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# Shear-wave sources for soft tissues in ultrasound elastography

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## Abstract

Elastography is an imaging tool for soft-tissue characterization in the human body, and it is based on the propagation of shear waves. Since its first use in the ultrasound landscape, the generation of shear waves has had practical and theoretical issues. In this review, the use of four methods of shear-wave generation are considered: an external vibrating source; a radiation pressure source; a natural source; and an electromagnetic source. The pros and cons of these methods are detailed and discussed.

*Keywords:* Ultrasound, Elastography, Shear waves

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## 1. Introduction

The ultrasound community long considered the soft tissues of the human body as a fluid where only pressure waves can propagate, as because of the strong attenuation, ultrasound shear waves can barely propagate. The discovery of low-frequency shear waves in dynamic elastography redefined human soft tissues in terms of their solid properties. As in any solid, in soft tissues the elasticity can be characterized by two parameters: the Lamé coefficient  $\lambda$  which is related to compression waves; and the Lamé coefficient  $\mu$  for shear waves (also known as the shear modulus). Soft tissues are considered as quasi-incompressible tissues ( $\lambda \gg \mu$ ). This implies that the elasticity measured by palpation is related to the shear modulus. Measurement of the speed of shear waves in this medium is thus quantitatively equivalent to

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palpation. Therefore, studies have usually been based on the different approaches that can be used to observe the shear waves. In the present paper, we review the methods used in elastography for shear-wave generation, as an external vibrating source, a radiation pressure source, a natural source, and an electromagnetic source. Other studies have been carried out in elastography, such as that of Ophir *et al* that was based on quasi-static elastography [34]. However, this is not the main purpose of the present review.

## 2. External vibrating source

In 1983, Eizenscher *et al* presented an ultrasound method for use in soft tissues that was called 'echosonography' [15]. This method used a mechanical piston placed on the surface of the skin that produced low-frequency vibrations. Eizenscher *et al* were thus the first to mix ultrasound with low-frequency mechanical vibration. However, this only provided qualitative characterization of the tissues.

In 1987, Krouskop *et al* proposed a method for quantitative measurements of wave propagation in tissue through the measurement of the shear-wave speed [28]. This experimental method consisted of the use of an external vibrating source in contact with the limb tissue, and the measurement of the induced displacement by the ultrasonic Doppler method (see Figure 1). These authors showed that this method can detect the local displacement field and further quantify the global elasticity properties of the soft tissues.

In 1988, Lerner *et al* also used an external vibrating source, but with a color-flow map imaging system that was designed for real-time display of blood flow [29]. In this method, the frequency of the vibrations might have been limited to a few  $Hz$  because of the low frame rate of the imaging device. Contrary to that of Krouskop *et al* [28], this method was only qualitative, although it allowed the creation of an image. This method is now known as 'sonoelasticity'.

The measurement method of Lerner *et al* [29] was modified by Yamakoshi *et al* in 1990 [48]. They still used an external vibrating source, but they replaced the measuring device by an ultrasound phased-array transducer. This was used to obtain amplitude and phase maps from the Doppler frequency. This method allowed them to use higher frequencies (i.e., several hundred  $Hz$ ), because of the higher frame rates. Increasing the frame rate thus allowed them to create quantitative images.

Previous methods for sonoelasticity were based on harmonic imaging. However, there was a problem here because the shear-wave speed did not agree with the theoretical models, as observed by Fujii *et al* in 1995 [16]. These authors tried to use a different model that took into account the source. However, it was only in 1999 that this issue was solved, with the development of transient elastography by Catheline *et al* [12, 11]. These authors used a similar set-up, but changed the emitted vibration to a pulse. This was made possible by the development of ultrafast ultrasound imaging by Sandrin *et al* [39]. The difference between the shear-wave propagation models and the experiments were due to a longitudinal component of the near field. The correct description was then made possible in soft solids by the use of pulse emission and the elastic Green's function. This harmonic Green's function is defined as the angular frequency  $\omega$  between two points at a distance  $r$  apart and between the direction of polarization  $m$  and  $n$ , according to [1]:

$$G_{mn}(\omega, r) = \frac{1}{4\pi\rho\alpha^2} \frac{\gamma_m\gamma_n}{r} e^{iqr} + \frac{1}{4\pi\rho\beta^2} \frac{\delta_{mn} - \gamma_m\gamma_n}{r} e^{ikr} + \frac{1}{4\pi\rho} \frac{3\gamma_m\gamma_n - \delta_{mn}}{r^3} \left[ \frac{e^{ikr}}{i\omega} \left( \frac{r}{\beta} - \frac{1}{i\omega} \right) - \frac{e^{iqr}}{i\omega} \left( \frac{r}{\alpha} - \frac{1}{i\omega} \right) \right] \quad (1)$$

where  $\alpha$  and  $\beta$  are the compression and shear-wave velocities,  $q = \omega/\alpha$  and  $k = \omega/\beta$  are the corresponding wave numbers, and  $\gamma_i = x_i/r$  is the cosine director. Transient elastography was then developed in 1-D for hepatic fibrosis [41, 40], as a study of hepatic fibrosis and in 2-D for breast tumors [4]. These techniques were based on the measurement of the longitudinal component of the shear waves, as described in Equation (1) [12, 8].

