White Paper

ShearWave™ Elastography

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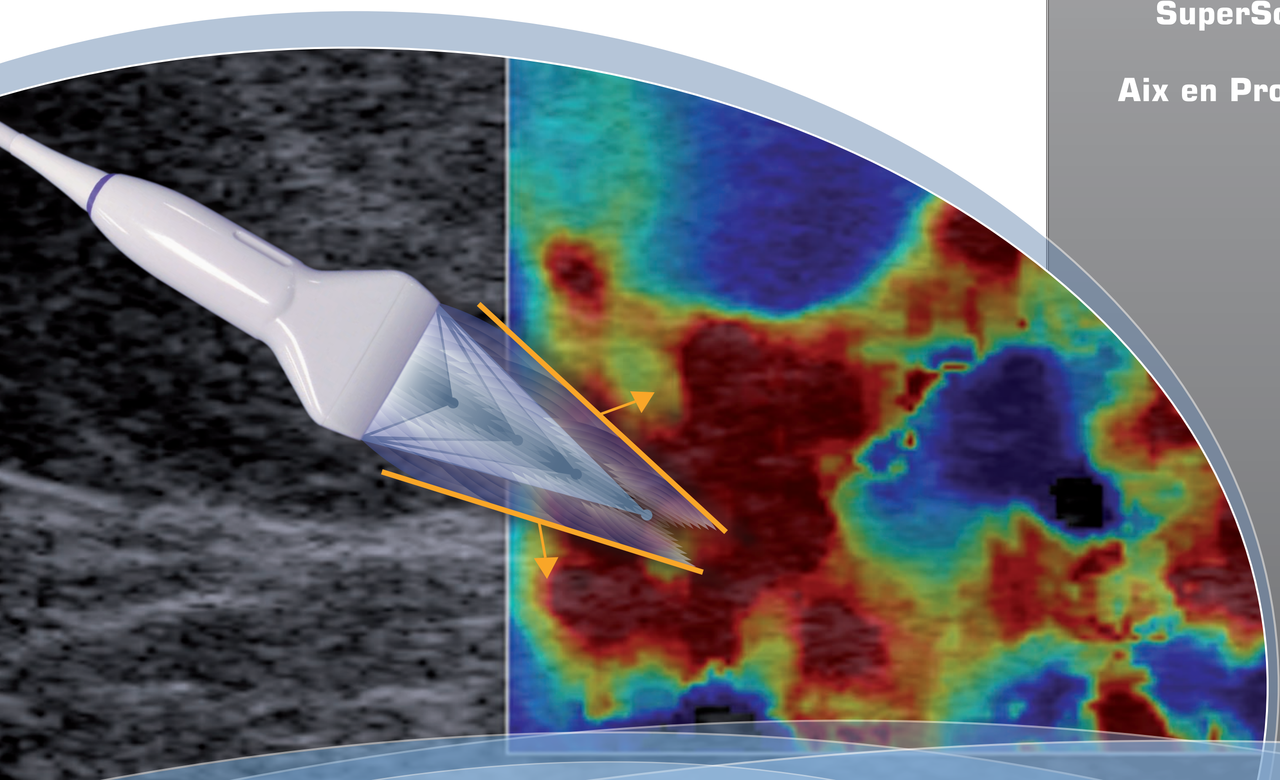


Introduction

One of the key medical methods for detection and characterization of pathologies is the assessment of tissue stiffness by palpation. The importance of clinical assessment of tissue stiffness has been known since ancient times: In Pharonic Egypt, more than 5000 years ago, physicians practiced palpation of body parts to determine tissue stiffness. They knew that a hard mass within an organ was often a sign of an abnormality. Since then, palpation has been used for screening and diagnosis, but is also used during interventional procedures to guide the surgeon to the area of pathology.

Today, a new diagnostic imaging modality has emerged, called elastography, which uses ultrasound to assess tissue differences in stiffness (or elasticity). It provides an imaging representation of what was historically assessed qualitatively by palpation. The main objectives of elastography are to improve diagnostic confidence and increase specificity of the ultrasound exam.

SuperSonic Imagine's ShearWave™ Elastography is a new ultrasound imaging concept designed to achieve these objectives. Based on automatic generation and analysis of transient shear waves, the mode has the major advantage of being quantitative, real-time and user-skill independent.

The Basics of Human Tissue Elasticity

Tissue stiffness is generally measured by a physical quantity called Young's modulus and expressed in pressure units - Pascals, or more commonly kilo Pascals (kPa). Young's modulus can be defined through a simple experiment illustrated in Figure 1. An external uniform compression (or stress S) is applied to a solid tissue and this induces a deformation, or strain (e) inside the tissue.

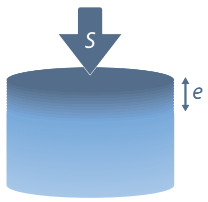


Figure 1: *Deformation of a soft solid under an external stress.*

As one might expect, the induced strain is smaller in harder tissue than in softer tissue. The relationship between stress and strain is expressed in the equation (1) below. The Young's modulus is defined simply as the ratio between the applied stress and the induced strain:

$$E = \frac{s}{e} \qquad (1)$$

Young's modulus, or elasticity E, quantifies tissue stiffness. Simply put, hard tissues have a higher Young's modulus than soft ones. Typical values of elasticity in different tissue types have been reported in the literature [1-3] and are summarized in Figure 2.

