

Elastography Basic Concepts and Different Elastographic Techniques

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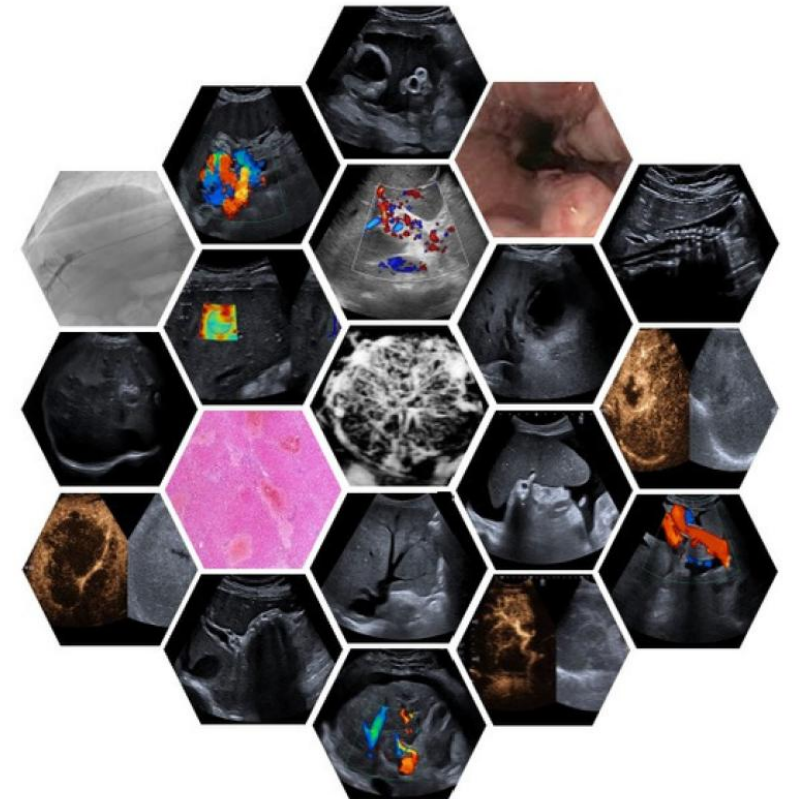
Co-Chair of Attenuation Working Group
PEQUS Biomarker Committee
Quantitative Medical Imaging Consortium (QMIC)



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Disclosures

Canon Medical Systems: speaker; research grant/support

Fujifilm: speaker; research grant/support

Mindray Medical: speaker

Philips Medical Systems: speaker; advisory board member

Loan of ultrasound systems for research purpose:

- Arietta 850, Fujifilm, Japan
- Aplio 800 iSeries, Canon Medical Systems, Japan
- EPIQ Elite, Philips Medical Systems, Bothell, USA
- MyLab 9, Esaote SpA, Italy

Elsevier Publishing: Royalties

Elastography

- Elastography shows the biomechanical properties of tissue whereas B-mode ultrasound shows their acoustic properties.
- These properties are not related to each other.



Virtual Palpation

Under a stress, stiffer tissues shows less longitudinal displacement and higher speed of transverse displacement.

Elastography Techniques

Assessment of:

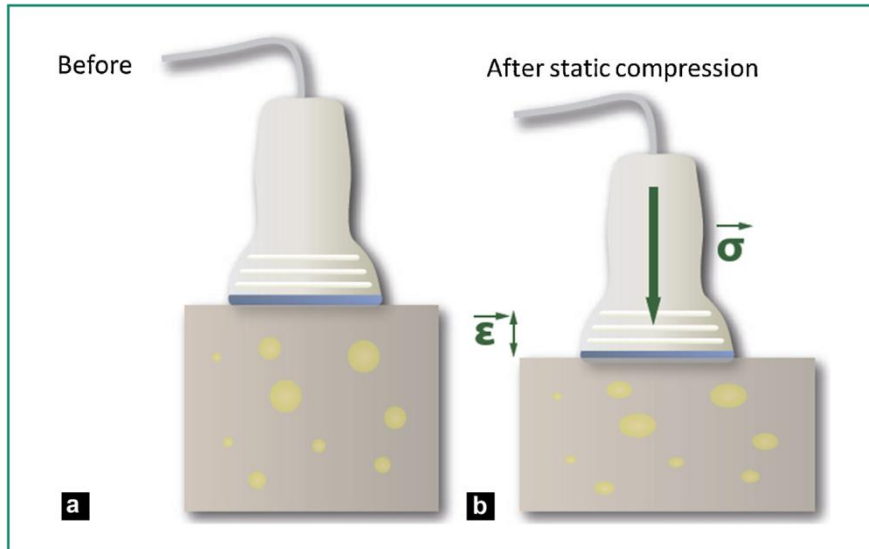
- Longitudinal displacement (strain elastography)
- Speed of the transverse displacement (shear wave elastography)

