate and Velocity

To see how the velocities are related to the strain rate, consider the small tissue segment in Figure 2. Assume that, at a given time instant, the velocities vary linearly over this segment as

$$v(x) = a_0 + ax \,. \tag{10}$$

Notice that the slope can be expressed as the spatial velocity gradient $a = dv/dx$. Furthermore, if $x_1$ and $x_2$ are the positions of the end points of the segment, the instantaneous length is $L = x_2 - x_1$. The instantaneous change in length is then

$$L' = \frac{dL}{dt} = \frac{dx_2}{dt} - \frac{dx_1}{dt} = v(x_2) - v(x_1) = a(x_2 - x_1) = aL \,. \tag{11}$$

Inserting this into equation (9) it can then be seen that the natural strain rate is in fact the spatial velocity gradient

$$\dot{e}_N = \frac{L'}{L} = a = \frac{dv}{dx} \,. \tag{12}$$

Notice that the strain rate may vary over time. Also note that it is independent of the translational velocity $a_0$.

### Estimation of Strain Rate

As shown in the previous section, to estimate the strain rate, it is sufficient to estimate the velocity gradient. The simplest estimate for the velocity gradient relies on only two velocity samples:

$$\dot{e}_N \approx \frac{v_2 - v_1}{\Delta x} \,. \tag{13}$$

Here $v_1$ and $v_2$ are velocity estimates from two sample volumes spaced a distance Ä$x$ from each other along the ultrasound beam. This estimate assumes that the velocity varies linearly within the region defined by Ä$x$. Notice that Ä$x$ does not need to be identical to the instantaneous segment length $L(t)$ used in the previous section.

Estimation of Strain

Strain rate is defined as the temporal derivative of strain. The strain is therefore the temporal integral of the strain rate:

$$\varepsilon_N(t) = \int_{t_0}^{t} \dot{\varepsilon}_N(t)dt \ . \tag{14}$$

Notice that strain depends on the definition of the start and end times of the integration, $t_0$ and $t$. Since it is the natural strain rate that is integrated, the result is the natural strain. The Lagrangian strain can be found using the conversion formula in equation (5).

## LIMITATIONS

Being estimated as the spatial derivative of the velocities, the strain rate is highly dependent on the quality of the velocity data. Small variations or errors in the velocity data will produce large errors in the strain rate estimates. This may be overcome by increasing the sample distance $\Delta x$ in equation (13) and by performing spatial averaging of the strain rate estimates. The cost is reduced spatial resolution.

As it is only the velocity component along the ultrasound beam that is available, only the strain rate in the beam direction can be calculated. Since the tissue can be considered incompressible, a deformation in one direction will always be compensated by opposite deformations in other directions. The result is that the strain rate estimates will be more angle dependent than velocity estimates. It is therefore important to attempt to align the ultrasound beam as close to the desired deformation direction as possible. Notice, however, that as long as the alignment is perfect, it is the exact strain rate that is measured, irrespective of the other strain rate components.

When integrating the strain rate samples to estimate the strain, ideally the strain rate samples should originate from the exact same location in the tissue. This may be difficult to achieve in practice when the tissue is moving, both within and outside the image plane. As a consequence, it may be necessary to use strain rate samples from slightly different parts of the tissue in the integration process. This may result in an error in the strain estimate. In addition, if the angle between the ultrasound beam and the tissue is changing during the same time, for example due to twisting of the tissue, it is not the exact same strain rate components that are being used. This will also add to the error. As a result, there may be a drifting of the strain curve. For a cyclic deformation, as in the heart muscle, the drifting can however be compensated for, since it is known *a priori* that the strain at the end of the cycle should be zero.

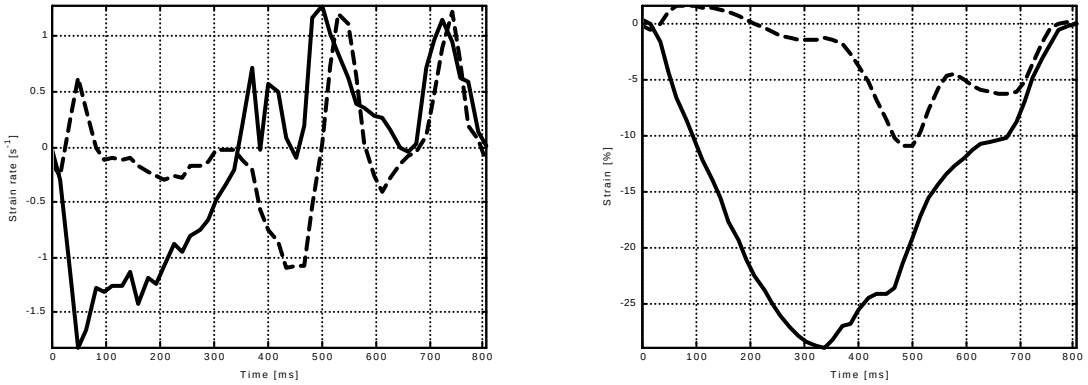


**Figure 3.** Estimated strain rate (left panel) and strain (right panel) in a region of interest in the interventricular septum of a healthy volunteer (solid line) and a patient with an acute apical infarction in the region (dashed line).

## CLINICAL EXAMPLES AND POTENTIAL APPLICATIONS

The solid lines in Figure 3 show the extracted strain rate and strain from a region of interest in the interventricular septum of a healthy volunteer during one cardiac cycle. An apical view was used when acquiring the data, so the ultrasound beam was in the longitudinal direction through the muscle. Therefore, it is the longitudinal strain rate and strain that is estimated. During systole, there is a negative strain rate and a decrease in strain, indicating that the muscle shortens in the longitudinal direction. In diastole there are several phases with positive strain rate and increasing strain, indicating a lengthening of the muscle.

The dashed lines in Figure 3 show the extracted strain rate and strain from a region of interest in the interventricular septum of a patient with acute ischemia. As seen, the systolic shortening is reduced, indicated both by a reduced negative systolic strain rate, and a reduced strain at end systole (approximately at 350 ms). Notice also the post-systolic shortening.

Current topics in clinical strain rate imaging research include assessment of regional myocardial function [8] and viability [9] using the peak systolic strain rate and strain. There has also been an interest and debate about the potential usefulness of the post-systolic shortening as a possible marker of viability [10]. Finally, strain rate imaging has also been used to assess diastolic function [11].

## CONCLUSIONS

The strain rate can be estimated from tissue Doppler velocity data as the spatial velocity gradient, and the strain can further be found as the temporal integral of the strain rate. These parameters are potentially useful tools in the quantification of regional myocardial function. However, the clinical relevance of the parameters is not yet well established.

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