### 3. Acoustic radiation force

The previous section dealt with external sources for shear-wave production. However, the use of an external vibrating source has practical limitations, such as not being 'user-friendly' for clinical application by a physician, because it can be too heavy and/or too large. Another method was proposed by Sugimoto *et al* in 1990 [43]. This consisted of the use of an acoustic radiation force. An acoustic radiation force is a unidirectional force that can be applied to absorbing and reflecting targets [45]. This corresponds to a transfer of momentum between the acoustic wave and the target. Therefore,

in a medium, displacements can be created due to this force. Thus, this corresponds to shearing created by a compression wave. In their study, the acoustic radiation force was created by a geometrically focused transducer, and the shear strain was measured by an ultrasonic transducer. Sugimoto *et al* [43] wanted to investigate the different parameters that they could use to measure the tissue hardness.

One of the first ideas was to use the acoustic radiation force in order to mimic the palpation by a physician, shear wave propagation was not considered yet. So, one of the possibilities was to measure the elastic modulus from the relation between the force and the deformation of the medium, which is also known as the spring ratio. They also observed the relaxation time of the medium. In 2001, Nightingale *et al* applied this idea to the use of an ultrasonic transducer array [32]. This allowed the generation of multiple pushes and track beams, to create a two-dimensional map of the stiffness. This method was based on the measurement of the displacement. They showed the feasibility of this method in a phantom, and later they showed the clinical feasibility *in vivo* [33]. However, this method has some limitations, as it is a qualitative method and it requires many pushes to image the medium. Using too many ultrasonic pushes can also exceed the US Food and Drugs Administration recommendations.

Previous studies have used an acoustic radiation force to create inner tissue palpation through a quasi-static method. However, some studies began to consider the case of the shear waves. In 1998, Sarvazyan *et al* proposed methods based on the analytical scalar solution for shear waves for near-field assumption [42]. They still used an acoustic radiation force, and they derived the equations for propagation for the focal spot as a source. Their idea was to measure the displacement at the spot, which corresponds to the spring ratio. It was also possible to estimate the wave front near the focal spot as a function of time and radial distance, to obtain the velocity. However, in this study, they used MRI to detect the propagation; this detection method implies a low frame rate, and is relatively expensive to use.

In 2004, Bercoff *et al* presented a method that was entirely based on ultrasound, not only for the acoustic radiation force, but also for the imaging technique [5]. The main idea here consisted of focusing in multiple points to generate a wave front as a Mach cone (see Figure 2). This required a displacement of the ultrasonic focal spot at a faster rate than the shear-wave velocity in the medium. With this coupled to ultrafast ultrasound imaging that was developed by Sandrin *et al* in 1999 [39] (at more than 1000 frames

per second), they measured the shear-wave velocity, and thus the stiffness. This imaging technique is particularly different from the former methods because it is based on propagation of the transient wave front, and not on the displacement created by the force. This depended strongly on improvement of the frame rate of the ultrafast scanner. This method is an improvement of the method developed by [39] because it does not require a vibrating source held by the physician, as in [4].

Acoustic radiation force has been used in many studies for different organs and it is now a widely used method in shear-wave elastography. For liver fibrosis, a clinical study based on ARFI-SWS method was reported in 2010 by Takahashi *et al* [44]. More recently, Urban *et al* studied myocardial anisotropy [46] with harmonic imaging method, and Pernot *et al* measured diastolic myocardial stiffness [35] in using the SWE method.

Using acoustic radiation force imaging also allowed the combination of different push methods. For example, several shear waves can be created that interfere with each other, to create crawling waves [22].

#### 4. Electromagnetic source

A recent method to create shear waves in a medium is based on the Lorentz force. The principle is that an electrical current in a magnetic field induces displacement due the Lorentz force [23].