Longitudinal Displacement

- Strain Elastography
- Acoustic Radiation Force Impulse (ARFI) Imaging

Strain Elastography

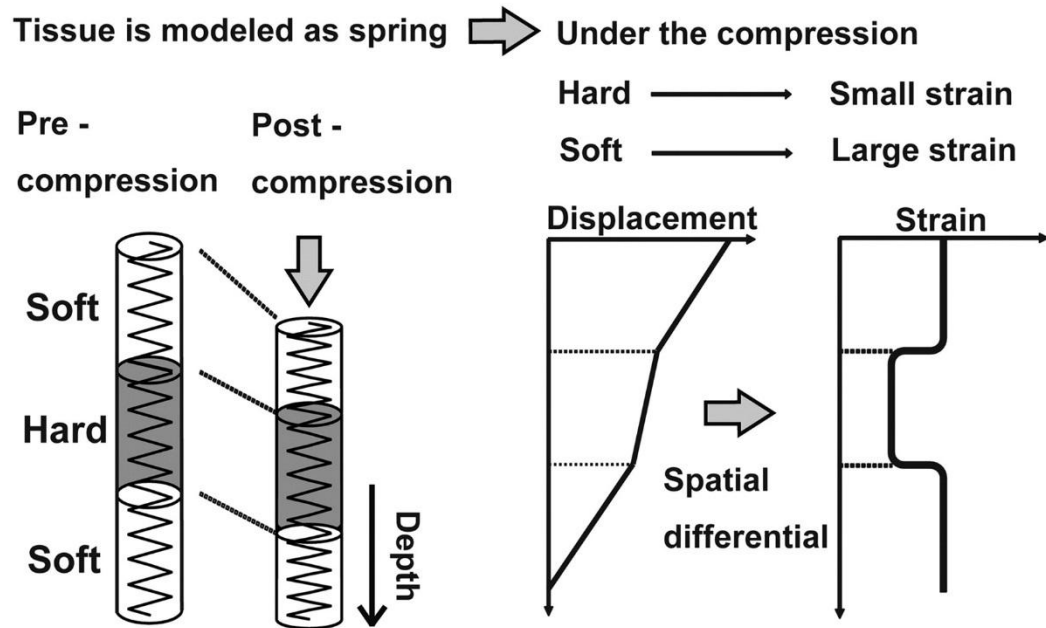
Quasi-static stress



(Gennisson JL et al. Diagn Interv Imaging 2013)

A force is applied by pushing the body axially or by naturally occurring internal physiological motion.

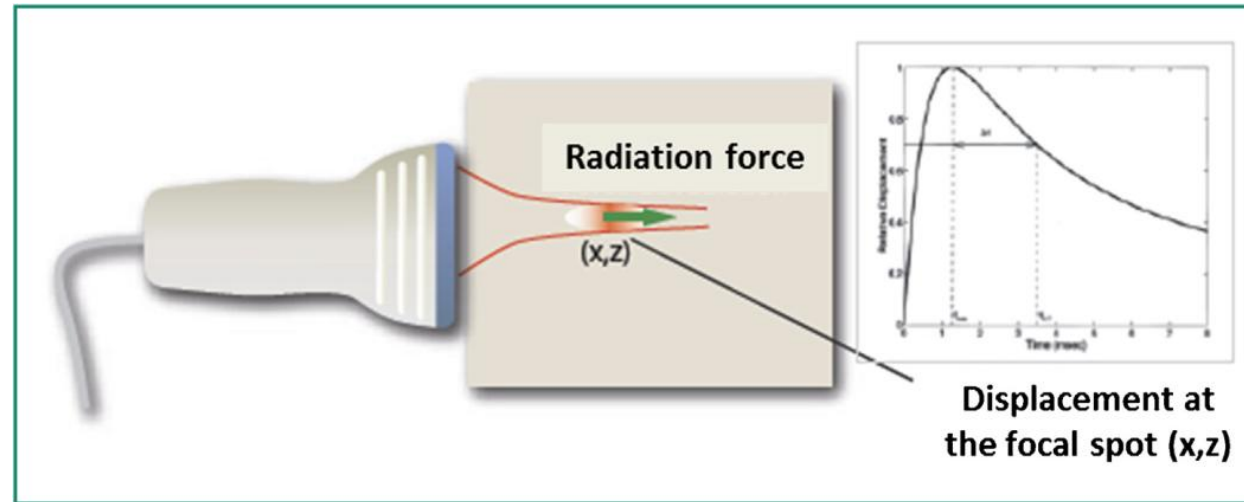
Strain Elastography



The internal tissue displacement is converted to a strain image (percentage of deformation) because the percentage of deformation is constant while the displacement decreases with depth.

