Elastography

'*Elastography* ***is a non-invasive method, based on diagnostic*** *ultrasound* or **magnetic resonance**', showing the **elastic properties of biological tissues**. The method is similar to the palpation of tissues, when palpable stiffness in the tissues is usually a sign of some disease or health complication. Elastography is based on the fact that different biological tissues have different elasticity, and that changes in elastic properties are often related to pathology or tissue abnormalities. The essence of the method is the investigation of the response of the displayed tissues to force action.

> The history of ultrasound elastography dates back to approximately the early 1980s. The name of the method was first used in 1991 by Ophir and his collaborators. The measurement of the elastic properties of tissues using magnetic resonance (so-called Magnetic Resonance Elastography - MRE) was introduced for the first time in 1995 by Muthupillai et al.

The introduction of elastographic methods into clinical practice is based on the experience that many pathological tissues (e.g. tumor) show weak contrast during ultrasound or MR examination or cannot be visualized at all. Ultrasound or MR elastography based on mapping the elastic properties of tissues is therefore a very suitable method for imaging the structure and pathology of such tissues.

The measurement of elastic properties brings completely new information about tissues, which can be advantageously used for medical diagnostics. Elastographic methods are usually used in clinical practice as additional methods that '*help to increase the specificity of the diagnosis of many diseases*. The use of elastography is very common in the examination of the liver, thyroid gland and lymph nodes, in the screening of breast and prostate cancer, or in gynecological examinations. The measurement of elastic properties can also be advantageously used in the examination of the brain, tendons, mammary gland, pancreas, skin or other soft tissues. Changes in elasticity can also provide important clinical information in the assessment of cardiac dysfunction, renal failure or neurodegenerative diseases. An interesting application is the invasive examination of the elastic properties of blood vessels in the form of so-called ultrasound intravascular elastography. The measurement of tissue elasticity using magnetic resonance is mainly focused on the examination of the liver, brain and breast tissue.

Ultrasonic Elastography

Ultrasound waves are used to visualize the elastic properties of tissues, similar to diagnostic ultrasound. The output of ultrasound elastography is an ultrasound "B-image overlaid with a color map", where each tissue point (pixel) in the area of interest is assigned a certain color that encodes the elastic properties of the respective point of the displayed tissue. Soft tissues are usually coded with warm shades (red, yellow), hard tissues with cold colors (blue, violet). Ultrasonic elastography methods are divided into static (compression) or dynamic (shear waves).

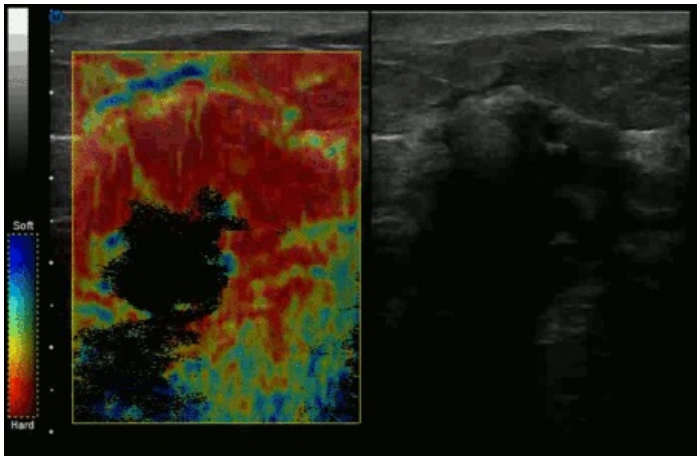
Static ultrasound elastography

In this method, the elastic properties of tissues are determined on the basis of '*the difference in the ultrasound signal before and after tissue compression*. Tissue compression is most often performed directly with a measuring ultrasound probe or with the help of a suitable external device, but the acoustic pressure of a focused ultrasound beam or physiological movements in the body (e.g. heartbeat, pulsation of blood vessels, breathing) can also be used. The degree of deformation of the tissue structures is determined from the captured pairs of tissue images before and after compression with appropriate correlation algorithms for each point (pixel) of the region of interest (ROI) of the image. Most often, tissue displacement is evaluated as the time difference of US signals (A-mode beams) reflected at different tissue depths (measurement windows) before and after compression. The time offset of the measurement windows before and after compression ΔT is usually related to the time distance of the measurement windows T before compression:

$$\Delta l \approx \frac{\Delta T}{T} \rightarrow \varepsilon$$

If we know the stress σ (applying force), then after substituting the previous equation into the Hooke's law equation, we can determine tissue elasticity quantitatively as a calculation of Young's modulus of elasticity in pascals.