Type of soft tissue		Young's Modulus (E in kPa)	Density (kg/m^3)
Breast	Normal fat	18-24	1000 +/- 8% ~water
	Normal glandular	28-66	
	Fibrous tissue	96-244	
	Carcinoma	22-560	
Prostate	Normal anterior	55-63	
	Normal posterior	62-71	
	BPH	36-41	
	Carcinoma	96-241	
Liver	Normal	0.4-6	
	Cirrhosis	15-100	

Figure 2 : *Typical values of elasticity in different types of tissues .*

While the density of tissue remains relatively constant in the body, i.e. very close to the density of water (1000 kg/m^3), tissue elasticity may differ significantly compared to tissue of a different pathological state.

If the mechanical perturbation applied to tissue is more complex than a static compression, such as a transient impulse or "punch", mechanical waves can be induced in tissue.

There are two types of mechanically induced waves:

- Compression (or bulk) waves: These propagate very quickly in tissue (1500m/s) by successively compressing tissue layers. Echoes of compressional waves on tissue scatterers are used to perform standard ultrasound imaging.
- Shear waves: These are much slower than compressional waves (1 to 10 m/s) and propagate by creating a tangential "sliding" force between tissue layers. Shear waves have not been explored so far in medical imaging despite the fact that they are explicitly related to tissue stiffness. In fact, elasticity (E) and shear wave propagation speed (c) are directly linked through the simple formula:

$$E = 3\rho c^2 \quad (2)$$

where ρ is the density of tissue expressed in kg/m^3.

Given that the density of tissues is well known (1000kg/m^3), if the shear wave propagation velocity c can be measured the elasticity of the tissue can be determined.

What is Elastography?

Elastography is a term referring to imaging techniques that aim to assess tissue elasticity. All approaches that have been introduced to date are based on a common three step methodology:

1. Generate a low frequency vibration in tissue to induce shear stress
2. Image the tissue with the goal of analyzing the resulting stress
3. Deduce from this analysis a parameter related to tissue stiffness

If the Young's modulus, or elasticity of the tissue, can be determined directly from the analysis, the technique is considered quantitative.

Elastography techniques are commonly classified according to the type of vibration applied to the tissue. There are three classes of elastography: static, dynamic and shear wave based.

- Static elastography uses a uniform compression at the surface of the body to cause deformation of the tissue. The compression is applied by the user and the ultrasound scanner calculates and displays the induced deformation in the imaging plane (Figure 3) [4,5]. Young's modulus cannot be reconstructed (using equation 1) as the stress within the tissues induced is unknown. Consequently, static Elastography is not a quantitative imaging mode. The clinical relevance of static elastography has been extensively studied. While promising results have been demonstrated, many pitfalls have been reported by users, including poor reproducibility, inter-operator variability and lack of quantitative information [6-10].

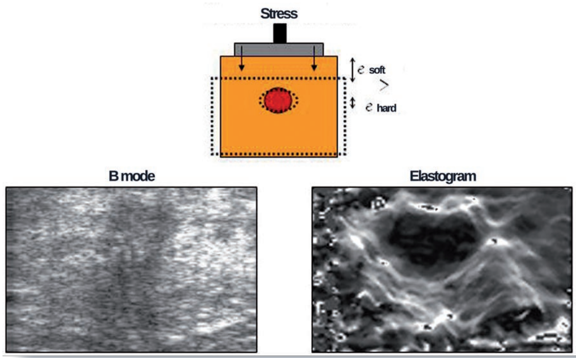


Figure 3 : *Static Elastography. Bmode (left) and elastogram (right). On the elastogram, less deformed tissue appears darker.*

- Dynamic elastography utilizes a continuous (monochromatic) vibration (Figure 4). Stationary waves induced in the body are analyzed to deduce tissue elasticity [11,12]. Dynamic elastography is well suited for MR systems as the vibration pattern is not time dependent but must be assessed in a volume [13]. It is a quantitative approach but suffers from the usual MR drawbacks: high cost, limited availability, and lack of real time imaging.

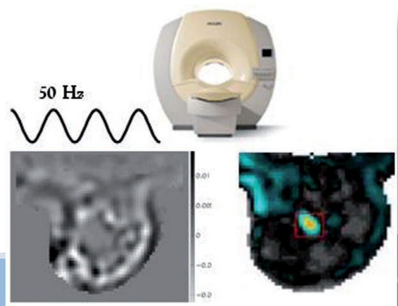


Figure 4 : *Dynamic elastography images from MRI . Displacements @ 50 Hz (bottom left). Elasticity map (bottom right).*

• Shear wave based elastography makes use of transient pulses to generate shear waves in the body [14-16]. The tissue's elasticity is directly deduced by measuring the speed of wave propagation as indicated in formula (2).

Shear wave based elastography is the only approach able to provide quantitative and local elastic information in real time [17]. However, its implementation as an imaging mode requires major technological breakthroughs in the ultrasound medical imaging field.

The SuperSonic Imagine Aixplorer™ is the first ultrasound system to leverage this technology and implement a true shear wave based elastography imaging concept.

ShearWave™ Elastography

Presentation

ShearWave™ Elastography (SWE) provides quantitative elasticity maps in real time as illustrated in Figure 5.

