Review Article

Current Trends in Ophthalmology
A Diagnostic Imaging Method – Shear Wave Elastography

Marketa Zemanova*

Department of Ophthalmology, Masaryk University, Brno, Czech Republic

*Correspondence: Markéta Zemanová, Department of Ophthalmology Masaryk University, Brno, Jihlavská 20625 00, Czech Republic, Tel: +420 532 233 002; E-mail: marketa.zemanova@fnbrno.cz

Abstract

Shear Wave Elastography (SWE) is a non-invasive diagnostic imaging technique, that maps the elastic properties of tissues. Nowadays this modality develops increasingly in medicine across its disciplines and opens a new era of high-quality ultrasound examination because it increases the specificity and thus improves diagnostic assurance. This method is similar to manual palpation, shows elastic properties of biological tissues and provides a kind of reconstruction of the internal structure of soft tissues based on measurement of the response of tissue compression.
Results: This method is already used routinely in the detection and diagnosis of breast cancer and thyroid cancer, prostate cancer, in hepatology, cardiology, view of the carotid arteries and lymphatic nodules. Standards of elasticity values for human tissues such as the mammary gland, liver, prostate or thyroid gland are progressively being created across the medical fields. Finally, the article examines its unquestioned benefit in ophthalmology. In ophthalmology, it already appears as an up-and-coming method in diagnostics and in evaluating the changes in oculomotor muscles and orbital tissues in patients with endocrine orbitopathy.
Conclusion: Shear wave elastography offers three main innovations: the quantitative aspect, dimensional resolution, and real-time imaging ability. Determination of the utilization rate of this method and its inclusion into the diagnostics of endocrine orbitopathy is still a question and the subject of presently conducted clinical studies.

Keywords: Ultrasound; Elastography; Young's modulus; Shear-wave; Ophthalmology

Introduction

Ultrasound examination is one of the most wide-spread diagnostic imaging methods across modern medicine. Ultrasonography is still a developing method which underwent an intense advancement in the last century. Due to its non-invasiveness, relatively low acquisition cost, and thereby excellent availability, it became the most frequently used diagnostic imaging method in a number of medical fields. The discovery of ultrasound waves is ascribed to the Italian biologist and physiologist L. Spallanzani who demonstrated in 1794 the ability of bats to orient themselves in the dark using the reflection of high-frequency inaudible sound (so called echolocation) [1]. Of major importance for medicine in the early 1940s was the work of the American scientist F. A. Firestone who stood at the birth of the ultrasonic reflection defectoscope as a technique of a non-destructive proof of material defects used in the industry. The first ultrasound diagnostic devices developed in 1950s based on the findings of the industrial defectoscopy field used the historically oldest A-scan. They started to be employed especially in ophthalmology and neurology [1-3]. In 1942, the Viennese neurologist and psychiatrist K. T. Dussik published his findings on the possibility of using ultrasound to diagnose brain tumours, as well as the first results of using high-frequency mechanical vibrations as a diagnostic tool [4,5]. The above-mentioned method

was put into medical practice by the doctors G. D. Ludwig and F. W. Struthers who were the first to publish a study mentioning ultrasound reflected from foreign objects and bile stones in the human body [6]. By the end of 1950s, the first diagnostic devices using the two-dimensional B-scan were produced. Along with the reflection method, another method was gradually being developed based on the Doppler effect for the detection of tissue motion and measurement of the blood flow rate. This effect was first described in 1842 by the Austrian physicist Ch. A. Doppler [7]. A symbolic conclusion of this phase is the work of F. E. Barber et al. published in 1974 which defines a duplex system joining the advantages of both ultrasound modules, i.e. the two-dimensional B-scan, and the measuring of the Doppler signal from the flowing blood [8]. Crucial research and developments of ultrasound diagnostic devices were conducted mainly in Great Britain, Australia, Germany, and the USA; since 1970s also in Japan.The use of ultrasound in ophthalmology was first reported in 1956 by Hughes and Mundt who showed among other things the exceptional diagnostic contribution of A-scan for intraocular tumours [9]. The two-dimensional real-time B-scan and the immersion scan technique were employed in ophthalmology by Baum and Greenwood in the late 1950s [1,3]. In 1972, Bronson implemented a contact examination method, thereby allowing a wider use of the B-scan in ophthalmology. The scan of the anterior segment of the eye originated in 1990s by the implementation of a high-frequency ultrasound biomicroscope, allowing *in vivo* observation of the structures of the anterior eye chamber [1,3]. In Czech Republic, the study of ultrasound has had a long tradition. The first research studies were published in the early 1940s by important doctors and scientists from Brno (Herčík, Šprindrich, Hrdlička) [10]. The technical and biological effects of ultrasound are reported in Czech literature by Šimonová-Čeřovská [11]. The tradition of the biophysical study of the effects of ultrasound was then assumed by the Department of Biophysics of the Faculty of Medicine of the Masaryk University in Brno. There were the best results achieved by a team led by Professor Hrazdira. In the field of ophthalmology, we must not leave out Professor Vanýsek who in 1955 pointed out the possibility of detecting foreign intraocular objects using high-frequency ultrasound, and his close collaborator and assistant Preis. They created a number of Czech as well as foreign publications together [12,13]. The history of elastographydates back to the early 1980s, the name of the method was coined in 1991 by Ophir et al. [1,3].

