Learning objectives

Sonoelastography (SEL) is a recently developed imaging technique which is able to evaluate the mechanical properties of tissues. It is based on the principle for which, applying an extrinsic stress (mechanical or physical), it is possible to induce changes in a determined tissue, depending on the elastic properties of the tissue itself; hence, qualitative and/or quantitative measurements of the elastic changes induced through the tissue could be obtained, usually by mean of an ultrasound transducer in clinical practice. The recent diffusion of SEL into commercially available ultrasound systems has promoted the development of many studies regarding the potential clinical applications of this novel technique in different clinical fields and, in particular, in the musculoskeletal system.

The aim of our work is to provide a clear description of shear wave and strain sonoelastographic methods, to describe their applications focusing on muscle-tendon unit and to assess the potential benefits of the sonoelastographic evaluation in different conditions.

Background

To date, SEL has been demonstrated to be a useful method for the assessment of tissue elasticity in various clinical fields, such as breast, thyroid, liver and musculoskeletal imaging. Despite its variability and its availability on recent US machines, both strain and shear wave elastography has been widely used and seem to be a promising tool for radiologists in the next years.

ELASTICITY: BASICS PRINCIPLES

The elasticity of a material represents its tendency to resume its original size and shape after being subjected to a deforming force or stress. Fluids resist a change in volume, but not in shape: they have only 'volume elasticity'; solids instead resist changes in volume and shape: they present rigidity or 'shear elasticity', as well as volume elasticity; viscoelastic fluids also exhibit elasticity in certain conditions. Because the elasticity of a material is described in terms of a stress-strain relation, it is essential that the terms stress and strain be defined: the relative deformation in volume or shape, is produced by a
force per unit area (called 'stress'), and is referred to as the 'strain'. For a homogeneous isotropic solid, the ratio of stress/strain is a constant, called the 'modulus of elasticity'. A modulus (usually expressed in units of Pa) measures the amount of force per unit area (stress) needed to achieve a given amount of deformation. A higher modulus typically indicates that the material is harder to deform. Three moduli are commonly used to define elasticity:

- Young's modulus (E), represents longitudinal elasticity;

- Shear or torsion modulus (G) represents transverse elasticity;

- Bulk or volume modulus (K) represents volume elasticity.

Solids can support mechanical waves in four principal modes: in longitudinal (or compressional) waves, the particles move in the direction of propagation, whereas in transverse (or shear) waves, they move in the direction normal to the direction of propagation. The shear modulus describes the response to shear forces, Young's modulus describes the response to linear stress (tensile stress) and bulk modulus represents the response (in all directions) to uniform compression; it is usual for values of shear and Young's modulus to be reported in the studies regarding the investigation of elastic properties of tissues by mean of ultrasound. The other two principal wave modes are hardly relevant to propagation in biological soft tissues and so they are not given further consideration here.

MODALITIES

There are several elastographic techniques depending on the difference in the stress application and the method used to detect tissue displacement and build the image. Two main types of SEL have become established in clinical practice, in particular for soft-tissue evaluation:

*Strain elastography*

It is also described as 'quasi-static elastography', 'compression elastography' and 'real-time elastography'; the stress is applied by repeated manual compression of the transducer, and the amount of tissue deformation (strain) relative to the surrounding normal tissue is measured, usually with a tracking algorithm working on the radio-
frequency data. The resulting data can then be used to form an image that is coded in colour or grey-scale to show the pattern of strain, which is inversely related to tissue stiffness and can be assessed subjectively (Fig. 1 on page 7a). These are qualitative data, however regions of interest (ROIs) can be positioned over target areas in the screen in order to obtain semi-quantitative analysis (Fig. 1 on page 7b).

Fig. 1: Strain Elastography. A) qualitative analysis: the modulus of elasticity of the soft tissue scanned in the B-mode image is represented by a superimposed color-coded map in which (in this case) the lower values are depicted in red and the higher ones in blue; B) it is shown the possibility to perform a also semi-quantitative analysis of the strain elastogram with placement of two ROIs in order to take definite measurements of the Young’s modulus of elasticity of the targeted tissue.. The green-coloured spring-shaped figure shown in the left bottom of both the elastograms indicates that the pressure the operator performed with the transducer was appropriate to produce an adequate stress to get the elastogram.