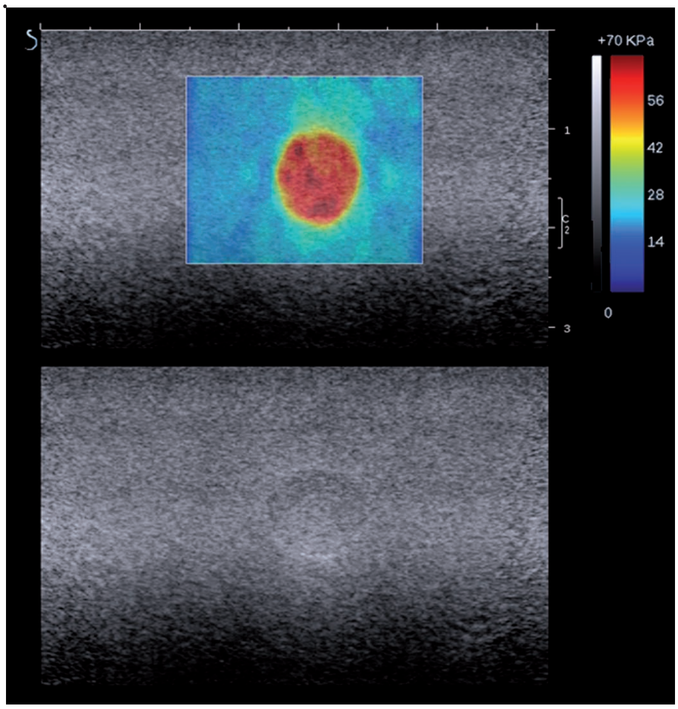


Figure 5 : *SWE mode overview on a phantom containing a harder inclusion.*

Elasticity is displayed using a color coded image superimposed on a B-mode image. The color scale is quantitative with values expressed in kPa. Stiffer tissues are coded in red and softer tissues in blue. The elasticity image is refreshed in real time. The image resolution remains around 1mm. The imaging frame rate is optimized to meet acoustic output limitations defined by international standards [18].

The ability of SWE to measure quantitative values of elasticity has been evaluated using calibrated phantoms of different elasticity that represent typical elastic values of breast tissue and pathologies (ranging from 10 to 110 kPa) [19]. Results are shown in Figure 6.

	Medium 1	Medium 2	Medium 3	Medium 4	Medium 5
Reference Elasticity	14	20	37	72	105
Elasticity measured by SWE	15.1	21.3	37.4	74.7	105.7
Std dev	2.3	3.1	5.4	9.6	11.5

Figure 6 : *Elasticity measured by SWE on calibrated phantoms. All measures are in kPa.*

ShearWave™ Elastography quantitatively images tissue elasticity. This is achieved using an ultrasound probe without requiring any external compression by the user.

Shear Wave Generation

Shear waves can be generated in the body in different ways. The beating heart is a natural source of shear waves but its vibrations remain localized in its vicinity. The use of external vibrators, such as those used in dynamic MR elastography, are not ideal in the ultrasound environment as they require the manipulation of two devices simutaneously [20]. ShearWave™ Elastography uses the acoustic radiation force induced by ultrasound beams to perturb underlying tissues. This pressure or "acoustic wind" pushes the tissue in the direction of propagation. An elastic medium such as human tissue will react to this push by a restoring force. This force induces mechanical waves and, more importantly, shear waves which propagate transversely in the tissue. This is illustrated in Figure 7.

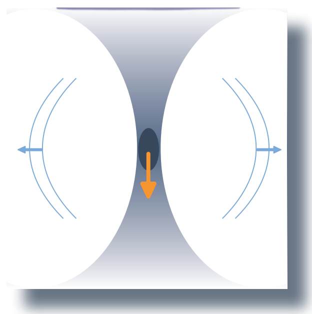


Figure 7 : *Radiation force induced by a traditional focused ultrasound beam.*

A limitation of ultrasound generated shear waves is that they are very weak, amounting to only a few microns of displacement. Therefore, dissipation occurs after a few millimeters of propagation. In order to generate a stronger shear wave, larger perturbation is required, therefore increasing ultrasound power at the focus. However, this condition leads to transducer over-heating and concerns over acoustic power [18,21].

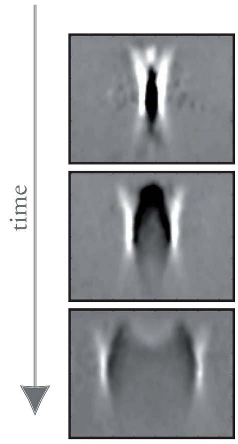


Figure 8 :

A shear wave induced by an ultrasound beam focused in the center of the image.

The challenge is to find a way to increase the amplitude of the shear wave while limiting the acoustic power to safe levels. SuperSonic Imagine's patented SonicTouch™ technology generates a supersonic shear wave source within tissue [22]. Using SonicTouch™, ultrasound beams are successively focused at different depths in tissues (Figure 9). The source is moved at a speed that is higher than the speed of the shear waves that are generated. In this supersonic regime, shear waves are coherently summed in a "Mach cone" shape, which increases their amplitude and improves their propagation distance. For a fixed acoustic power at a given location, SonicTouch™ increases shear wave generation efficiency by a factor of 4 to 8 compared to a non supersonic source.