The first methods in the literature to generate shear waves using electromagnetic sources were based on external coils [31], which represented another way to create an external vibrating source. This method was modified in 2005 by Basford *et al*, who performed experiments in conductive gel phantoms using MRI [2]. An electrical current was passing through the phantoms and the magnetic field was created by the MRI. They illustrated this using displacement maps. This idea was also applied to soft solids in 2013 by Grasland-Mongrain *et al* [20, 18]. This study included experiments in gels of polyvinyl alcohol with graphite powder and salt. They applied low frequency electrical currents ( $10 - 1000Hz$ ) to the gel, which was placed in a constant magnetic field. However, in this study, the imaging device was an ultrafast ultrasound scanner, where they used the speckle due to graphite to measure the displacement. The magnetic field was created by magnets instead of MRI. Waves were observed in the medium. The advantage here was the possibility to create displacement in a smaller environment than with

an MRI system. This might also allow elastography to be performed for the brain, for example.

In previous studies, an electrical current was generated in contact with the gel by electrodes, or through the gel. Then in 2016, Grasland-Mongrain *et al* presented a contactless experiment that was performed with a commercial transcranial magnetic stimulator [21]. The source was interesting, because it did not require further development, with the commercial devices used directly.

Montalescot *et al* also used electrical currents to create shear waves [30]. For their study, the idea was to perform water electrolysis in soft solids, and thus to induce bubbling. The bubble growth induced compression waves and shear waves. However, the difference in the time scale for the propagation allowed the separation of these two types of waves. This technique still needs some work on it, because it would require relatively high electrical currents for human experiments. However, this study might allow the use of bubbles to create waves in different media, and the bubbles would not have to be created by electrical currents.

In another study, they also presented the use of another electromagnetic wave: light (see Figure 4), based on laser beams [19]. The optical energy of the laser is converted into heat. This corresponds to a small local increase in temperature, and thus dilatation of the tissue. This induces displacement that can generate shear waves. This method can then be extended to create waves in small media or for surface waves, to perform elastography of media like the cornea.

Indeed, these last methods usually created waves near the electrodes or the target of the laser. They can be considered as similar to the methods that used vibrating sources to create shear waves.

## 5. Natural source

The previous imaging and characterization techniques were based on shear-wave generation using an active source. However, a medium can be analyzed using the inner natural waves that can be observed with ultrasound, as shown by Dickinson *et al* as early as 1982 [14]. For example, in the human body, this can be achieved through muscle activity, cardiac activity [47], or arterial pulsativity. The best candidate for the first passive methods was the heart. This has been studied since 1996, initially by Kanai *et al*, who demonstrated the possibility to measure tissue displacement by

Doppler effects [26]. Then, they used their method to characterize cardiac tissue [26, 25, 24]. Another example of passive elastography for the heart was reported by Konofagou *et al* in 2000, where they measured the displacement and strain created by cardiac activity [27].

Other studies have used noise correlation, a method that can be used to retrieve the wave Green's function in a medium, as in Equation 1 [7, 13, 36, 38]. In other words, this method extracts the speed properties from any complex field. It shares the same physical background as time-reversal techniques. It can be formally demonstrated that given  $\vec{u}(\vec{r}, t)$ , the displacement measured at position  $\vec{r}$  and at time  $t$ , the time-reversed signal between points  $\vec{r}$  and  $\vec{r}_0$  is:

$$\Psi^{TR}(\vec{r}_0, \vec{r}, t) = \frac{\partial}{\partial t} [\vec{u}(\vec{r}_0, -t) \otimes \vec{u}(\vec{r}, t)]. \quad (2)$$

This method was used for a first time in 2007 by Sabra *et al*, to characterize muscle stiffness [37]. Their first experiment consisted of using 15 transducers on the surface of the leg (see Figure 3). To measure the phase velocity, the correlation between the signals measured by each of these transducers was determined.

About the same time, Catheline *et al* presented a time-reversal experiment in a gel [9]. This corresponds to an improvement on the previous technique because an ultrafast scanner was used with a transducer array. This allowed the Green's function to be determined in a two-dimensional plane.

Soon after, one-dimensional measurements were performed with a unique transducer, to determine the possibility of measuring the elasticity with this method [3]. This study showed that even if the Green's function is not isotropic, the width of the focal along the direction of propagation of the ultrasound is approximately the wavelength of the shear waves, which thus allows the elasticity to be measured.

In 2011, Gallot *et al* combined both of these more recent ideas to determine the elasticity of the liver [17]. They directly measured a two-dimensional wave field with a transducer array, and determined the shear-wave displacement using a speckle-tracking method. Determination of the shear-wave velocity was then based on the space-time representation of the Green's function, as in the one-dimensional case, with a calculation along the depth. This study thus proposed a method to obtain elasticity maps that was contrary to [28], based on global characterization.

Catheline *et al* presented a new algorithm in 2013 that was based on



plane-wave approximation near the focal spot of the Green's function [10]. This consisted of comparing the time-reversed wave field in the strain and in the particle velocity, to obtain an approximate group velocity.

However, an interesting part of their study was the demonstration of the feasibility with the use of a classical slow scanner. The pulse repetition frequency was too low to obtain any time information, but the resolution was high enough to obtain the central wavelength.