Review

Ultrasound is the mechanical (acoustic) wave motion or vibration of particles of the environment around a balanced resting position. This wave spreads within an elastic environment at a frequency exceeding the upper limit of human ear's audibility, i.e. at a frequency exceeding 20 kHz (kilohertz), while the area of audible sound ranges within 20 Hz–20 kHz (Hz = 1 vibration/s). For diagnostic purposes, frequencies around 2–40 MHz (megahertz) are used; in ophthalmology it is 8–20 MHz. Ultrasound vibrations spread through tissues in the form of predominantly longitudinal waves (in soft tissues and fluids), less frequently in the form of transversal waves (e.g., in bones). The sources of ultrasound vibrations are electrically stimulated piezoelectric transformers. The basis for ultrasound examination is the principle of reflection of ultrasound waves at the interface of environments with different acoustic impedances. Every environment is characterized by basic parameters such as the rate of ultrasound spread (so called phase rate, dependent on the ultrasound wave frequency), acoustic impedance, attenuation, and echo. Acoustic impedance of the environment is calculated as the product of environmental density and the phase rate of ultrasound spread. The amount of acoustic energy reflected at the acoustic interface is the function of the difference of acoustic impedances of the tissues at this borderline. We distinguish between two main types of ultrasound scans in practice. The A-scan (Amplitude modulated – reflections modulating the amplitude of divergences) means a one-dimensional, linear method of imaging in the direction of the sent ultrasound waves. Impulses from individual tissue interfaces are registered on the screen as vertical divergences, so called echoes. The time base marks the time of the passing of the impulse; the distance of divergences corresponds with the proportion of real distances of individual tissue interfaces and the place of reflection; the amplitude corresponds with the amount of energy reflected. It is the simplest type of ultrasound imaging used in ophthalmology mainly for measuring the biometrical values of the eye globe. The B-scan (Brightness – captured reflections modulate the brightness of the track on screen) is a two-dimensional scan that can be divided into 3 types: The older, so call static B-scan (the scan was created very slowly by manually shifting and tilting the probe consisting of one transformer) which failed to capture moving structures or the inner structure of tissues or organs. The M-scan (originally TM-scan, using also the A-scan to capture moving structures such as the so called floating echoes) and the presently exclusively used dynamic B-scan during
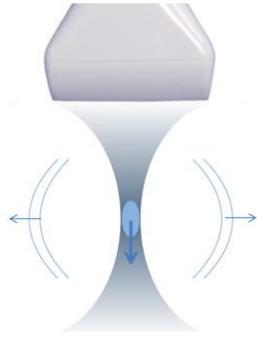
Figure 1: Propagation of shear waves [16].

Sound pressure is induced in ultrasonic beam and excites tissues lying beneath him, called acoustic vortex. The human tissue responds to this action by resistive force which induced mechanical waves and transverse waves (shear waves), which are propagated in tissue transversely.
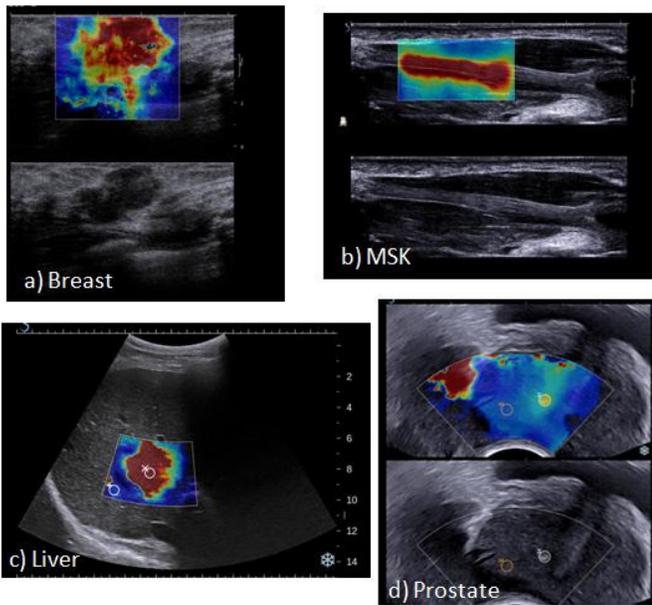