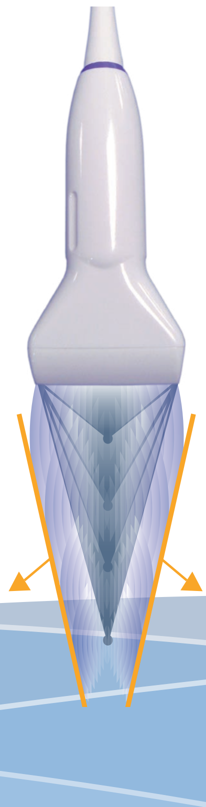


Figure 9 : *Radiation force induced by SonicTouch™. Shear waves are amplified in a Mach cone shape (in yellow), which increases the propagation distance of shear waves while minimizing acoustic power.*

Ultrafast™ Imaging

The shear waves generated using the SonicTouch™ excitation need to be captured by the ultrasound system. Shear waves typically propagate in tissues at speeds between 1 and 10 m/s (corresponding to tissue elasticity from 1 to 300 kPa). Consequently, they cross an ultrasound image plane of 3 to 6 cm width in 10 - 20 milliseconds (less than 1/50 of a second). Modern radiology ultrasound systems generate only 50 - 60 images per second. This is too slow to image a propagating shear wave since the shear wave will have disappeared in the time needed to make a single frame. In order to capture shear waves in sufficient detail, frame rates of a few thousands of images per second are needed. That is 100 times faster than the frame rates offered by current state-of-the-art ultrasound technology. Aixplorer™ is the first ultrasound system able to reach ultrafast frame rates of thousands of Hz. Ultrafast™ imaging is performed by sending ultrasound plane waves into the tissues to insonify the full imaging plane in one shot, as illustrated in Figure 10. The maximum frame rate achievable is determined by the time it takes the ultrasound wave to travel from the transducer to the tissue and back. For a typical breast image of 4 cm depth, the maximum frame rate achievable is 20,000 Hz.

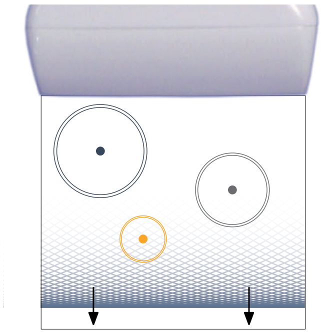


Figure 10 : *Ultrafast imaging. A flat wave insonifies the whole medium in one shot.*

The technological challenge is the ability to process the ultrasound images acquired at these ultrafast frame rates. In conventional systems, this capability is limited by the number of lines of an image the system is able to compute in parallel. This number is usually between 4 and 16 on radiology systems. Thanks to its full software architecture (SonicSoftware™), Aixplorer™ computes all the lines of each image in parallel, therefore managing to achieve ultrafast frame rates of thousands of Hz.

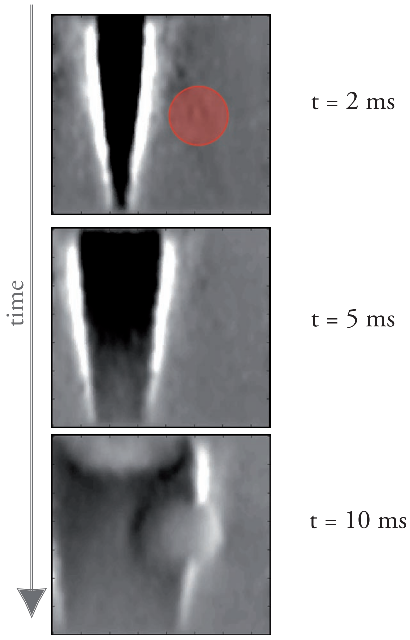


Figure 11 : *Plane shear wave induced by SonicTouch™ technology in a medium containing a harder inclusion (red circle). The plane shear wave-front is deformed because the shear wave travels faster in the harder inclusion.*

Ultrafast™ imaging allows detailed monitoring of the shear waves travelling through the imaging plane. Propagation of the shear wave induces small tissue displacements which are recorded by the Ultrafast™ imaging system, and quantified using tissue Doppler techniques. In this manner, a movie of the particle velocity induced by the shear wave is formed. This provides a faithful representation of the propagation of the shear wave-front as illustrated in Figure 11.

The shear wave propagation speed is estimated at each pixel from the shear wave particle velocity movie (Figure 11) using cross correlation algorithms. The resulting speed map is shown in Figure 12.

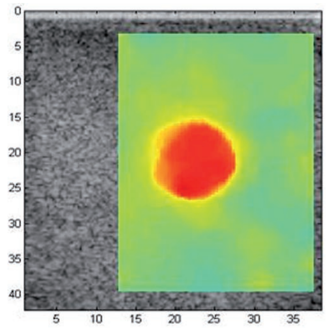


Figure 12 : *Map of the shear wave propagation speed in m/s deduced from the velocity movie.*

Elasticity Estimation

To compute a full elasticity image as displayed on the system screen (Figure 5), several supersonic lines are generated using SonicTouch™ Technology, as illustrated on Figure 13. For each line, several ultrafast images are acquired and the shear wave propagation velocity movie is computed. Shear wave speed maps from all the pushing lines are calculated and then combined into a final image. The elasticity map in kPa is directly derived from the final speed map using equation (2).

SonicTouch™ technology reduces the number of pushing beams necessary to compute a full elasticity map in a region of tissue. SonicTouch™ technology is the key to real time ShearWave™ Elastography. Its efficiency enables continuous refreshing of the elasticity image while remaining in the classic acoustic power limitations of ultrasound systems.

