Doppler Technologies and Ultrasound Elastography

2

Riccardo Sartoris and Alessandro Muda

2.1 Doppler Imaging

Doppler imaging is an established ultrasonographic method employed for the accurate non-invasive evaluation of the blood flow. As the name implies, US Doppler technique uses the *Doppler effect* to assess how blood flows through the major blood vessels.

Focus On

The *Doppler effect* is based on an essential principle: the sound frequency of a target changes as the target travels towards or away from a point of reference. Since the blood red cells can be considered moving targets, this effect is used to obtain information about the blood flow. In particular, when the US beam, produced by the probe, is transmitted into a vessel, the frequency of the received wave is different from that of the transmitted wave because the source (red cells) moves relative to the given receiver (probe). The change of frequency detected between the transmitted and the received US frequency is named "Doppler shift". The received US frequency would be higher if the direction is towards the receiver, lower if the direction is opposite.

The equation which describes this phenomenon is as follows:

$$\mathrm{Dn} = 2vf \cos\ q/c$$

- Dn: Doppler shift
- v: velocity of the blood (red cells)
- f: frequency of the incident wave
- q: angle between the direction of the movement and the direction of the US beam
- c: acoustic velocity

This equation allows the measurement of an important parameter, the velocity of the blood flow.

The Doppler shift of the moving blood red cells is continuously monitored to produce the Doppler signal; it is in the audible range and can thus be heard. The resulting sound is distinct and provides feedback to the operator.

US Doppler imaging allows to perform the following:

- *Qualitative analysis:* evaluating the presence, site and direction of the blood flow

R. Sartoris
Dipartimento di Radiologia,
Università degli studi di Genova, Genoa, Italy
e-mail: riccardo.sartoris@hotmail.it

A. Muda (✉)
Dipartimento di Radiologia,
IRCCS Ospedale San Martino IST, Genoa, Italy
e-mail: alessandro.muda@tiscali.it

E. Silvestri et al., *Ultrasound Anatomy of Lower Limb Muscles: A Practical Guide*,
DOI 10.1007/978-3-319-09480-9_2, © Springer International Publishing Switzerland 2015

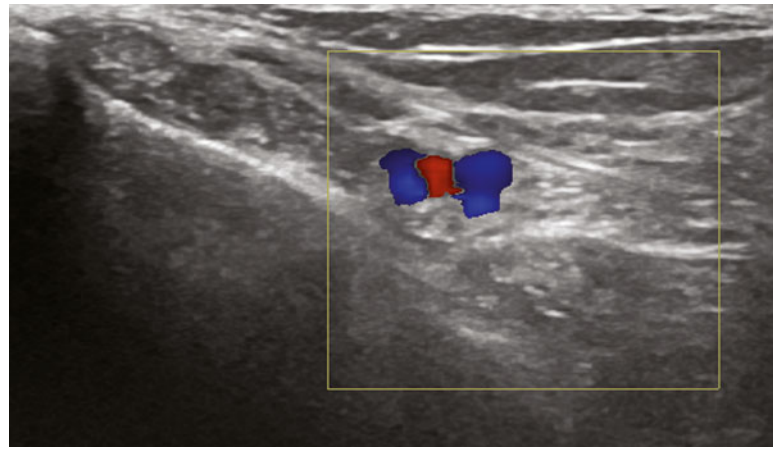

Fig. 2.1 Colour Doppler imaging shows the posterior tibial artery (*red*) and veins (*blue*) at the level of the medial malleolus. Especially in imaging soft tissues, identifying neurovascular bundles with US colour Doppler technique can be very useful to correctly localize tendinous and muscular structures

- *Quantitative analysis:* evaluating flow velocity and flow rate
- *Semiquantitative analysis:* evaluating the spectrum of the waves frequencies

Four main systems are developed to measure the velocity of the blood flow: continuous-wave Doppler, pulsed-wave Doppler, colour Doppler and power Doppler.

Continuous-Wave Doppler (CW-Doppler): It uses two separate crystals: one to emit and one to receive US beams continuously. This infinite pulse repetition rate allows insufficient time for the first pulse to return to the probe before the next is emitted. Consequently, the US machine cannot determine which sound pulse was frequency shifted and, therefore, cannot precisely define the location of the moving target. In conclusion, this technique enables the measurement of high-velocity blood flow, but the depth from which the returning echoes originate cannot be evaluated.

Pulsed-Wave Doppler (PW-Doppler): It uses the same crystal to emit and receive signals. The probe produces US beams in pulses, alternating the transmission and reception of the US beam. One important advantage of pulsed Doppler systems is their ability to provide Doppler shift data selectively from a small segment along the US beam, referred to as the "sample volume". The position of the sample volume is decided by the operator. When the US beam is transmitted into tissues, it travels for a given time until it is reflected by a moving red cell; then, it returns to the probe over the same time interval but at a shifted frequency. Calculating the total transit time, the US machine is able to measure the distance of the sample volume ("reflector"). In respect to the CW-Doppler, PW-Doppler is able to evaluate the depth from which the returning echoes originate, displaying an ultrasound image and waveform; however, it cannot correctly depict higher velocities (blood flow velocity measurements are limited to the physiologic range, usually around 1.5 m/s).