Another option for evaluating tissue elasticity is based on the ``tissue doppler *method (Doppler Tissue Imaging - DTI). Through Doppler measurement, the speed of tissue movement is calculated during deformation − during compression, the tissue moves away from the ultrasound probe; during relaxation, the tissue moves towards the ultrasound probe. From the time sequence of DTI images of the velocity of tissue movement, the gradient (change) of the velocity is subsequently evaluated. Finally, the elasticity (Young's modulus) of the imaged tissues is estimated based on the velocity gradients. In order to achieve sufficient movement velocities in the tissue needed to calculate the elastic properties, the tissue must be compressed by up to several millimeters. With such a large compression, however, there is a risk of the investigated structure moving outside the imaged area, and the so-called halo effect (blurring of the boundaries of the object in the image) often occurs, which negatively affects the quality of the resulting image.*



Invasive ductal carcinoma, manual compression elastography

The method based on the ``radiation force of the ultrasound beam *(Acoustic Radiations Force Imaging - ARFI) uses high acoustic pressure of focused ultrasound to compress tissue structures focused in the focus zone of the scanned area. The radiation force has the direction of propagation of the ultrasound beams, the magnitude of the force increases with the intensity of the ultrasound waves and is greatest precisely in the focusing zone. A very intense US pulse is required to produce measurable tissue displacements (typically 1 to 20 µm). Measurement of tissue displacements is provided by imaging (reading) US pulses sent before and after the application of an intense pulse. Tissue displacements are evaluated as changes in US signals (A-mode beams) before and after tissue compression. In practice, one imaging pulse is usually sent to determine the position of the tissue before compression, an intense pulse to cause tissue compression, and one or more imaging pulses to determine the position of the tissue after compression and monitor the return of the tissue to its original position. While with other methods of tissue compression (e.g. with an ultrasound probe, an external device or physiological movements of organisms), the effective range of compression in the tissue decreases with the distance from the source of deformation force (range typically approx. 5 cm), the method based on the radiation power of the ultrasound beam overcomes this limitation . In the case of ARFI, tissue compression is guaranteed at virtually any depth to which the focus zone of the ultrasound is aimed. Due to the attenuation of part of the radiation force in the tissues, the magnitude of the force may not be precisely known. The result of the measurement is therefore not a quantitative description of elasticity, but only an estimate of Young's modulus based on the amount of tissue displacement. In addition, the high intensity of focused ultrasound also brings with it a higher biological risk of tissue damage and greater heating of the ultrasound probe.*

The general ``advantages *of static elastographic methods are* ``*simplicity*, ``wide availability *and* ``*low cost*. Elastic properties can be visualized with classic diagnostic ultrasounds, which are supplemented with suitable software with an algorithm for calculating elasticity. Only ARFI systems require specially designed ultrasonic probes to generate intense ultrasonic waves. It goes without saying that static methods display elasticity in real time.

The ``disadvantages *of static methods include the frequent* ``*not knowing the size of the deformation force*, which does not allow determining the elastic properties of the tissue (Young's modulus) quantitatively. Elasticity is then estimated based only on the amount of deformation. The elasticity estimate is then related to other limitations of the method. The **comparison and reproducibility** of multiple elastograms is problematic. Each elastogram is more or less original, taken individually for each patient under different conditions (e.g. tissue is compressed differently by each doctor, physiological movements in the body depend on the patient, etc.). The quality of the image and its analysis then strongly depend on the knowledge and experience of the doctor. A certain disadvantage is also the measurement and display of elasticity only in the direction of the ultrasound beam.