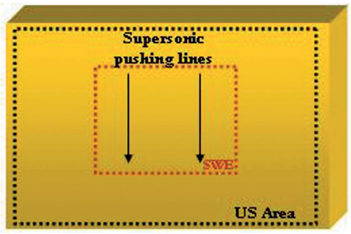


Figure 13 :

A small number of supersonic lines generate a full elasticity map. The number of lines depends on the tissue and the elasticity box size.

ShearWave™ Elastography in the Clinical Workflow

SuperSonic Imagine's ShearWave™ Elastography offers a new level of information and diagnostic confidence to the user and its simplicity in use fits well into the clinical workflow pattern. SWE offers three major innovations: its quantitative aspect, its high spatial resolution and its real-time capabilities.

Normal breast tissue elasticity varies from 1 to 70 kPa whereas the elasticity of carcinoma covers a much wider range, from 15 to more than 500 kPa. Breast lesions having elasticity above 100 or 120 kPa are commonly considered to be hard. SWE mode is able to image fine elastic contrast as well as large elasticity differences. This is illustrated in the following two examples.

Providing quantitative information for breast imaging

The elasticity range of different types of tissues have been published (table in Figure 2). Figure 14 summarizes values for breast tissues.

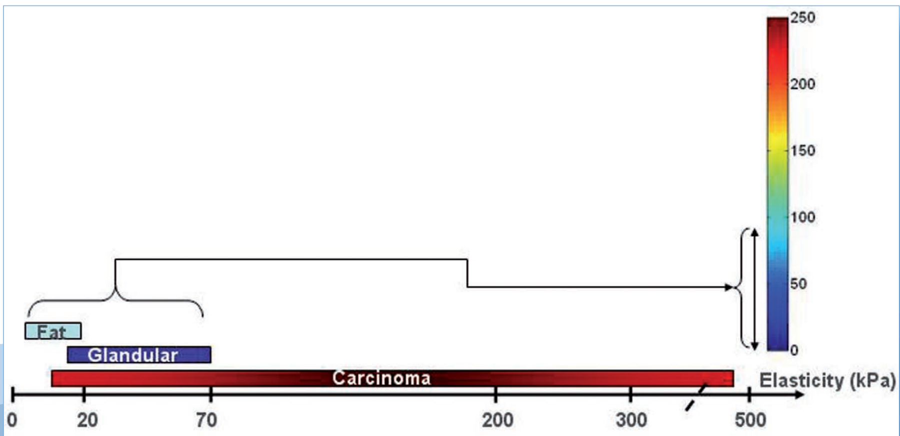


Figure 14 :

Typical values of tissue elasticity in the breast. Tissues with relatively low elasticity (fat and glandular) are coded in blue using SWE.

The fibroadenoma in Figure 15 exhibits a mean low elasticity value (mean 28 kPa) but has slightly harder contours that can be seen both on the ultrasound and elasticity image (mean 40 kPa).

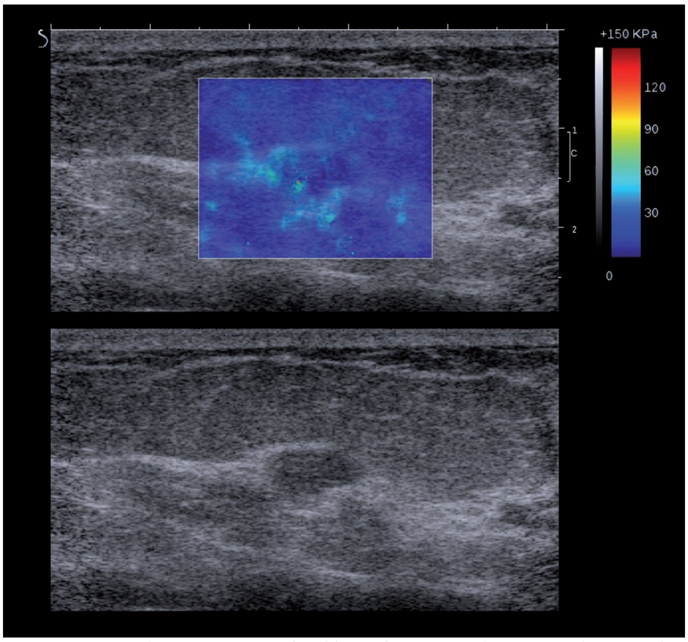


Figure 15 : *Elasticity map of a fibroadenoma. The mean elastic value of the lesion is 28 kPa.*

The lesion in Figure 16 (an invasive ductal carcinoma), which was classified as ACR4 using the BI-RADS® lexicon [23], appears as very hard on the elasticity image (mean of 270 kPa) while surrounding tissues are around 30 kPa.