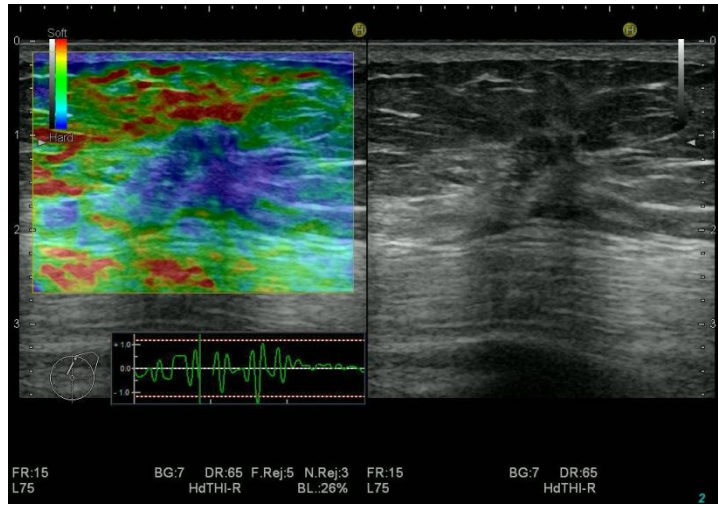
Koizumi Y et al. Radiology 2011

Acoustic Radiation Force Impulse (ARFI) Imaging

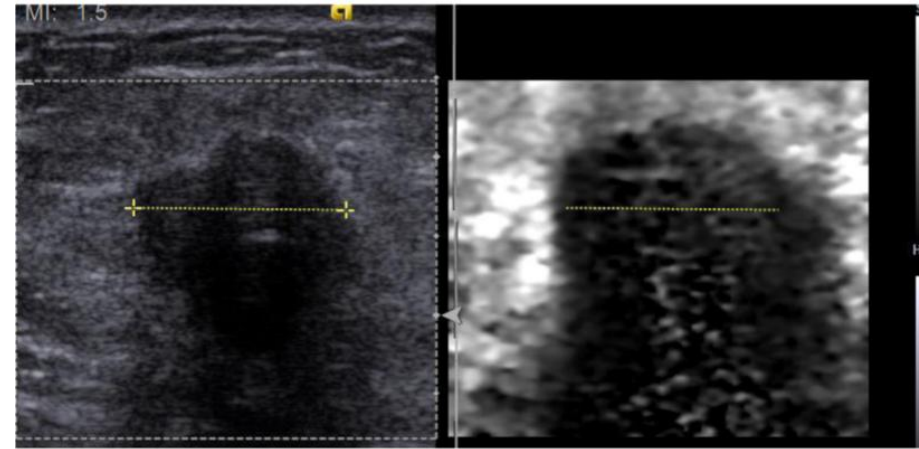


(Gennisson JL et al. Diagn Interv Imaging 2013)

A focused acoustic radiation force generates a localised displacement in the ultrasound axial direction.



Strain Elastography



Elastogram in gray scale. (courtesy of Siemens)

Acoustic Radiation Force Impulse (ARFI) Imaging

(From: Shiina T et al. WFUMB Guidelines and Recommendations on the Clinical Use of Ultrasound Elastography. Part 1: Basic principles and terminology. Ultrasound Med Biol 2015)

In strain elastography and ARFI imaging the quantity of the applied stress is unknown, thus a quantitative measure is not possible.

Speed of the transverse displacement (Shear Wave Elastography)

Methods for Generating Shear Waves

- **External mechanical stress:**

Vibration controlled transient elastography (VCTE), magnetic resonance elastography (MRE)

- **Acoustic radiation force impulse (ARFI):**

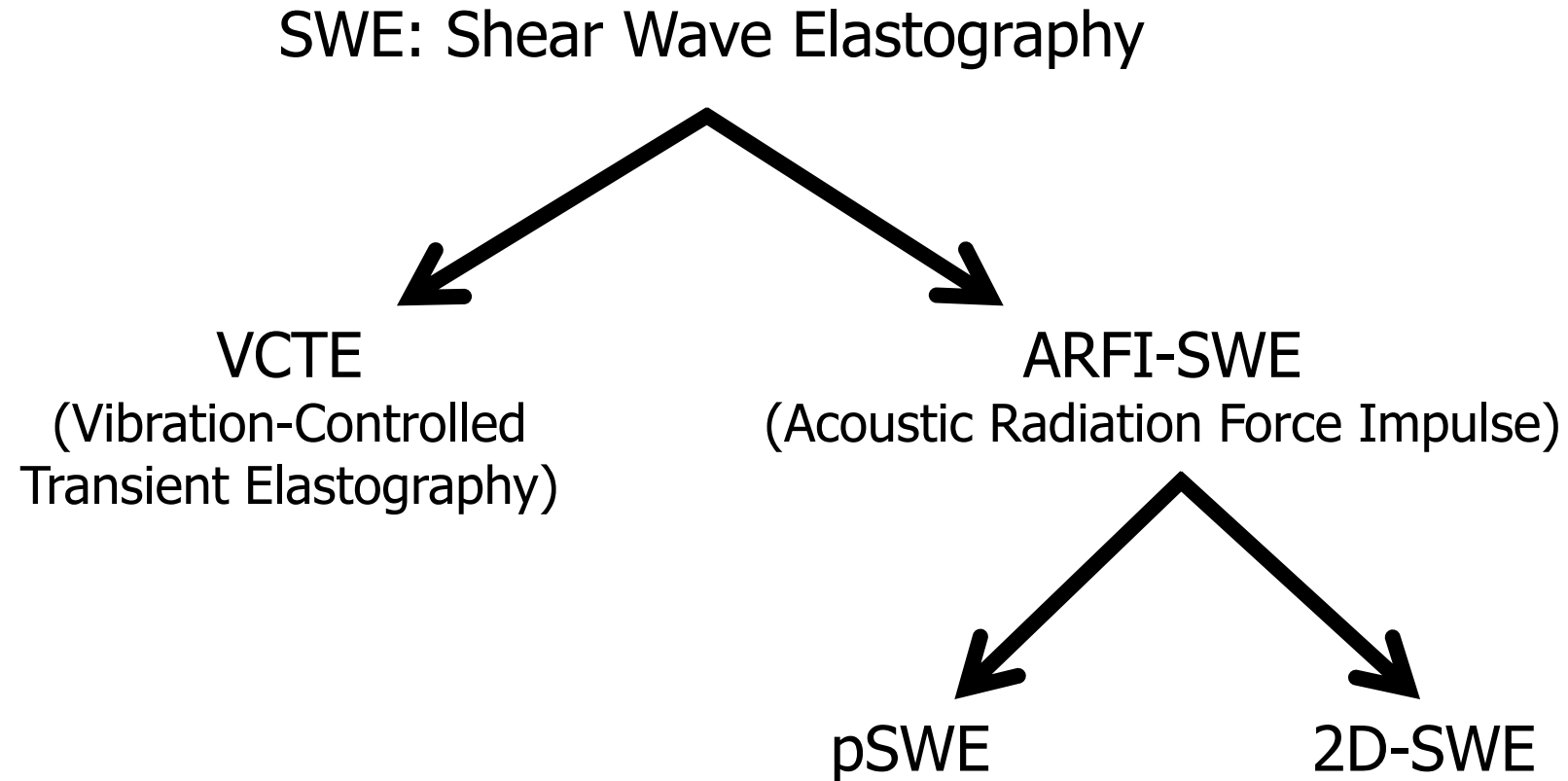
Point shear wave elastography (pSWE), 2D-shear wave elastography (2D-SWE)