References: Department of Radiology, OELGe, Genova, Italy 2014

Shear wave elastography

Shear wave imaging is a very potential technique for the non-invasive quantification of tissue stiffness. Shear waves in the body can be induced by various methods, including physiological motion, external mechanical excitation, or acoustic radiation force (by a focused ultrasound beam). Shear waves are transverse, they are rapidly attenuated by tissue, they travel much more slowly (between 1 and 10 m/s) and they are not supported by liquids of low viscosity. Using a real-time imaging modality such as ultrasound (but also magnetic resonance), the underlying tissue stiffness can be estimated measuring the produced shear waves speeds: Their speed is commonly expressed in meters per
second (m/s); it is closely related to the modulus of elasticity of the tissue and there is a simplified formula for converting, with some assumptions (based on the conventional tissues mechanical properties), between the shear wave speed and the elastic modulus of the tissue to locally quantify its stiffness in kilopascals (kPa). In contrast to strain elastography, this technique allows for the performance of quantitative analysis of the tissue stiffness. There are some variations of this method in clinical practice, depending on the difference in the modality of stress application:

- Transient Elastography (TE): is a system developed and commonly used for liver fibrosis assessment, in which a mechanical piston within a ultrasound transducer is used to apply a push to the skin over an intercostal space. The speed of the produced shear waves into the liver, along the direction of the ultrasound beam, is measured in a way similar to M-mode.

- Acoustic Radiation Force Imaging (ARFI): in this technique a ‘pushing’ focused ultrasound beam (with intensity below the threshold for bioeffects) is used to induce tiny displacements in soft tissue along its direction and generate orthogonal shear waves that propagate sideways in tissue. The shear waves speed or amplitude is detected by conventional ultrasound using tracking algorithms and is used to quantify the underlying tissue stiffness. Shear wave speed measurement could be made by a single small measurement box positioned by the operator within the tissue adjacent to the pushing beam (Fig. 2 on page 8), and/or could be extended to sequential multiple pushing and measurement points in order to construct a colour-coded map of the shear wave speed, which is also quantitative with positionable ROIs (Fig. 3 on page 9). Resuming, ARFI images represent the spatial distribution of tissue stiffness.

- Supersonic Shear Imaging (SSI): is a similar system which uses multiple acoustic radiation force impulses focused at different depths to create an extended cylindrical wavefront. These excitations are applied supersonically so that the shear waves generated from different depths constructively interfere adding each others and dedicated ultrasound transducers could detect and measure them.
Fig. 2: Shear Wave Imaging. In this figure one of the applications of the shear waves elastography is shown: shear wave speed quantification is obtained by a single small measurement box positioned by the operator within the tissue (fifth segment of the liver in this case) along the direction of the pushing beam. Data regarding liver segment, depth of the box placement and shear waves speed expressed in meters per second are represented right to the B-mode image.

References: Department of radiology, OEIGe, Genova, Italy 2014
Fig. 3: Shear wave Elastography. The figure shows a soft-tissue (a rectus femoris muscle in this case) shear wave elastography: after the generation of the ‘pushing’ beam by the transducer, the values of the shear modulus in the targeted area are represented by mean of a color-coded map set as represented by the coloured bar on the left of the screen. It is possible to get also a quantitative analysis of the investigated tissue by placing some ROIs (with modifiable dimensions) over the map and get the corresponding value at the left bottom angle of the screen. Note on the right elastographic map the stiffer areas in the center of the map corresponding to the central rectus femoris aponeurosis.

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Images for this section:
**Fig. 1:** Strain Elastography. A) qualitative analysis: the modulus of elasticity of the soft tissue scanned in the B-mode image is represented by a superimposed color-coded map in which (in this case) the lower values are depicted in red and the higher ones in blue; B) it is shown the possibility to perform a also semi-quantitative analysis of the strain elastogram with placement of two ROIs in order to take definite measurements of the Young’s modulus of elasticity of the targeted tissue. The green-coloured spring-shaped figure shown in the left bottom of both the elastograms indicates that the pressure the operator performed with the transducer was appropriate to produce an adequate stress to get the elastogram.
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![Shear Wave Imaging](image)

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![Shear wave Elastography](image)
Findings and procedure details

Twenty-four healthy volunteers and thirteen patients with clinical sign of lower limb tendinous and/or muscular pathology were consequently evaluated with conventional sonography and SEL in order to have useful representation of the elastic modulus of such structures in different conditions and get a useful depiction of SEL patterns. As it follows, a series of explanatory images regarding our preliminary results has been provided to illustrate SEL applications.

