(iv) Basic science: ultrasound

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Summary
Ultrasound is the investigation of choice for imaging soft tissue disease, offering resolution significantly greater than CT or MRI. It is low cost and readily accessible allowing dynamic imaging which is particularly useful for assessing musculoskeletal abnormalities. It also allows real-time image-guided interventional procedures including biopsies and injections.

Basic physics

Ultrasound involves the use of very high-frequency sound waves typically in the range of 3–15 MHz. Sound waves over 20 KHz are inaudible to the human ear. Unlike CT, plain X-rays and scintigraphy, ultrasound does not employ ionising radiation.

Production of ultrasound

The transducer of an ultrasound machine contains a material which has the ability to produce ultrasound waves when an electric current is passed through it. This phenomenon is called the piezoelectric effect. The material can be a crystal, such as lead zirconate titanate (PZT) or a plastic such as polyvinylidene difluoride (PVDF). Each substance has a 'Curie temperature' above which the basic structure is destroyed and the piezoelectric property lost permanently. For PZT, this is approximately 350°C. Therefore, transducers should not be placed in an autoclave.

Transmission of ultrasound

The ultrasound beam will be produced at a particular frequency, depending on the transducer used. These waves are then transmitted from the probe, through a coupling device "gel" and into the patient. The transmission through the layers can be summarised in the following diagram:
The density of a transmission substance will determine the velocity and wavelength with which the ultrasound travels through it. At the junction of each interface (e.g. skin and subcutaneous fat) a proportion of the ultrasound waves will be reflected back to the probe and it is these reflected waves which are analysed and converted into a 2D grey-scale image seen on the monitor. The remaining waves are transmitted into the next layer at a different velocity and wavelength. The waves then travel to the next interface where again a proportion of waves are reflected and some are transmitted. This process of transmission and reflection is also occurring at a much smaller level within each layer. For example, the muscle layer contains muscle fibres surrounded by a thin membrane of connective tissue (epimysium) and since these have different densities, a few waves will be reflected back to the probe which is then able to create a detailed image of the muscle.

The probe is therefore able to make a detailed 2D image of not only the different tissue layers, but also the finer structures within each compartment, giving a resolution significantly greater than CT or MRI. The superficial structures (e.g. skin and subcutaneous fat) will reflect waves first and will be seen at the top of the monitor. To image deep structures, a lower frequency probe must be used at the expense of resolution.

The proportion of waves that are reflected at each junction is determined by the differences in acoustic impedance between the two structures. The acoustic impedance is the product of density of the material and velocity of the sound traveling through it. The difference in acoustic impedance between, say, fat and muscle is not great and so the majority (99%) of sound will be transmitted at a fat–muscle interface and only 1% reflected back to the probe. However, the difference between, say, gas and tissue is very great and less than 0.1% of the waves will be transmitted at this interface. That is why viewing retro-peritoneal structures in an abdomen distended with bowel gas is virtually impossible as all the waves are reflected back. Likewise, the difference in acoustic impedance between soft tissue and the cortex of bone is high and therefore structures beyond the cortex cannot be visualised. The importance of removing air between the ultrasound probe and skin by using a coupling agent can also be explained. If no gel is used, then the difference in acoustic impedance between the probe and an air pocket is so large that all the waves would be reflected and none transmitted into the body.

**Doppler effect**

During ultrasound examination of a stationary tissue (e.g. muscle), the frequency of the ultrasound which is produced by the probe is the same as that which is reflected back to it. The only changes are in the velocity and wavelength, depending on the density of the tissue.

However, if the object is moving (e.g. flowing blood in a vessel), the frequency of the waves reflected back would be different to that produced by the probe. This frequency shift will be proportional to the velocity of the flowing blood. If the angle of incidence of the ultrasound beam to the vessel is also known, an equation can be used to calculate the precise velocity. The direction of flow and the velocity can be represented on a colour flow image and duplex scanning is when this colour image is superimposed on a grey-scale image.

In normal grey-scale imaging, the angle of incidence of the ultrasound beam should be 90° to optimally view a structure. However, with Doppler imaging, the beam must not be at 90° to the blood vessels otherwise it would not be possible to calculate the shift in frequency. The optimum angle of incidence, which has been shown to give the most accurate measurements of velocity is 60° and the beam can be electronically steered to produce this angle (Fig. 1).

**Choice of probe**

The choice of probe depends on the area being imaged. Probes can vary in frequency, shape and size. Transducer frequency is proportional to the spatial resolution achieved but inversely proportional to the depth of penetration. Most musculoskeletal ultrasound examinations are of relatively superficial structures and a high-frequency transducer (e.g. 10–20 MHz) can be used to give the best resolution. If the depth has to be increased, for example, adult hip examination or intra-abdominal scanning, then the frequency of the transducer needs to be reduced at the expense of resolution. A low frequency transducer is typically 3–6 MHz.