US Shear Wave Elastography:

ARFI-SWE techniques

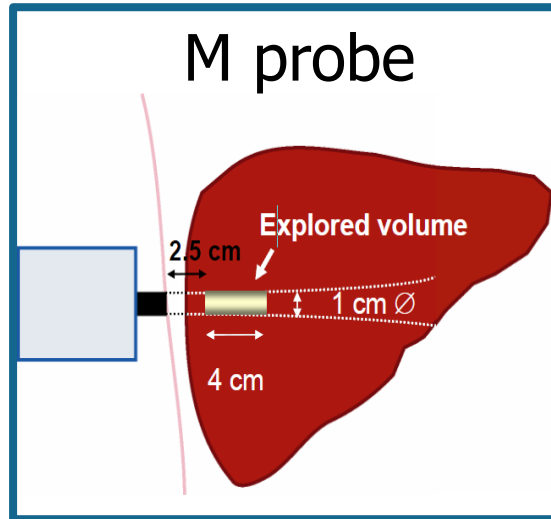
Vibration-Controlled Transient Elastography (VCTE)

Shear Wave Elastography: Terminology



The manufacturers have registered names for the elastography method that they produce

Vibration-Controlled Transient Elastography (FibroScan)



The slope of the white dotted lines represents the shear wave propagation velocity.

The velocity increases with increasing fibrosis.

Compression wave travelling in the liver along its longitudinal axis

ARFI-based Shear Wave Elastography

Dynamic stress

The pulses of the US beams are longer than those of the B-mode (50 - 1000 μ s) in order to produce a measurable tissue displacement in the micrometer range.