Figure 2: SWE image of selected tissues [16].

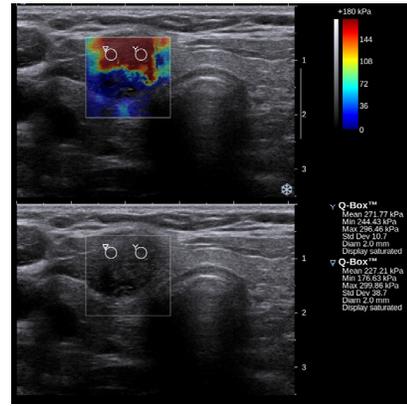SWE image a) breast, b) musculoskeletal system, c) liver, d) prostate

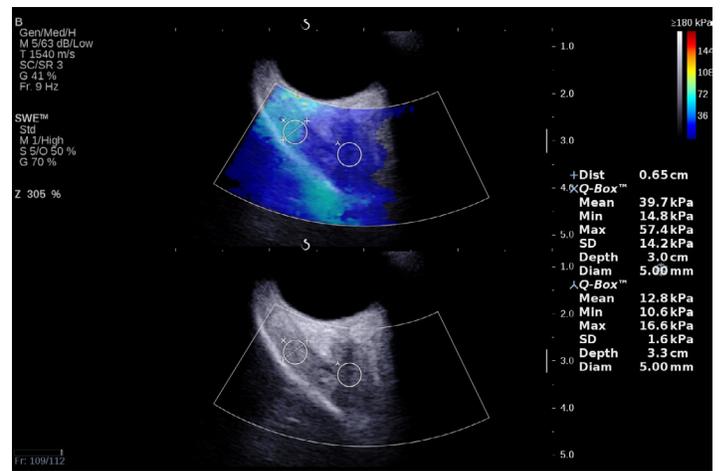**Figure 3:** SWE image – color code map, values of elasticity [20].

Figure 4: SWE image of extraocular muscles in orbitopathy [16].
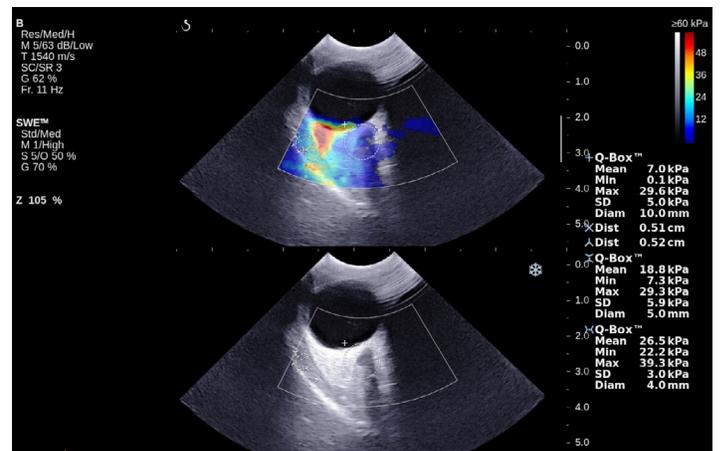

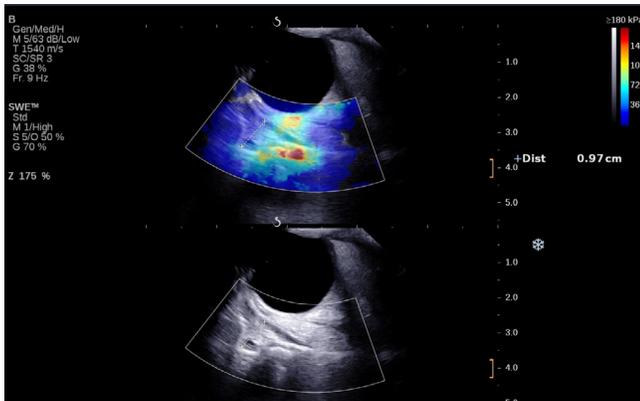**Figure 5:** SWE image of extraocular muscles of healthy population.