![Fig. 4](image)

**Fig. 4**: Strain Elastography of normal skeletal muscle. A) transverse scan B) longitudinal scan. Both images show a homogeneous elastographic map of the skeletal muscle with the green color representing the muscular fibres which present an intermediate elastic module relative to the surrounding tissue; blue and red coloured spots may represent both artifacts and connective and/or fat tissue between the fibres; note the fat subcutaneous tissue on the top of the elastogram in B which present homogeneous softer appearance in comparison to the muscular tissue below.

**References**: Department of radiology, OE1Ge, Genova, Italy 2014
Fig. 5: Shear wave elastography of normal skeletal muscle. A) longitudinal/oblique scan at the level of the gastrocnemius medialis-soleus aponeurosis; B) transverse scan of the rectus femoris muscle. Note in B the stiffer areas in the center of the map corresponding to the central rectus femoris aponeurosis. In our study the resulted mean values of elasticity of normal skeletal muscle examined at rest ranged 22±14 kPa±SD on longitudinal scans and 18±13 kPa±SD on transverse scans.

References: Department of radiology, OEIGe, Genova, Italy 2014

Fig. 6: Elastography of the normal tendon. A) Strain elastography of the proximal tendon of the rectus femoris muscle showing an homogeneous blue pattern which reflects the stiffer tissue composition in relation to the surrounding muscles (red and
green). B) Shear wave elastography of the flexor longus tendon of the first finger depicts tendinous structure with 'stiffer colors': quantitative analysis performed by the placement of three ROIs provided a mean value of elasticity of 87 kPa. In our study the resulted mean values of elasticity of normal tendons (examined at rest and along their long axis) ranged 103±75 kPa±SD.

**References:** Department of radiology, OEIGe, Genova, Italy 2014

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**Fig. 7:** Shear wave elastography of the calcaneal tendon. The image shows two ROIs placed over two different homogeneous tissue: ROI 1 over an area corresponding to Kager’s fat tissue, ROI 2 over an area corresponding to part of the Achille’s tendon fibres. Both the elastographic map and the quantitative values well reflect the difference in elastic shear modulus between these two tissue, with good spatial resolution.

**References:** Department of radiology, OEIGe, Genova, Italy 2014
**Fig. 8**: Muscle tear. The image on the left is a B-mode transverse scan over the dorsal aspect of the calf showing a deep tear of the soleus fibres. The image on the right is the corresponding strain elastographic analysis performed on the lesioned area: there is a clear depiction of the injured area which is represented as softer tissue (red coloured) in relation to the surrounding normal one.

**References**: Department of radiology, OEIGe, Genova, Italy 2014

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**Fig. 9**: Scar tissue - strain elastography. A) This figure illustrates the identification of an area of scar tissue in the deep hamstrings by mean of the B-mode evaluation; B) the strain elastographic analysis conducted over the same area shows the relative higher stiffness of the whole area (which could suggest a limitation in the biomechanical properties of the muscle fibres at that site).
Fig. 10: Scar tissue - shear wave elastography. Shear wave elastography conducted on a transverse scan of the rectus femoris muscle. The B-mode image on the left shows a hyperechoic area around the central aponeurosis; the image on the right shows the elastographic map superimposed over the injured area which well shows the stiffer structure of the scar tissue, also confirmed by the quantitative analysis performed by the placement of the ROI.

References: Department of radiology, OEIGe, Genova, Italy 2014

TECHNICAL CONSIDERATIONS

Sonoelastography has been improved a lot for recent years together with its use in the clinical practice, scientific research and ultrasound machines developments. Despite these significant implementations, some technical considerations have to be made in order to fully understand the actual potential of this technique and to make the sonoelastographic examinations as accurate as possible.