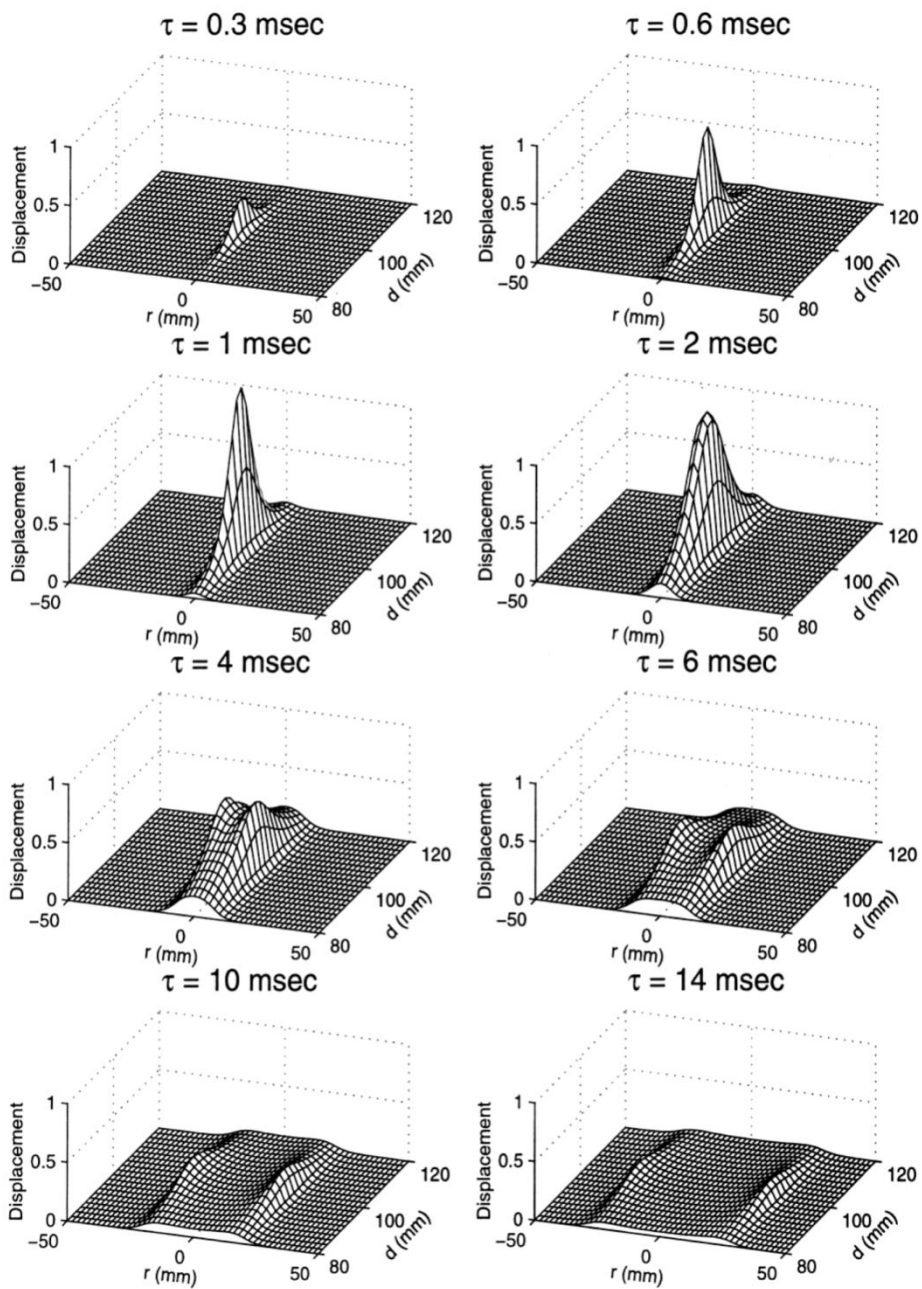


Tissue displacement

The deformation propagates as shear wave



The software measures the velocity of the shear wave



ARFI

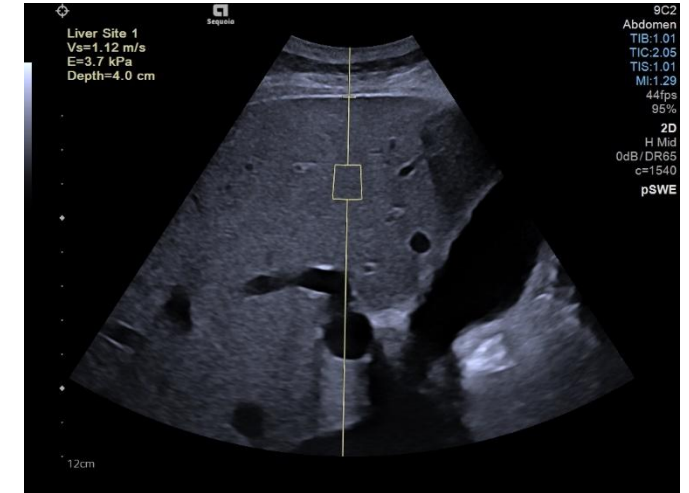
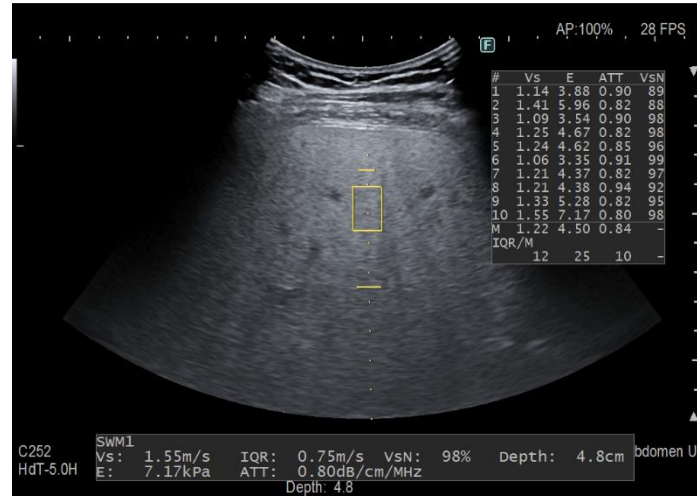
Shear waves

In soft tissues shear waves propagate with speed 1000 times slower than the speed of sound and they attenuate very fast.