Figure 6: SWE image of orbital pseudotumor.

which a sequential series of images is created of the examined region, including the monitoring of movement. Due to a quick scanning of the reflections and a wide scale of grey, the dynamic scan provides basic information on the reflectance of individual tissue structures [2,14].

Elastography represents an imaging modality using the advantages of ultrasound to find differences in the mechanical elasticity of tissues. This non-invasive diagnostic method substitutes the traditional examination by palpation necessary and used as standard in the clinical physical examination of the patient. Palpation helps in the diagnosing and screening of pathologies and qualitatively determines tissue elasticity, however, it has its limitations as it is not always easily feasible when lesions are inaccessible due to their deep position or small size. Tissue ultrasound elastography analyses tissue elasticity by generating low-frequency vibrations that stimulate strain in tissues, which is subsequently analysed. Elastography studies the response of the tissues to the action of force [15,16].

Shear wave elastography (SWE) is an ultrasound concept that images the elastic properties of tissues, increasing the specificity of ultrasound examination, and thereby improving diagnostic certainty. This method is independent of the subjective abilities of the examiner and presents a quantitative evaluation (as opposed to the qualitative evaluation during palpation). This method is based on an automated generation of transient shear waves and relies on the fact that a change in the mechanical properties of tissue (especially the change in elasticity) frequently reflects pathological processes.

Tissue elasticity can be most easily described by Hooke's law where the constant of proportionality is the physical quantity called Young's modulusof elasticity (E) given in units of pressure (kiloPascal – kPa). Young's modulus of elasticity is defined as the ratio between compression (= deformation stress, outer homogeneous compression – S) and the induced strain (= deformation of the solid – e): $E = S/e$ [kPa]. The higher the Young's modulus of elasticity, the more rigid the tissue, and vice versa. Shear waves or in other words, transverse waves are mechanically provoked after compression of tissue. They spread through tissues in the transverse direction by creating tangential gliding forces between individual tissue layers at a rate of 1–10 m/s. That means that they are much slower than the pressure (so called bulk) waves which are the basis of standard ultrasound scan and spread very quickly (at a rate of approx. 1500 m/s) by gradually compressing tissue layers. Shear waves are the response of the elastic resistance of tissue to the mechanical vibrations with low frequency (50–200 Hz). If we can measure the spreading rate (c) of the shear wave while knowing that the tissue density (ϱ) is constant, we can directly express tissue elasticity (E) according to the formula: $E = 3\varrho c^2$. The presence of shear waves is therefore connected with the elasticity of the given environment. Fluid has no elasticity but in the solid and firm environment, shear waves spread very well. Thus, if the environment is elastic, we can calculate the spreading rate of the shear wave. Tissue elasticity varies due to pathological processes; malignant foci mostly show greater rigidity (30–270 kPa) compared to benign foci (1–70 kPa) or healthy tissue. Meanwhile, tissue density (ϱ) in the human body is relatively constant, close to the density of water (1000 kg/m³) [15-17].

Classification of elastography: Static (compressive) elastography uses the homogeneous compression of the surface of the body (compression is conducted by the examiner), provoking deformation of tissue which then shows itself on the scanned plane. Young's modulus of elasticity cannot be used here because we do not know the strain in tissue. It does not provide quantitative information, is very dependent on the abilities of the examiner, and is hardly reproducible. Dynamicelastography is the basis of magnetic resonance imaging (MRI) and uses coupled vibrations. For the expression of elasticity, stagnant waves induced in the body are analysed. The scanned region, however, is not in real time. Elastography based on shear waves uses transitional pulses that generate shear waves in the body. Tissue elasticity is directly expressed here by measuring the spreading rate of the wave. It provides

Table 1: Elasticity of selected human tissues.

Type of tissue		E (kPa)	ϱ (kg/m³)
breast	fat	18-24	1000 ± 8% (water)
	normal gland	28-66	
	cyst	0-53	
	fibroadenoma	96-244	
	carcinoma	22-560	
prostate	anterior part	55-63	
	posterior part	62-71	
	benign hyperplasia	36-41	
	carcinoma	96-241	
	infammation	20-27	
thyroid gland	parenchyma	5-40	
	thyreoiditis	15-55	
	follicular carcinoma	6-59	
	carcinoma	7-202	
kidney	fibrosis	10-55	
liver	normal liver tissue	0,4-6,0	
	cirhosis	15-100	
tendon		800	
artery		700-3000	
cartilage		790	
enamel		20000000-84000000	

Table 2: Color code map.