In strain elastography data acquisition and interpretation of elasticity images are largely dependent on the operators’ experience and skills. SEL softwares derive elastograms which usually depend on the changing probe pressure experienced during freehand
scanning and on the individual capability of images interpretation: consequently possible significant intra- and inter-observer variability has to be taken in consideration. Further, this technique provides only qualitative and/or semi-quantitative analysis with elasticity data resulting from the relative stiffness of the targeted region and the remaining tissue area. Hence, this technical feature may significantly influence the clinical use of strain elastography in terms of reproducibility and accuracy.

In contrast, the quantitative nature of shearin wave elastography is an advantage and seems to let this technique to be more reproducible; the fact that the system displaces the tissue could improve consistency since the examiner does not need to move the transducer. The localised nature of the applied force should also improve the relationship between displacement and elasticity compared with applying the force at the surface, as well as improve contrast and spatial resolution. Despite the overall promising features of shear wave sonoelastography, in particular if compared with those of the strain elastography, some limitations have to be mentioned. Shear wave speed measurements using radiation force produced by a focused ultrasound beam can be dependent on transducer geometry, focusing depth, lateral tracking range and frequency of the shear wave used for imaging. Further, the shear wave speed in tissue is dependent on the shear modulus and its density, usually calculated by making some conventional assumptions which not always reflect the actual characteristics of the investigated tissue.

In normal skeletal muscle, fibres are arranged in parallel fasciculi with different orientation and stiffness results from active tension produced by muscle contraction and passive tension produced largely by connective tissue. Due to this geometric structure, it does not conform to the isotropic mechanical behavior usually assumed for tissue and its mechanical properties make shear wave sonoelastographic 2D-imaging a harder challenge in skeletal muscle. As the shear wave speed in muscle is anisotropic, it depends on the direction of propagation with respect to the fiber orientation but the muscle fiber orientation is not usually precisely known, so the usual assumption of isotropy used in shear wave speed based shear modulus reconstruction techniques does not always apply properly. In an ultrasound study where the transducer is not aligned with the muscle fibers, it may be more accurate to report only shear wave speed, rather than converting to shear modulus. As skeletal muscle may be considered transversely isotropic the best way to minimize the effect of anisotropy on measurements in muscle is by orienting the transducer imaging plane with respect to the fiber or in a plane of symmetry of the muscle: the drawback is that the actual fiber orientation relative to the imaging plane is estimated by manual inspection of the operator in B-mode. This approach suggests that measurements can be made relatively independent of the push angle but it is very important to remember that less accurate shear wave speed measurements can occur for oblique tilt angles of the transducer in respect to fibres orientation.
Resuming, SEL offers clinicians an advanced level of diagnostic information for the evaluation of tissue stiffness, but measurement bias have to be considered in terms of clinical relevance and therefore require careful monitoring and/or correction.

**Images for this section:**

**Fig. 4:** Strain Elastography of normal skeletal muscle. A) transverse scan B) longitudinal scan. Both images show a homogeneous elastographic map of the skeletal muscle with the green color representing the muscular fibres which present an intermediate elastic module relative to the surrounding tissue; blue and red coloured spots may represent both artifacts and connective and/or fat tissue between the fibres; note the fat subcutaneous tissue on the top of the elastogram in B which present homogeneous softer appearance in comparison to the muscular tissue below.
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![Image of shear wave elastography of the calcaneal tendon](image)

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![Image of muscle tear](image)
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Conclusion

Sonoelastography is a very promising tool in the evaluation of tendons and muscles, it can be used to depict stiffness changes in various soft-tissue structures such as muscles, tendons and ligaments. Strain elastography provide quick, easier and qualitative or semi-quantitative measurements of such structures, shear waves elastography adds a more precise quantitative characterization with a much more difficult learning curve and a longer examination time. As reported before, both these techniques are characterized by some technical limitation but we can argue that SEL represents a very helpful tool in clinical practice, in addition to B-mode sonography and color-power Doppler techniques, allowing for a careful depiction of tendon and muscle stiffness both in pathologic and normal conditions. Future studies will help to better investigate the inner features of this potential technique with the aim to improve the diagnostic confidence of musculoskeletal imaging.

Personal information

Angelo Corazza, MD
angelcoraz@libero.it

References