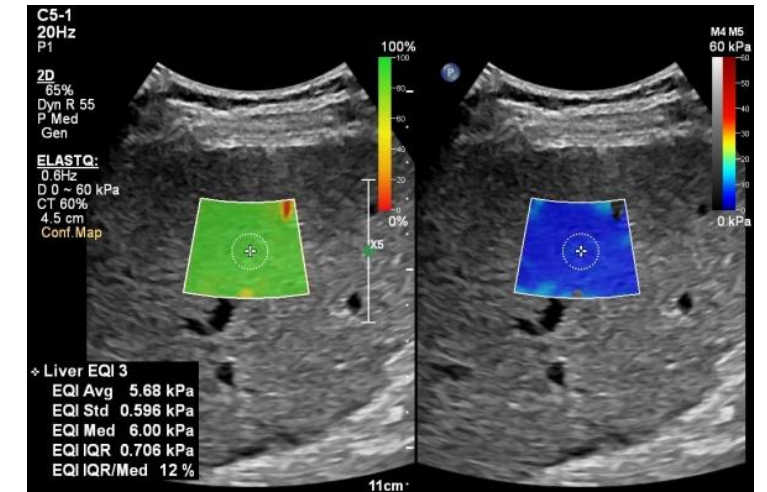
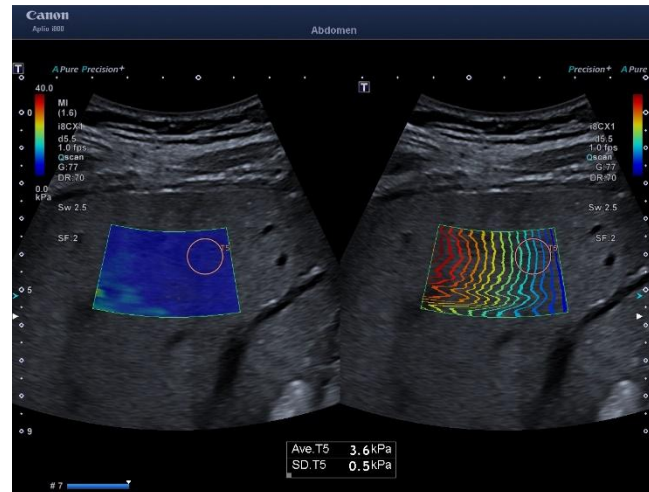
Sarvazyan AP et al. Ultrasound Med Biol 1998

ARFI-Based Shear Wave Elastography

Point shear wave elastography:
Regional values of stiffness



2D shear wave elastography:
Parametric images of stiffness

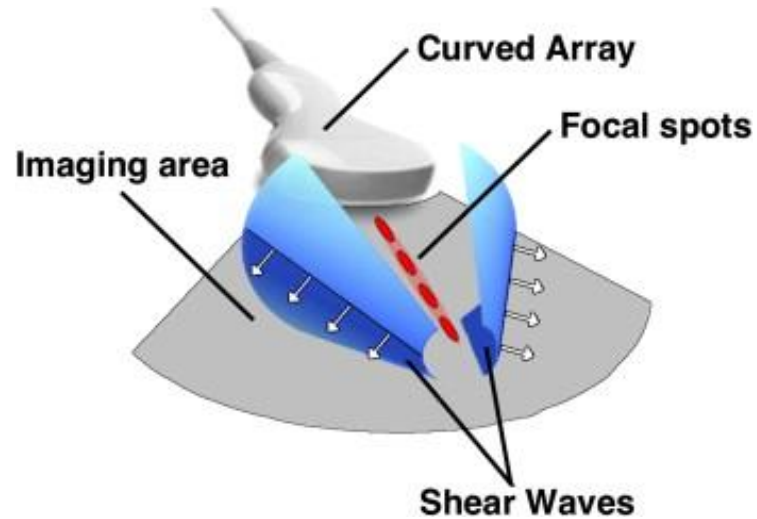


2D Shear Wave Elastography

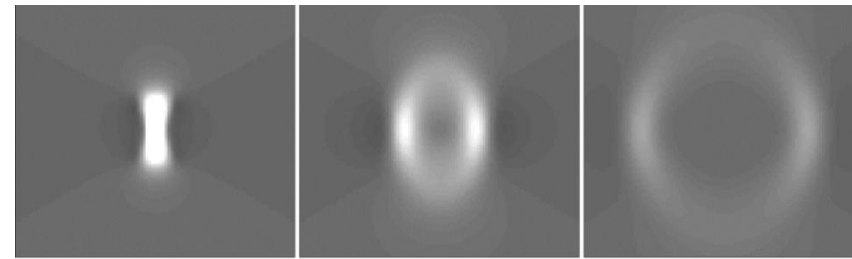
Quantitative images of the shear wave velocity (or stiffness) in a large ROI are obtained by placing the ARFI focus (push) at multiple sequential locations and measuring the shear wave arrival time at multiple lateral locations.

2D Shear Wave Elastography

supersonic shear wave imaging



(Bavu E et al. Ultrasound Med Biol 2011)



(Bercoff J et al. IEEE Trans Ultrason Ferroelectr Freq Control 2004)

Ultrasound plane-wave transmission that enables ultrafast frame rates (typically faster than 1000 frames per second).

The acoustic radiation force focus is swept down the acoustic axis faster than the shear-wave speed to produce tissue displacements at all positions along the acoustic axis almost simultaneously.

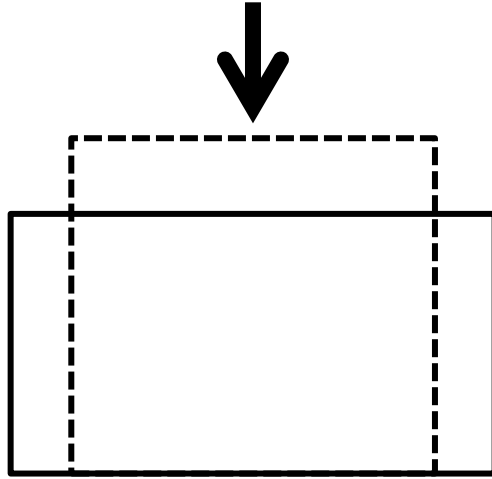
This produces a conical shear wave, known as a Mach cone, that propagates away from the push line and decays less rapidly with distance than that from a single push focus.