Aliasing phenomena are an artefact that happens with PW-Doppler when the blood flow velocity is too high and causes an error in frequency measurement. When the interval of the US pulses, expressed by the US machine as pulse repetition frequency (PRF, number of pulses within 1 s), is too long relative to the velocity of the blood flow, it will not be possible to determine the direction of blood flow. In particular, aliasing occurs when the velocity is more than one half of the PRF; in this case velocities above, this limit will be displayed on the tracing opposite to the true direction of blood flow. To correct for aliasing, the operator can increase the PRF or increase the angle between the US beam and the flow direction towards perpendicularity.

Colour Doppler: It is an ultrasound system in which the energy of the returning echoes is displayed as an assigned colour; by convention, echoes representing flow towards the probe are seen as shades of red, and the US machine displays coloured blood flow superimposed on a greyscale image, thus allowing simultaneous visualization of anatomy and flow dynamics (Fig. 2.1).

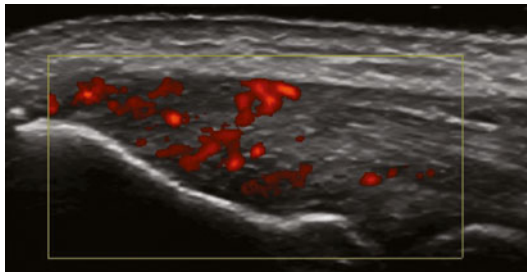

Fig. 2.2 Power Doppler imaging demonstrates the presence of tendinous hyperaemia

To optimize the colour Doppler evaluation, it is crucial to set the US beam at an optimal angulation <60° in respect to the vessel, basing on the physical Doppler equation (cos 90° = 0).

Power Doppler: It is a type of colour Doppler, more sensitive to blood flow compared with conventional colour Doppler; it shows small vessels and slow flow rates, indeed it is most commonly used to evaluate blood flow through vessels within solid organs. Power Doppler assigns a colour to blood flow regardless of direction (Fig. 2.2).

As the main interest is in detecting low-velocity microvascular flow in soft tissue imaging, power Doppler is generally preferred to colour Doppler, and although on new ultrasound machines, the difference is often negligible.

Power Doppler is extremely sensitive to the movement of the probe, which produces a flash artefact. It is important to optimally adjust the colour gain for Doppler imaging to avoid artefact if the setting is too sensitive and for false-negative flow if sensitivity is too low. Power-Doppler should be optimized while the probe is not in contact with patient's skin. The gain should be set at maximum level and then decreased up to the disappearance of all artefact. Further, it is important to set low wall filters (WF) and pulse repetition frequency (PRF) between 700 and 1,000 Hz in order to better evaluate low-velocity blood flows.

Combining with greyscale ultrasound, colour and power Doppler imaging allow unique real-time evaluation of the regional blood flow, enabling a wide range of applications for the evaluation of soft tissues. At first, these systems can be used to confirm that an anechoic structure is a blood vessel and to confirm the presence of the blood flow. Often blood vessels are used in musculoskeletal imaging as anatomical landmarks.

Increased blood flow on colour or power Doppler imaging may occur with greater perfusion, inflammation and neo-vascularity. For example, increased muscle perfusion can be physiologically seen after physical exercise.

Colour and power Doppler are very helpful in detecting inflammatory diseases. They also enable the differentiation between complex fluids and a mass or synovitis; the former typically has no internal flow, and the latter may show increased flow. After treatment for inflammatory diseases, such as arthritis, colour and power Doppler imaging can show interval decrease in flow, which would indicate a positive response.

When a mass is identified, increased blood flow may suggest neo-vascularity, possibly related to malignancy. Although the finding is nonspecific, a neoplasm without flow is more likely to be benign, and malignant tumours usually demonstrate increased flow and irregular vessels.

Colour and power Doppler findings represent a useful tool also for the quick assessment of vascular anomalies and post-traumatic vascular lesions.

It is also important to use colour Doppler imaging during a biopsy to ensure that major vessels are avoided.

2.2 Ultrasound Elastography

Ultrasound elastography (EUS) is a recently developed ultrasound-based method, which allows for qualitative visual or quantitative measurements of the mechanical properties of tissues. It is based on the general principle that mechanical stress applied to tissue causes changes within it, which depend on the elastic properties of tissue. Since disease alters the biomechanical properties of muscles and tendons, US elastography has been recently employed in clinical practice for research in biomechanics of the musculoskeletal system.

Two main forms of elastography are currently used in clinical practice, though other important implementations are to be expected.