Color code map blue encodes under standard conditions	shear vawes propagate	solid tissues liquid with detritus
Black color or shades of gray	any shear waves do not propagate	liquid
	very weak shear waves	very thin solid tissues
	very fast propagation of shear waves	very hard (rigid) solid tissues

Table 3: Elasticity of thyroid gland.

Elasticity of thyroid gland pathology (kPa)		
	Study ECR 2011 (France)	Study endocrinol. 2010
Normal thyroid tissue	31 ± 12	15.9 ± 7.6
Benign thyroid nodules	34 ± 17	36.0 ± 30.0
Malignant thyroid nodules	114 ± 61	150.0 ± 95.0

quantitative and local information on tissue elasticity in real time [15-17]. First generation ("manual strain-stress") elastographyuses the rhythmic pressure of the probe manually, when compression and release of tissue is exerted by the examiner upon the tissue of the examined person. It determines tissue elasticity based on the difference of the ultrasound signal before and after compression, compares the scans in sequence (or their particular pixels), and in the selected region of interest (ROI) mutual distances of these scans are calculated. Subsequent colour coding displays qualitative information on elasticity. The method depends on the skilfulness and experience of the examiner and is not quantitative or well reproducible. The second generation is more sensitive than first generation. It uses rhythmic tissue compression induced by the own body of the examined person (breath excursions, heart movement). The following signal processing is identical to that of the first generation. The evaluation of tissue elasticity is, however, poorly reproducible. It is suitable for evaluating formations in the breasts, the thyroid gland, etc. The third generation uses the method of Acoustic Radiation Forced Impulse Elastography (ARFI). It presents two techniques of use. The first technique of ARFI is the Virtual Touch Tissue Imaging using again the manual type of imaging. Deformation is induced automatically by a high-performance acoustic impulse of the electronic probe, not manually. The ARFI is used predominantly for examinations of the liver and deeper-seated soft tissues. The result is a qualitative evaluation of the relative elasticity of the tissue in the ROI on a greyscale (light regions = soft tissue, dark regions = more rigid tissue). The other technique of ARFI is the Virtual Touch Quantification – shear wave elastography where a strong acoustic impulse induces the spread of the shear wave through a very small selected ROI. The examiner initializes standard (longitudinal, axial) ultrasound measuring of the shear wave rate in m/s, the value of which will appear in m/s on the display. The value is quantitatively proportional to the average tissue elasticity in this ROI. It is not a dynamic mode but rather individual static measurements. An elasticity map is not created. The fourth, dynamic generation, real time Shear Wave Elastography (SWE) has been patented at the MultiWavesonograph-elastographAixplorer (SuperSonic Imagine, France). Standard wide-band probe is the source of vibrations, generating pulses of acoustic pressure created by a focused ultrasound ray that are focused into various depths of tissue at a supersonic speed. The acoustic pressure (so called acoustic vortex) induced in the ultrasound bundle arouses the tissues lying below and acts on the tissue in the direction of spread. However, the

tissue resists this pressure (regenerating force) and the pressure further induces mechanical waves and shear waves that spread in the given tissue transversely (Figure 1). These shear waves are, however, very weak, and their attenuation is noticeable already after several millimetres of spread. The SonicTouch™ technology eliminates this undesirable effect as it is based on the principle of the excitation phenomenon due to the gradual focusing of ultrasound bundles into various depths of the tissue. It enhances (coherently sums) the shear waves into the form of the so called Mach cone, thereby increasing the amplitude of the shear waves and the distance of their spread, while concurrently minimizing the acoustic performance to a safe level. More focus zones of the ray allow inducing the formation of shear waves in more depths. Shear waves spread in tissues at a rate of 1–10 m/s (corresponding to elasticity of 1–300 kPa) which implies that they pass through the 3–6 cm wide plane scanned by ultrasound within 12–20 ms. In this way, however, the shear waves would disappear during the time needed for creating one scan, without being captured by the system. For this reason, scanning frequencies of several thousands of scans per second are necessary for the correct capture of shear waves. In the Aixplorer device, these ultrafast scanning frequencies are called Ultrafast™ imaging which sends in one sole moment flat ultrasonic waves into the tissue to arouse the whole scanned plane. The maximum scanning frequency is then affected by the time in which the ultrasonic wave covers the course from the probe into the tissue and back (e.g., for a typical mammography scan of a depth of 4 cm, the maximum achievable frequency is 20 kHz). This very high pulse repetition frequency (PRF) works in dependence on the depth and speed of ultrasound, and depends on the tissue type. Thanks to the Ultrafast™ imagingwe are able to observe in detail the spreading of the shear waves through the scanned plane as they induce small shifts of the tissue that are recorded and quantified similarly as with the Doppler scan. The spreading rate of the shear waves depends on tissue elasticity. It scans shear waves in the whole ROI, quantitatively displays the resulting map of the rates, and a scan of tissue elasticity in kPa, which renews itself continually in real time. The rate of data processing is very high (several Gbyte/s). The technique is conducted by using conventional linear, convex or rather intracavitary probes [15-18].