This method is thus only based on spatial information. The possibility of performing measurements with very low frame rates allows this to be used with MRI, for example. It would also be possible to use a non-constant frame rate here. This was thus used in 2015 by Zorgani *et al* to measure the elasticity of the brain [49].

## 6. Discussion

The previous sections present the different types of sources: as external vibrating sources where the control is at the origin of the development of the elastography, as ultrasonic radiation sources, as electromagnetic sources, and as natural noise.

The nature of each generation technique leads to different advantages and limitations. For external vibrating sources, the methods are strongly dependent on the depth to be studied, because the shear-wave penetration has to be taken into account, and thus the frequency. In considering the case of an acoustic radiation force, the depth is still an issue because the ultrasound must create a push, while the difference is that the source of the shear waves is within the medium. However, using endoscopic techniques can solve this issue, with the push provided near to the area of interest.

The efficiency of electromagnetic methods depends on the type considered. Methods that create bubbles or currents at the surface have the same problems as external vibrating sources, while methods that use Lorentz force with a variable electromagnetic field, like a transcranial magnetic stimulator, can create the wave in the medium. The shear-wave formation is less limited by the depth here. The limitations associated with passive elastography are particularly different. Indeed, passive methods depend strongly on two aspects: the natural noise with its frequency bandwidth, and the imaging technique. This last point implies that this method can work at any depth, and that this parameter depends only on the imaging technique. For example, passive elastography is possible in the brain using MRI, but not using

ultrasonic imaging, because of the skull. However, passive elastography based on low frame rate imaging devices can only estimate the shear wavelength. The loss of time information results in a relative elasticity map. High frame rate imaging used in optics or ultrasounds conduct to quantitative speed imaging.

Another difference between these methods concerns the size of any device and the difficulties that might be associated with using the device. External vibrating sources are relatively difficult to use, which is why a project for transient elastography for the breast was abandoned [4]. This was not user-friendly enough for the physicians. The issue of size also explains the interest in the acoustic radiation method. In many organs, such as the liver or the heart, this just requires an array of ultrasonic transducers. This advantage is similar to that of passive elastography: the technique only requires an imaging device. For the electromagnetic sources, there is no correct device that is already used. The feasibilities of these methods still need to be further demonstrated, although the user-friendly properties can be relatively difficult to analyze.

A third main difference between these techniques is the time required for a measurement. Recent acoustic radiation force techniques require a few milliseconds. For example, to study the cardiac elasticity during a cycle only requires acquisitions of the order of  $50ms$  [47]. This study would be impossible when using natural noise, because this method usually requires between  $500ms$  and  $1000ms$ . In the case of electromagnetic sources, the methods based on a transcranial magnetic stimulator or a pulse source at the surface only require a duration that is similar to the time of flight of the shear waves. For external mechanical sources, the requirement is almost the same, although the duration of the emitted signal must also be considered. The measurements needed thus represent an important criteria in the choice of the method, and these need to be taken into account.

## 7. Conclusion

The present review details the four main techniques that have been used to generate shear waves in soft tissues. The first method is based on an external vibrating source. This strategy is much less used nowadays because it is relatively difficult to image the medium at depth and the devices needed can be cumbersome. The acoustic radiation force allows rapid measurements to be performed with smaller devices. However, there is still the problem re-

lated to the depth or the propagation through complex structures, although these problems might be avoided using interstitial probes. Passive elastography removes the problems with depth, and here only the imaging device matters. However, the duration of the acquisition is longer, and this can prevent some types of measurements. However, the acoustic radiation force method appears to be under continued development and will be difficult to replace. On the other hand, the use of the other methods can co-exist for certain applications. For example, in the case of electromagnetic sources, these are useful with their coupling to an MRI device. A laser can also be used to perform elastography of thin media, like the cornea, and bubble resonance can create shear waves directly in the media. In the case of passive elastography, the method does not require an emitting device, and thus only depends on natural noise and on the imaging device; it can thus be used where acoustic radiation force cannot be, such as for the brain.

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Figure 1: Ultrasonic sensor used to characterize the modulus of soft tissue by Krouskop *et al* [28].

Figure 2: Experimentation (a) and simulation (b) of longitudinal displacement induced by a radiation force [6].

Figure 3: Experimental set-up and muscle vibration noise measured as the surface mechanomyogram (S-MMG) and recorded from the vastus lateralis during isometric voluntary contractions with a skin-mounted accelerometer. Weight load, 10 lb [37].

Figure 4: Experimental set-up. A laser beam emitted onto a soft medium. This generated shear waves following thermoelastic (a) and/or ablative (b) regimes. The medium was observed with an ultrasound probe. A speckle-tracking algorithm calculated the displacement from the ultrasound images [19].