Dynamic Ultrasound Elastography

Dynamic elastography (or Shear Waves elastography, or Transient elastography} is a method based on shear waves. These waves arise as a response of the elastic resistance of the tissue to low-frequency mechanical vibrations (about 10-500 Hz) and spread throughout by the volume of tissue in the transverse direction (tissue particles vibrate perpendicular to the direction of ultrasound propagation), similar to waves on a water surface. The **source *of vibrations can be*** *physiological movements''* in the organism (e.g. heartbeat or pulsation vessels), more often *external vibrators* or intense pulses of acoustic pressure created by a focused *Ultrasound beam* (ARFI). The problem with the short range of deformation forces in the tissue can be solved in the case of ARFI, for example, by using more focusing zones of the US beam, which enable the creation of shear waves in multiple tissue depths.

Ultrasonic waves propagate through the medium in a longitudinal direction. The particles of the substance oscillate in the direction of wave propagation, while the particles of the environment are condensed and diluted in the direction of propagation. The propagation speed of longitudinal waves c_l is influenced by the elastic properties (bulk modulus of elasticity K) and the density of the environment ρ. Longitudinal waves can propagate through any material medium: gas, liquid and solid. In biological soft tissues, the propagation speed of longitudinal waves is about 1400 to 1600 m/s.

$$c_l = \sqrt{\frac{K}{\rho}}$$

Shear waves can only propagate through a medium that resists shear stress, i.e. only in a solid medium. Shear waves do not occur in gases or liquids. The speed of propagation of shear waves v_s in tissues is very low compared to the speed of propagation of longitudinal waves (approx. 1–10 m/s) and depends on shear elastic properties (G ≈ E/3) and to the density ρ of the medium:

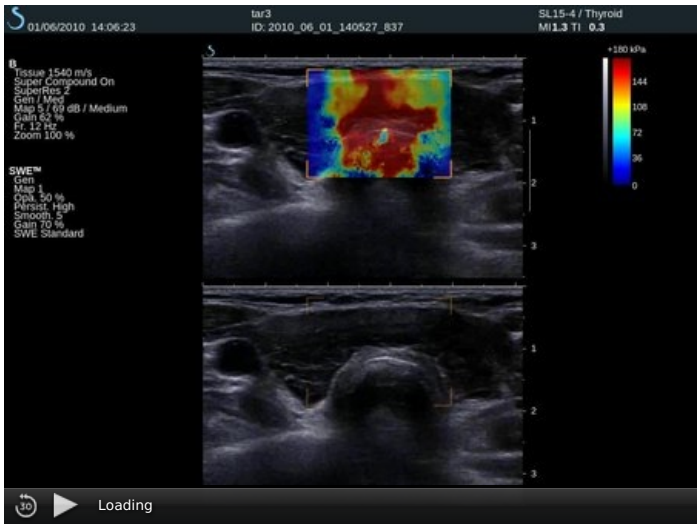
$$v_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{3\rho}}$$

Tissue elasticity (Young's modulus *E*) can be estimated from the previous equation based on the measured velocity of shear wave propagation (v_S) in the tissues. We usually set the density of biological tissues (ρ) as a constant. The average density of soft tissues (breast tissue, prostate, liver, kidney) is approximately 1047±5 kg/m^3.

The speed of wave propagation is determined by correlation algorithms as a result of the displacement rate of each tissue point (pixel) over time. Tissue displacement is determined similarly to static US elastography as changes in US signals (A-mode beams) before and after tissue compression. In order to determine the speed of propagation of shear waves through tissues, it is necessary to image the area of interest with a very high repetition rate, in the order of thousands of Hz (often 5,000 to 20,000 frames/s). At a shear wave speed of approx. 1–10 m/s, these waves leave the scanned area in a very short time (e.g. for a scanned area size of 10 cm, the waves leave the scene in 1/10 to 1/100 s). At the repetition rate of conventional US systems (50-60 Hz), shear waves from the scanned scene disappear already during the image acquisition and therefore cannot be detected. Vibrations that create shear waves in tissues can mask useful signals at the beginning of the measurement and must be filtered out of the signal before calculating the velocity of shear waves. The evaluation of the speed of shear waves and thus the elastic properties of tissues is carried out in real time.