The output of the SWE examination is the B-mode ultrasound image covered by a color-coded map. The resulting elasticity map shows us the real shifting of individual tissue structures based on their mechanical

properties. The color-coding of the image (Table 1) is on the scale of red to blue, where the more rigid tissues are depicted by warm shades (in red, yellow) and the softer tissues by cold colours (in blue, violet). In colour maps, blue colour is the standard measure and is used to depict soft solid tissue or viscose fluid in cysts. Red and yellow depict rigid tissue (malignancy). Black-outs or various shades of grey mean a loss of shear wave signal and they mark clear fluid e.g. in a cyst (shear waves do not spread there) or rigid tissue (shear waves are very weak, they are attenuated or quickly propagated into the environment). The resolving power of the image is around 1 mm. For each measurement, it is necessary to wait around 3 seconds for the SWE image to stabilize (Figures 2 and 3) and only then is it possible to freeze and evaluate the scan [15-18].

Discussion

Elasticity values of certain human tissues were evaluated using calibrated phantoms with different elasticity or with the results of other clinical studies (Table 2). There are standards of elasticity values for human tissues such as the mammary gland, liver, prostate or thyroid. The main studies from the years 2011 and 2012 providing basic data on human tissue elasticity that became ground breaking, were reports from hepatology [19], urology [20], and mammary oncology [21].

It has been shown by studies in the area of mammography that SWE images are frequently better than the mere B-scan modulus. SWE improves the identifiability of pathological lesions, resulting in better examination specificity and reduction of the number of needless biopsies. From the conducted studies we have learned that when deciding on an indication for biopsy of a suspect focus in the mammary tissue, we can be aided by the so called maximum value of measured elasticity. If the value is lower or equal to 80 kPa (Emax ≤ 80 kPa), it is unlikely that the tumour is malignant, and we should consider biopsy more carefully. In contrast, with values of Emax ≥ 160 kPa, biopsy should have already been done, and the diagnostic procedure should correlate with the finding [21].

In hepatology, SWE serves to monitor the degree of liver cirrhosis, to schedule patients awaiting liver transplantation as well as to evaluate the condition of the transplanted organ. SWE provides real-time quantitative mapping of liver elasticity along with the real-time B-mode, thereby improving the assessment of stages of fibrosis (F0-F1, F2-F4). For the differentiation of the stage

of fibrosis we already know that grade F2 (significant fibrosis) has an elasticity value of up to 7.1 kPa; stage F3 (advanced fibrosis) of up to 8.7 kPa; and stage F4 (cirrhosis) of 10.4 kPa, while the sensitivity and specificity of SWE examination is higher than 90% [19].

In the field of urology, SWE holds a primary position in the early detection and excellent characterization of prostate nodules. According to a study conducted in 2013 by Barr on a total of 53 patients, malignant foci were detected in 11 patients that were subsequently confirmed by biopsy. Thanks to this study, elasticity values were established ranging from inflammatory regions to benign hyperplasia to malignant foci, in the sense of carcinomas. Thus, SWE could become the first line screening method for the prostate carcinoma [20].

In endocrinology, SWE helps to determine the precise diagnosis when a nodule is found in the thyroid gland. From the studies available we already know that malignant nodules of the thyroid gland have greater rigidity than benign affections. The rigidity in the case of a malignant nodule is significantly increased compared to normal parenchyma or benign nodules. Normal thyreoideal tissue has elasticity values of 31 ± 12 kPa, whereas malignant nodules show a four- to five-fold increase in elasticity (Table 3). So far it regards only a small group of patients, opening up new possibilities of using SWE in clinical practice [22].