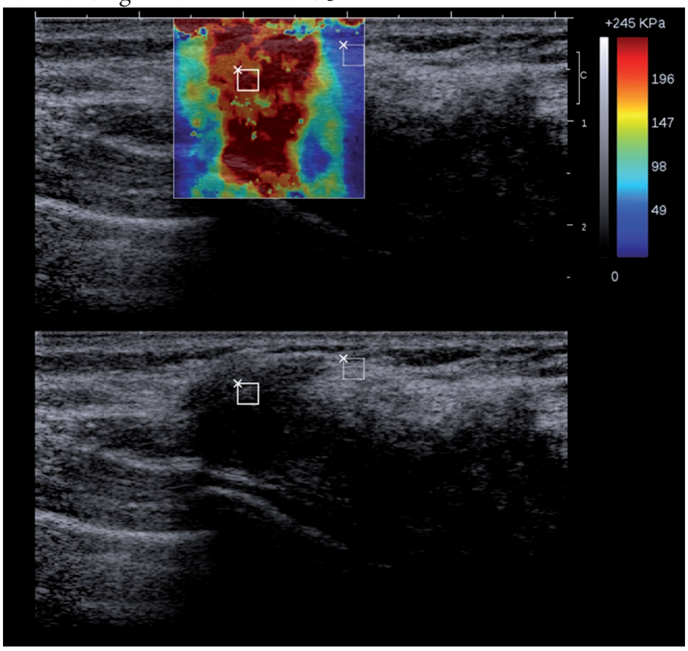


Figure 16 : *Example of a very stiff lesion (> 250 kPa)*

The absence of quantitative elasticity values can also be used as a source of information since shear waves cannot propagate through pure liquids.

Figure 17 shows an example of two small cysts which appear as black voids on the elasticity image, indicating a high probability of liquid content.

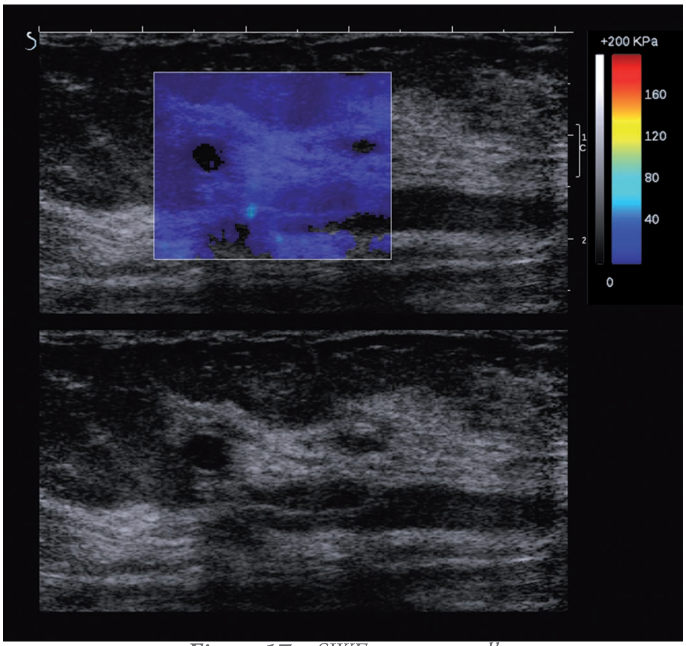


Figure 17 : *SWE on two small cysts.*

A clinical study† was performed on 138 patients using ShearWave™ Elastography in order to evaluate the quantitative findings. Tissue elasticity was compared to the pathology. The results are illustrated in the graphic Figure 18:

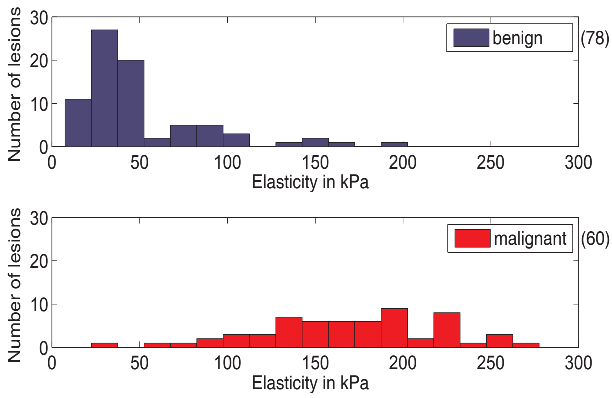


Figure 18 : *Distribution of elasticity as a function of pathology.*

The results of the study show that SWE values in the majority of benign lesions are in the 1-70 kPa range, while values of malignant lesions spread across a wider range from 30 to 270 kPa with a distribution mean around 160 kPa. These results are consistent with other findings published in the literature [1-3].

The quantitative estimation of tissue elasticity offers previously unavailable information that could be incorporated into the diagnostic decision making process.

Local estimation opens new perspective to lesion analysis

The local values of the elasticity measurements is one of the main benefits that ShearWave™ Elastography offers the clinician in comparison to static elastography techniques. The strain induced in tissue by an external static compression is not only operator dependent, but also tissue dependent. Under the same stress, a soft tissue area will be deformed differently depending on the presence and position of an adjacent hard area. In other words, the strain image created by static elastography does not provide an accurate localized representation of tissue elasticity. In contrast, the shear wave propagation speed relates directly to the local elasticity of the tissues. This allows SWE to provide local elasticity measurements with millimetric resolution. The stiffness of very small lesions (a few millimeters in diameter) can be characterized. The elasticity signature of a millimetric lesion is shown in Figure 19.