The clear **advantage *of Shear Waves elastography is the direct*** *quantitative description of the elastic properties of the tissue''* (Young's modulus), since all the parameters necessary for the calculation are known - the propagation speed of the shear waves and the density of the tissue. Another advantage is the very precise localization and detection of even millimeter lesions. The method does not depend so much on the doctor's experience and is simple to operate, tissue compression is usually ensured by the device according to the set parameters. The possibility of reproduction, comparison and easier analysis of images is also a significant advantage, since each elastogram is taken in more or less the same way.

The main *disadvantage* of dynamic elastography is mainly the greater technological complexity and associated higher price. The technique requires ultra-fast imaging and special ultrasound probes. When compressing tissue by the acoustic pressure of US waves, it is necessary to choose sufficient wave intensity so that the generated shear waves have a longer range and less attenuation in the tissues. A higher intensity of US waves is associated with a higher risk of biological effects on tissues and structural problems (e.g. heating of the probe).



Shear Wave Elastography, to play click the arrow

Intravascular elastography

Intravascular elastography is used to display the elastic properties of blood vessels. The measurement principle is similar to static US elastography. The ultrasound sensor is introduced into the scanned vessel in the form of a catheter. Vascular pulsations created by rhythmic heart activity are used to compress the vessel or an intravascular balloon is introduced into the vessel, which expands the vessel wall by changing the volume. The method is suitable for the *detection of thrombi and atherosclerotic plaques* deposited on the vessel wall.

Magnetic resonance elastography

Magnetic resonance elastography (MRE) evaluates the elastic properties of tissues based on the speed of shear waves. Shear waves are generated in the tissue in response to low-frequency mechanical waves (about 50 to 500 Hz) that are generated into the examined area using acoustic, pneumatic or electromagnetic devices. Shear wave propagation is detected by special motion-sensitive phase-contrast methods. The phase of the atomic nuclei contained in the tissue is encoded by phase gradients that are applied in synchronization with the same frequency as the mechanical vibrations. The phase change of the nuclei is directly proportional to the displacement of the tissue caused by the propagation of the shear waves. Atomic nuclei with different phases produce different MR signals, and their motion can be easily evaluated by detecting them. The phase-contrast method is very sensitive and detects tissue movement by hundreds of nanometers. The phase image carries information about the propagation speed of shear waves in the tissue (v_S). Finally, an elastogram is created from the image of shear wave propagation using special mathematical algorithms, which describes tissue elasticity (Young's modulus) quantitatively.

$$E = 3\rho v_s^2 = 3\rho(f\lambda)^2$$

'*Generators* of mechanical waves can be acoustic and pneumatic devices or electromagnetic coils (eg during MRE of the brain). The active element of an acoustic (e.g. speaker) or pneumatic (e.g. pneumatic pump) device creates mechanical vibrations that are conducted through a connecting plastic tube to the passive element. The active element can also be placed outside the MR room, which eliminates the occurrence of noise and artifacts when taking MR images. The passive part of the device is placed on the examined area (e.g. on the abdominal wall for MRE of the liver) and transmits vibrations to the patient's body.

The duration of an MR elastographic examination is very short compared to a classic MRI examination. The acquisition of the image usually takes about 15 to 30 s, which is made possible on the one hand by fast phase-contrast sequences, on the other hand by the lower resolution (about 3 to 5x) of the elastogram compared to native MR images. During image acquisition, the patient must hold his breath so that the resulting image is not degraded by motion artifacts.

Magnetic resonance elastography does not require any complex software or hardware additions to standard MR devices and offers a significant diagnostic benefit, especially when examining the liver, kidneys, and brain. However, pathologies can also be evaluated with advantage in other organs: breast tissue, prostate, heart, blood vessels, spleen, pancreas, lungs, muscles, bones, cartilage, eye, spinal cord, etc. The relative simplicity of the method allows MRE to be included in the standard examination protocol. A significant **advantage** is the possibility of measuring tissue movement in any plane. The ``disadvantage *of the method is the high cost of the examination.*

Links

References

- SADDLER, Martin – STAFFA, Erik – MORNSTEIN, Vojtěch. *Imaging methods using non-ionizing radiation* [online]. Brno : Institute of Biophysics of the Faculty of Medicine of the Masaryk University in Brno, 2013, Available from <http://www.med.muni.cz/biofyz/zobrazovacimetody/files/zobrazovaci_metody.pdf>.