In ophthalmology at present, studies are conducted that might in the future substitute in some cases the imaging diagnostic methods that are economically costly and burdening for the patient. SWE already seems to be a promising method in the diagnostics and assessment of changes in the oculomotor muscles and orbital tissue in patients with endocrine orbitopathy (Figure 4) in comparison with healthy population (Figure 5). The elastic properties of the outer oculomotor muscles in patients with endocrineorbitopathy (EO) are changed e.g. due to the fibrotic changes resulting from the disease. The tissue thus becomes more rigid (in the colour map it is depicted by warm shades) which is evidenced by findings in the first examined patients. As this method has been so far only modestly clinically tested, we can assume that the change in elasticity of the outer ocular muscles is correlated with the activity of this chronic disease. Upon a sufficiently large and representative group of patients with EO we will be able to determine the utilization rate of this method and its inclusion into the diagnostics of endocrine orbitopathy. We also assume that SWE may

help in diagnostics intraocular and intraorbitaltumours (Figure 6).

In literature [23] data can be found reported by authorscomparing ultrasound scans of horizontal oculomotor muscles (m. rectus lateralis, m. rectus medialis) and their different elasticity in the primary position and in the adduction or abduction. Another possibility of using the excellent properties of SWE might be the issue of differential diagnostics of myositis and other orbital affections [23].

A team of French researchers have published a study [24] documenting changes in the mechanical properties of the cornea following the corneal cross-linking (CXL) stabilization intervention. The study deals with the effect of the thickness and elasticity of the cornea on the measurement and correlation of intraocular pressure, and describes the effort to understand the ectatic diseases of the cornea such as keratoconus and others. In an ex vivo study on freshly enucleated pig eyes it was found using conventional 15 MHz linear probe that the cornea has almost homogeneous elasticity on the average of 190 ± 32 kPa. Following the stabilization treatment by CXL, cornea elasticity was significantly changed and the Young's modulus of elasticity increased in the anterior parts of the cornea – i.e. exactly where the intervention is done – to the average values of 890 ± 250 kPa (which means a 460% increase). Thus, this technique might have good prospects in these issues [24,25].

Shear wave™ elastography is the result of the research of shear waves, providing quantitative information on elasticity of human tissues scanned in real time. SWE is able to locate and image small lesion elasticity very quickly with a millimetre resolution. It provides reproducible imaging independent of the examiner thanks to the fully automated and effective generating of shear waves from the ultrasound probe using the SonicTouch™ technology without increasing the acoustic performance. The image is created by a combination of radial pressure induced in the tissue by the ultrasound bundle and the ultrafast scanning of the sequence capable of capturing in real time the spread of the induced shear waves. The SonicSoftware™ platform allows the acquisition of ultrasound images at ultrafast scanning frequencies (100 to 200 times faster than when using conventional systems) for capturing the spread of shear waves and for measuring tissue elasticity in kPa. SWE reduces the complexity and duration of the examination and offers the possibility of comparison and easy analysis of the images. The clinical benefits of SWE include very high reproducibility due to the acquisition of SWE maps, high reliability of measurement of the size and elasticity of lesions, and generally high sensitivity as well as specificity in comparison with conventional ultrasound examinations. SWE brings new and still not thoroughly researched possibilities into clinical practice. A disadvantage of SWE is especially its higher technological demand and a higher acquisition cost of the equipment [15-18].

Conclusion

Shear wave elastography is a non-invasive diagnostic imaging method that maps the elastic properties of tissues and offers three main innovations: the quantitative aspect, dimensional resolution, and real-time imaging ability. The output of the examination is the B-mode ultrasound image covered by a colour-coded map. In ophthalmology, it already appears as an up-and-coming method in diagnostics and in evaluating the changes in oculomotor muscles and orbital tissues in patients with endocrine orbitopathy. Determination of the utilization rate of this method and its inclusion into the diagnostic algorithm is still a question and the subject of presently conducted clinical studies.

Ethical Statements

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1964 and later versions.Informed consent was obtained from all patients for being included in the study.

Conflict of Interest

Marketa Zemanova declares that she has no conflict of interest.

References

1. Tsung J (2011) History of Ultrasound and Technological Advances. New York, USA.

2. Hrazdira I (2008) Introduction to Ultrasonography in Questions and Answers for Students. Brno: Klinikkazobrazovacích metodod LF MU, Fakultní nemocnice u Sv. Anne in Brno.