SWE: Units of Measurement

Shear wave velocity may be displayed in **m/s**.

Assuming that it does not vary with the magnitude or frequency of the applied force, or with position and direction in the tissue, the velocity can be converted to either **Young's modulus E** or **shear modulus G**.

Modulus: Measure of Stiffness

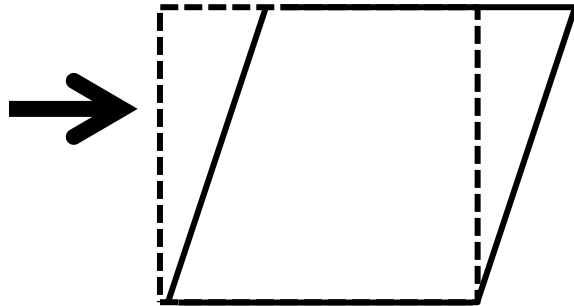


Young's modulus

It indicates how difficult it is to deform a material by stretching or compressing it.

$$E = \text{uniaxial stress} / \text{uniaxial strain}$$

units of pressure (Pascal or N/m²)



Shear modulus

It measures the ability of a material to resist transverse deformation.

$$G = \text{shear stress} / \text{shear strain}$$

units of pressure (Pascal or N/m²)

Shear Modulus (G) and Young Modulus (E)

Shear modulus: $G = \rho V_s^2$ (kPa) \longrightarrow MRE

Young modulus: $E = 3\rho V_s^2$ (kPa) \longrightarrow US SWE

The choice of whether to display velocity or modulus is be under user control.

It is preferable to report results in units of m/s rather than kPa. In fact, this is the unit of shear wave velocity, which is the quantity measured by the system.

Conversion to kPa using a simple equation is based on many assumptions that may not be valid.

Nevertheless, the measurement of stiffness using Young's modulus in kPa has become quite popular in clinical practice since the availability of the Fibroscan.

Factors affecting data quality and producing errors or loss of signal

- Strength of the push
- Variations in attenuation
- Absorption and reflection of the pushing beam
- Ultrasound scatterer density

US

- Very high or very low shear-wave velocity
- Shear-wave scattering
- Reflection or refraction of the shear waves

Shear waves

EFSUMB Guidelines and Recommendations on the Clinical Use of
Ultrasound Elastography. Part 1: Basic principles and technology.
Ultraschall Med 2013

Be aware that:

We assume that the medium is linearly elastic, homogeneous, isotropic, infinite, and continuous

but

biological tissues are visco-elastic.

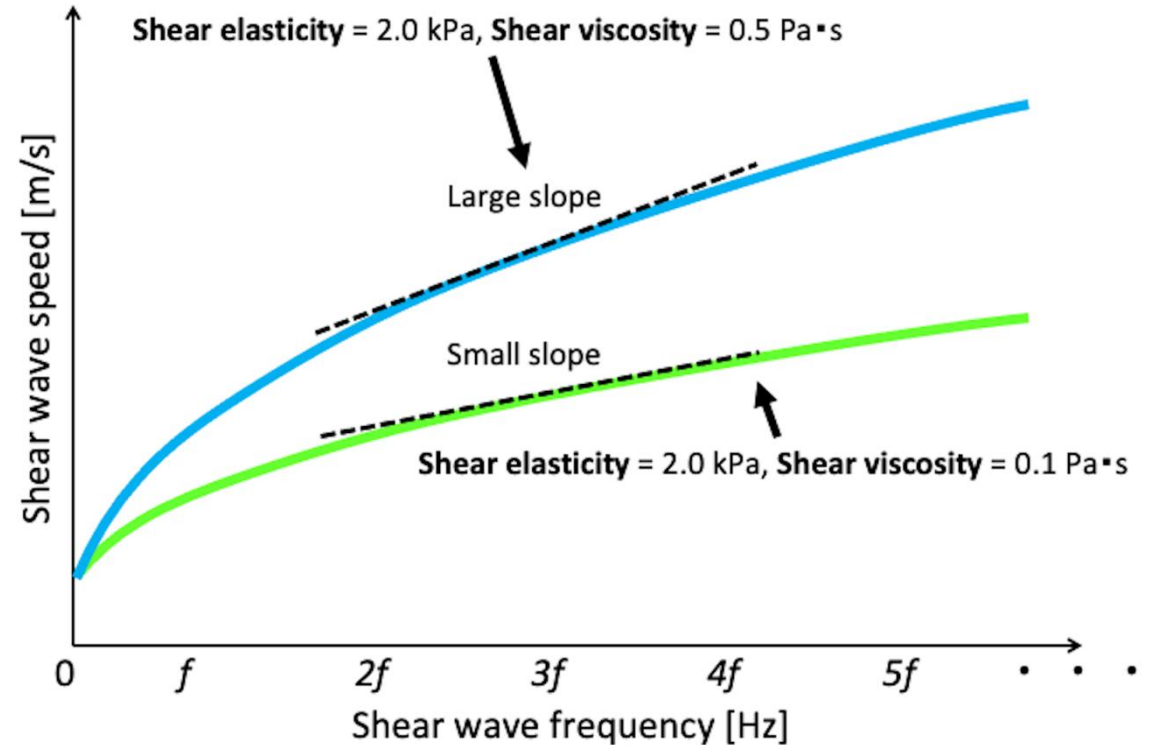
Dispersion of Shear Waves: Related to Viscosity?