The first is known as *strain elastography* (SE) (also described as compression elastography,

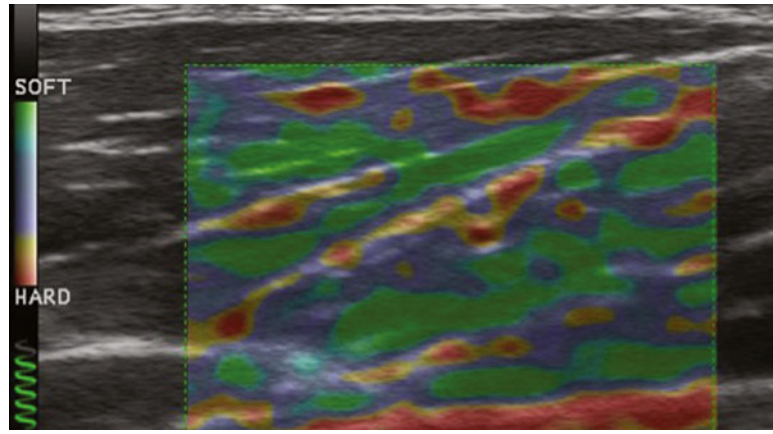

Fig. 2.3 Real-time elastography. Applying manual compression with the probe, the ultrasonograph shows soft structures in *green* and hard structures in *red* (qualitative measurement)

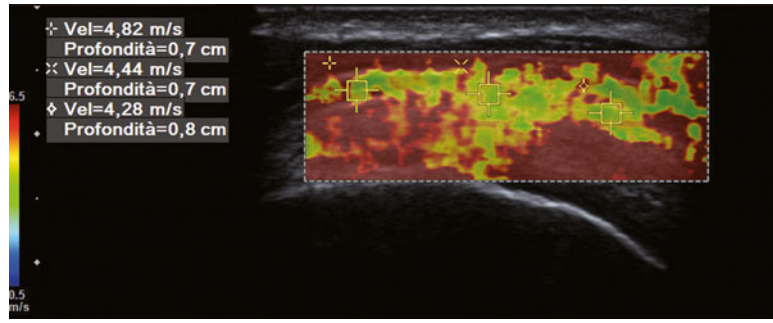

Fig. 2.4 ARFI elastography (share wave) of the gluteal insertion onto the greater trochanter. Note the quantitative measurements on the left of the image

sonoelastography and real-time elastography). The soft tissue deformation (which is the strain) is produced by an external palpation manually applied with the probe, and it is assessed by following the way the speckle in the image moves, usually with a tracking algorithm working on the radio-frequency data. Then, the data are used to form an image that is coded in colour or greyscale to show the pattern of strain, which is inversely related to tissue stiffness and can be subjectively assessed (Fig. 2.3).

The second typology, currently implemented, is *shear wave elastography* (SWE). Shear waves may not be familiar to clinical readers, but they frequently occur in human soft tissues. Shear waves are transverse waves rapidly attenuated by tissue (i.e. the particle movement is across the direction of travel); they travel much more slowly (between 1 and 10 m/s), and they are not supported by liquids of low viscosity. Shear waves are produced by any mechanical disturbance and occur naturally from muscular movements as well as being induced by the ultrasound systems used to measure their speed. A useful way to generate shear waves is to use acoustic radiation force: tiny displacements in soft tissue set up (shear waves) that travel sideways away from the "pushing" ultrasound beam. Though the amplitude of the resulting shear waves is minute (a few microns' displacement), they can be detected by conventional ultrasound using tracking algorithms (Fig. 2.4).

The recent introduction of EUS into commercially available ultrasound systems has driven research activity towards the potential clinical applications of this new technique also in the musculoskeletal system, such as the early detection of degenerative changes in tendinosis and the evaluation of elastic changes in muscular pathology (strain injuries).

In practice, elastography could be considered as an extension of conventional ultrasonography, in the same way as Doppler is integrated into clinical practice.

Suggested Reading

Arda K, Ciledag N, Aktas E, Kadri Arıbas B, Köse K (2011) Quantitative assessment of normal soft-tissue elasticity using shear-wave ultrasound elastography. AJR 197(3):532–536

Kot Wing BC, Zhi Jie Z, Chun Lee AW, Fong Leung VY, Ngor Fu S (2012) Elastic modulus of muscle and tendon with shear wave ultrasound elastography: variations with different technical settings. PLoS One 7(8):e44448

Martinoli C, Bianchi S (2007) Ultrasound of the musculoskeletal system. Springer, Berlin/New York

O' Neill J (2008) Musculoskeletal ultrasound: anatomy and technique. Springer, New York

Pavčec Z, Žokalj I, Saghir H, Pal A, Roić G (2006) Doppler ultrasound in the diagnosis and follow-up of the muscle rupture and an arteriovenous fistula of the thigh in 12 year boy. Radiol Oncol 40(4):211–215

Wells PN, Liang H-D (2011) Medical ultrasound: imaging of soft tissue strain and elasticity. J R Soc Interface 8:1521–1549