3. Mornstein V, Pospíšilová J (1995) Ultrasound - itshistoryworld and with us. Doctor and technician. Prague: CzMA JEP.

4. Dussik KT (1942) On the possibility of using ultrasound

waves as a diagnostic aid. Neurol Psychiat 174: 153-168.

5. Dussik KT (1942) Use the possibility of high frequency mechanical vibration as a diagnostic tool. Neurol Psychiat 174: 153.

6. Ludwig GD, Struthers FW (1950) Detecting gallstones with ultrasonic echoes. Electronics 23: 172-178.

7. Doppler Ch (1988) Life and work, the Doppler effect. Salzburg: Office d. Salzburger Landesregierung, state press office.

8. Barber FE, Baker DW, Nation AWC, Strandness DE, Reid JM (1974) Ultrasonic Duplex Echo-Doppler Scanner. IEEE Trans on Biomedical Engineering 21: 109-113.

9. MUNDT GH, HUGHES WF (1956) Ultrasonics in ocular diagnosis. Am J Ophthalmol 41: 488-498.

10. Hercik F, Hrdlicka M, Šprindrich J (1942) Biological effect of sonication. Sborníklíkařský 68: 15-23.

11. Šimonová-Čeřovská J (1941) Ultrasound and practice in practice. Praha: Elektrotechnický spojovoskomoravský 141.

12. Vanýsek J, Preisová J, Obraz J (1969) Ultrasonography in Ophthalmology. London, England: Butterworths.

13. Vanýsek J, Preisová J, Paul M (1969). Ultrasonic image of the anterior eye segment by TAU and SIMU. Ophthalmic Ultrasound. 213-217.

14. Biofyzikálníústav LF MU (2013) Ultrazvukovádiagnostika. Projekt FRVŠ 911: 58.

15. Bercoff J, Tanter M, Fink M (2004) Supersonic shear imaging: A new technique for soft tissues elasticity mapping. IEEE Trans. Ultrason Ferroelecr 51: 396-409.

16. Medata Supersonic Imagine TheTheragnostic Company™. Teoretickézáklady a principyShearWave™ Elastografie.

17. Bercoff J (2008) ShearWave™ Elastography. SuperSonic Imagine The Theragnostic Company™.

18. Bercoff J (2011) Ultrafast Ultrasound Imaging, Ultrasound Imaging – Medical Applications. 10: 5772-19729.

19. Ferraioli G, Tinelli C, Dal Bello B, Zicchetti M, Filice G, et al. (2012) Accuracy of real-time shear wave elastography in the assessment of liver fibrosis in chronic hepatitis C: A pilot study. Hepatology 56: 2125-2133.

20. Bercoff J, Tanter M, Fink M (2004) Supersonic shear imaging: A new technique for soft tissues elasticity mapping. IEEE Trans Ultrason Ferroelecr Freq Control 51: 396-409.

21. Kim H, Youk JH, Gweon HM, Kim JA and Son EJ (2013) Diagnostic performance of qualitative shear-wave elastography according to different color map opacities for breast masses. Eur J Radiol 82: 326-331.

22. Sebag F, Vaillant-Lombard J, Berbis J, Griset V, Henry JF, et al. (2010) Shear Wave Elastography: A New Ultrasound Imaging Mode for the Differential Diagnosis of Benign and Malignant Thyroid Nodules. J Clin Endocrinol Metab 95: 5281-5288.

23. Detorakis ET, Drakonaki EE, Tsilimbaris MK, Pallikaris IG, Giarmenitis S (2010) Real-time ultrasound elastographic imaging of ocular and periocular tissues: a feasibility study. Ophthalmic Surg Lasers Imaging 41: 135-141.

24. Tanter M, Touboul D, Gennisson JL, Bercoff J, Fink M (2009) High-resolution quantitative imaging of cornea elasticity using supersonic shear imaging. IEEE Trans Med Imaging 28: 1881-1893.

25. Nguyen TM, Aubry JF, Touboul D, Fink M, Gennisson JL, et al. (2012) Monitoring of Cornea Elastic Properties Changes during UV-A/Riboflavin-Induced Corneal Collagen Cross-Linking using Supersonic Shear Wave Imaging: A Pilot Study Monitoring of Corneae Elastic Property Changes. Invest Ophthalmol Vis Sci 53: 5948-5954.