- SWE provides biomechanical information regarding tissue elasticity. However, all tissues are viscoelastic.
- Dispersion is related to the frequency dependence of the shear wave speed (SWS) and is affected by the attenuation of shear waves due to the viscous component of the tissue.
- SWS and shear wave attenuation increase with frequency when a tissue is dispersive.
- Analysis of the dispersion characteristics of the shear waves can therefore be used as an indirect method to measure viscosity.

Shear Waves Dispersion Slope

The shear viscosity value can be estimated from the slope over the shear wave frequency bandwidth.

Units of measurement: (m/s)/kHz



- The slope does not measure viscosity directly; it provides the quantification of a parameter that is directly related to viscosity without the need to use a rheological model.
- The shear wave dispersion slope value is based on the frequency range; hence, different ranges give different values.

Shear Wave Dispersion Parameter

Phantom studies:

- Significant depth dependency.

(Obrist A et al. Ultrasound Med Biol 2023. doi: 10.1016/j.ultrasmedbio.2023.03.021)

- SWD exhibited two to three times greater variability than SWS. The lateral ROI position contributed as much as the acquisition depth to the total variance in SWD.

Korta Martiartu N et al. Ultrasound Med Biol 2021. doi: 10.1016/j.ultrasmedbio.2021.08.013

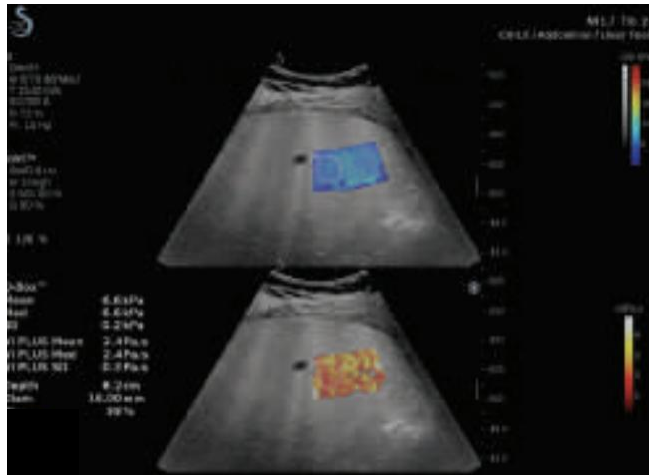
Dispersion of Shear Waves: Biomarker of Inflammation?

The dispersion parameter is acquired together with liver stiffness value.

Combined in a score, a good performance for detecting inflammation in MASLD has been reported.

Factors that may influence the dispersion slope results are not yet well understood.

There are conflicting results in the literature.



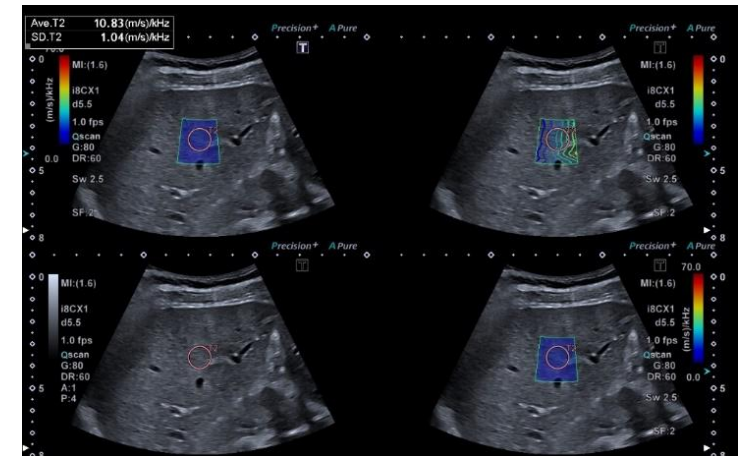
Paisant A et al. Eur Radiol. 2025
Ding X et al. Ultrasound Med Biol. 2026

Positive results (combined in a score)

- Sugimoto K et al. Ultrasonography 2020
- Lee DH et al. Radiology 2019
- Sugimoto K et al. Radiology 2020
- Jang JK et al. Radiology 2022

Negative results

- Cetinic I et al. Children (Basel). 2022
- Wang K et al. Eur J Radiol 2022
- Ohara H et al. J Clin Med 2020
- Su PY et al. J Ultrasound Med 2021
- Zhang XQ et al. Radiology 2022



In conclusion,

There are three options for displaying the mechanical property of the tissue:

- Display tissue strain, calculated from the percentage of axial displacement, as in strain elastography.
- Display the axial displacement without any further processing as in ARFI imaging.
- Display the shear wave velocity, which is calculated by using the time-varying displacement data to measure the arrival times of a shear wave at different locations, as in pSWE, 2D-SWE, and VCTE. Using the Young modulus, the measure of stiffness is displayed.