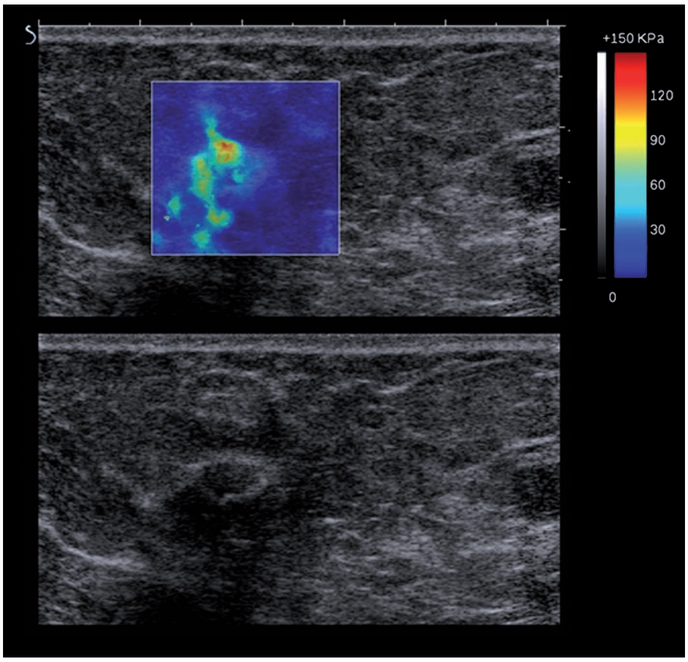


Figure 19 : *Millimetric lesion.*

SWE can help the radiologist to better understand tissue and pathologic morphology. The advantages of a local depiction of elasticity are shown in Figure 20. This lesion, classified as ACR5 using ultrasound BI-RADS® lexicon, shows a hypoechoic center and heterogeneous borders on B-mode ultrasound.

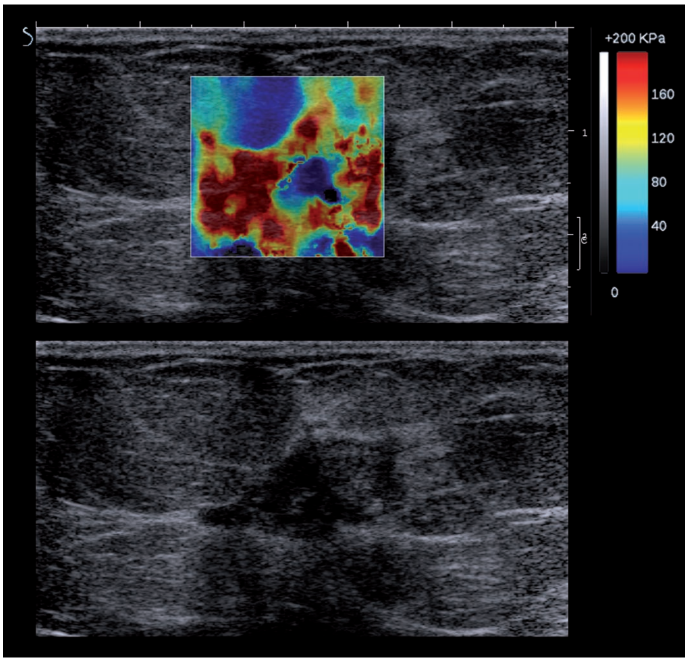


Figure 20 : *Lesion with a complex elasticity pattern on SWE.*

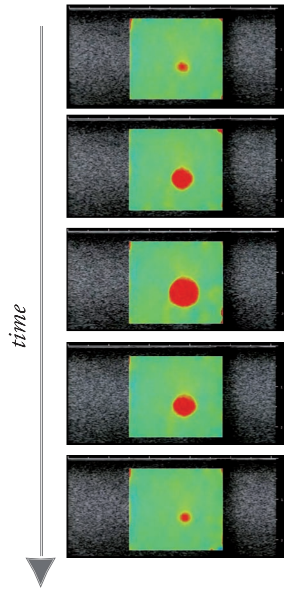
The elasticity image shows a hard shell (of more than 200 kPa, red) that is slightly larger than the lesion on B-mode. The shell is limited above left in the image by a fat island (shown in blue) with obvious ultrasound and elasticity features (soft ~30 kPa). The lesion has a soft center which could not be assessed using static approaches. A biopsy of the center of the lesion showed presence of necrotic cells.

Real-time operation improves scanning workflow

With static elastography systems, tissue strain is displayed in real-time but the elasticity information needs to be extracted by the user using a precise protocol. Typically, a set of real-time strain images is acquired while the radiologist manually vibrates the tissue. The acquired cineloop is then reviewed and one image is chosen as the best representation of the tissue's elastic properties. An indication of the quality of the strain image is usually provided to help the radiologist, but the choice ultimately depends on a subjective analysis of the strain image quality. In contrast, ShearWave™ Elastography is user-skill independent. The elasticity information in the image is updated in real-time and this information can be directly interpreted by radiologists in a straightforward manner, analogous to the workflow in standard ultrasound scanning. Figure 21 shows different sections through a lesion in a phantom acquired during a single real-time sweep.

Figure 21 :

A series of slices through a spherical harder "lesion" acquired in a phantom with real-time SWE.



Conclusion

SuperSonic Imagine's ShearWave™ Elastography is a new ultrasound imaging concept used to determine tissue elasticity.

ShearWave™ Elastography is the result of the exploration of a new type of wave – the shear wave - by a revolutionary new architecture which enables quantification of soft tissue elasticity in real time.

SonicTouch™ technology creates a supersonic vibration source within tissue, allowing efficient and automatic generation of shear waves without increasing the acoustic power delivered by the ultrasound system.

The SonicSoftware™ platform allows acquisition of ultrasound images at ultrafast frame rates (100 to 200 times faster than conventional systems) in order to capture shear wave propagation and measure tissue elasticity in kPa.

Combined, these powerful technologies deliver new capabilities to the clinical arena:

- A quantitative information on human tissue properties through the estimation of elasticity in kPa;
- The ability to visualize the elasticity of small lesions with millimetric resolution;
- Fully automatic generation of shear waves from the ultrasound transducer, allowing user-skill independent and reproducible imaging;
- Real-time scanning, which reduces the complexity and duration of the elastography exam as compared to other elastography ultrasound systems.

References

[1] Sarvazyan, A.P. (2001). Elastic Properties of Soft Tissue. Handbook of Elastic Properties of Solids, Liquids, and Gases. 3: 107-127.

[2] Skovoroda et al., (1995). Quantitative analysis of the mechanical characteristics of pathologically changed soft biological tissues. Biophysics, 40(6)1359-1364.

[3] Duck, F.A. (1990). Physical Properties of Tissue, a Comprehensive Reference Book. Academic Press.

[4] Ophir J, Céspedes I, Ponnekanti H, Yasdi Y, Li X. Elastography: A quantitative method for imaging the elasticity of biological tissues. Ultrason Imaging 1991;13:111–134.

[5] Hall TJ, Zhu Y, Spalding CS. In vivo real-time freehand palpation imaging. Ultrasound Med Biol 2003;29:427– 435.

[6] Locatelli M, Chervesani R, Rizzatto G. Real-time ultrasound Elastography: diagnostic tool or electronic gadget ? Eur Radiol 2005, supplement 1 to Vol 15 (ECR 2005, book of abstracts): abstract B-0255, page 139.

[7] Svensson W.E., Amiras D: Ultrasound elasticity imaging. Breast Cancer Online 2006,9:e24:7pages. Cambridge University Press.

[8] Barr RG. Clinical applications of a real time elastography technique in breast imaging. Proceedings of the 5th International Conference on Ultrasonic Measurement and Imaging of Tissue Elasticity 2006:112.

[9] Ako, Ei Ueno, Eriko, Hiroshi, Hideto, Tsuyoshi, Makoto, Takeshi. Breast Disease: Clinical Application of US Elastography for Diagnosis. Radiology 2006 Radiology; Volume 239.

[10] Tardivon A, El Khoury C, Thibault F, Wyler A, BarreauB, Neuenschwander S. Elastosonography of the breast: Prospective study of 122 lesions. J Radio 2007;88 :657-62.

[11] Muthupillari R, Lomas DJ, Rossman PJ, Greenleaf JF, Manduca A, Ehman RL. Magnetic resonance elastography by direct visualization of propagating acoustic strain wave. Science 1995;269:1854–1856.

[12] Parker KJ, Lerner RM. Sonoelasticity of organs: Shear waves ring a bell. J Ultrasound Med 1992;11:387–392.

[13] Sinkus R, Tanter M, Xydeas T, Catheline S, Bercoff J, Fink M. Viscoelastic shear properties of in vivo breast lesions measured by MR elastography, Magn Res Imag 2002;23(2):159 –165.

[14] Sarvazyan AP, Rudenko OV, Swanson SD, Fowlkes JB, Emelianov SY. Shear wave elasticity imaging:A new ultrasonic technology of medical diagnostic. Ultr. Med Biol 1998;20:1419 –1436.

[15] Nightingale KR, McAleavey SA, Trahey G. E. Shear wave generation using acoustic radiation force: In vivo and ex vivo results. Ultrasound Med Biol 2003;29(2):1715–1723

[16] Bercoff J, Tanter M, Fink M. Supersonic shear imaging: A new technique for soft tissues elasticity mapping. IEEE Trans Ultrason Ferroelectr Freq Control 2004;51(4):396–409.

[17] Tanter M, Bercoff J, Athanasiou A, Deffieux T, Gennisson JL, Montaldo G, Muller M, Tardivon A, Fink M. Quantitative Assessement Of Breast Lesion Viscoelasticity: Initial Clinical Results Using Supersonic Shear Imaging. Ultrasound in Med. & Biol., Vol. 34, No. 9, pp. 1373–1386, 2008.

[18] IEC 60601-2-37: 2001 + Amendment 1: 2004 + Amendment 2: 2005: Medical electrical equipment – Part 2-37: Particular requirements for the safety of ultrasonic medical diagnostic and monitoring equipment.

[19] Madsen EL, Hobson MA, Frank GR, Shi H, Jiang J, Hall TJ, Varghese T, Doyley M M and Weaver JB. Anthropomorphic Breast Phantoms For Testing Elastography Systems. Ultrasound in Med. & Biol., Vol. 32, No. 6, pp. 857–874, 2006.

[20] Bercoff J, Chaffaï S, Tanter M, Sandrin L, Catheline S, Fink M, Gennisson J-L, Meunier M. In vivo breast tumors detection using transient elastography. Ultrasound Med Biol 2003;29(10):1387–1296.

[21] Nightingale KR, Soo MS, Nightingale RW, Trahey GE. Acoustic radiation force impulse imaging: in vivo demonstration of clinical feasibility. Ultrasound Med Biol 2002;28(2):227–235.

[22] Bercoff J, Tanter M, Fink M. Sonic boom in soft materials: The elastic Cerenkov effect. Appl Phys Lett 2004;84(12):2202–2204.

[23] American College of Radiology. Breast Imaging Reporting and Data System (BI-RADS). Ultrasound. 4th ed. Reston, VA: American College of Radiology, 2003.

† AFFSAPS ID RCB : 2007-A00803-50

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