Probes also come in different shapes. When a wide field of view is required, for example for abdominal scanning, then a curvilinear probe is used which has a divergent beam and excellent depth of penetration. However, poor gel contact at the curved periphery of the probe, can occasionally be a problem. Most musculoskeletal ultrasound examinations involve localised imaging of an area and rectangular probes are used which provide
uniform linear beam giving excellent resolution but poor depth penetration.

Common artefacts

Anisotropy
For ordinary grey-scale imaging the angle of incidence of the ultrasound beam needs to be 90° to the target structure to get the best possible image. When this does not happen, an artefact called anisotropy occurs and the target tissue may appear artificially dark and may give the impression of being abnormal. This artefact is a particular problem in musculoskeletal ultrasound where the topography of the body may not allow a perpendicular beam to the target structure and it is commonly seen in tendons curving around a joint (Fig. 2).

Reverberation
This artefact can occur at strongly reflective interfaces where sound waves are transmitted back and forth between the probe and the interface. The result is a series of strongly echogenic lines separated by short distances. Reverberation is commonly seen at bone surfaces.

Acoustic shadowing
Strongly reflective structures, such as bone, calculi and gas do not transmit ultrasound beyond them and this is seen as a shadow posterior to the structure. This artefact can be used to diagnose calcific tendonitis.

Acoustic enhancement
Structures containing fluid allow more sound to be transmitted through adjacent structures resulting in an area of increased brightness. Fluid-filled cavities, such as the bladder and cystic lesions will demonstrate this effect. Certain homogeneous mass lesions, for example, neuromas and lymph nodes, which are less echogenic than muscle may also show acoustic enhancement (Fig. 3).

Limitations of ultrasound

Ultrasound is an operator-dependant technique that requires a long learning curve and inexperience can lead to failure to identify an abnormality or misinterpretation. One of the major difficulties is the inability to review another operator’s examination, particularly when only single images are presented and body markers and annotations are not used. The hardware required can be expensive and the cheaper portable machines do not have the quality or resolution for diagnostic imaging. There have been tremendous technical advances in recent years and machines available today are significantly better than those available even 3 years ago. However, not all high-frequency probes and machines are good for musculoskeletal imaging.
Applications of sonography in orthopaedics

Ultrasound provides a safe targeted imaging tool in the investigation of disease of the soft tissues of the musculoskeletal system. The exquisite near-field resolution lends itself perfectly to interrogation of superficial soft tissue structures such as muscle, tendons and ligaments of the appendicular skeleton. Ultrasound is patient centred with additional information available in the form of an up to date history, clinical examination and dynamic real-time assessment of the tissue under investigation, both at rest and during active or passive movement.

More information is available during dynamic examination than in static images. This limits the ability to review someone else's examination. Musculoskeletal US is a challenging technique to acquire with a long learning curve even for individuals possessing core US skills.

Not all US equipment has sufficient near-field resolution for musculoskeletal imaging, which demands advanced and expensive hardware and software to produce images of diagnostic quality.

Muscle

Although limited resolution at great depth, many muscles and their entheses are readily examined using US. The disruption of the normal pennate arrangement of muscle fibres by collections of fluid, haematoma or solid tumour can be demonstrated. In the acute trauma or sports setting, muscle tears can be diagnosed and graded according to severity to predict the clinical coarse and healing time. These are readily followed up with serial US studies. Complications of trauma such as myositis ossificans, fascial herniae, denervation and contractures are also well demonstrated (Fig. 4).

A dynamic tool with real time interaction with the patient, US can identify masses that are not seen on MR of resting muscle but become apparent with contraction of the muscle, such as muscle herniae, and chronic scars. Comparison with the
asymptomatic side, and careful respect of the anatomy can diagnose accessory or deviant muscle slips presenting as masses or nerve entrapment phenomena.

**Tendons**

Normal tendon structure: regular tightly packed fibrillar linear arrangement of fibres aligned in the direction of the pull of the muscle. High-frequency (10–20 MHz) linear array probes with compound imaging and Doppler software can be used to define clearly the presence of this normal anatomy and detect sub-millimeter disruptions in the tendon fibres, degenerative clefts, micro-tears and calcification, through to full thickness tears of the tendon. Extended field of view software can be used to display the entire length of the tendon. This makes it easier to demonstrate in a static image the nature and location of disease.

In the acute setting, the position and size of the tear can be documented and the function of the tendon can be dynamically assessed in the presence of an incomplete tear or repair. In chronic tendinopathy, the presence of cystic degeneration and calcification, peritendinous oedema, paratendonitis or synovitis, and neovascular injection of the tendon substance can be easily demonstrated. Care must be taken to identify and adjust for anisotropic artefact as described above. Having said that, anisotropy can be advantageous, delineating a tendon from surrounding structures by tilting the probe and demonstrating that the tendon becomes more or less reflective. This may be used to confirm that the tendon is normal. US soft tissue contrast resolution is far superior to that afforded by MRI, such that US is replacing other methods in the assessment of rotator cuff disease of the shoulder, and tendinopathy of the wrist, ankle and foot (Fig. 5).

**Ligaments**

US is useful when an isolated injury of superficial ligamentous structures is suspected, or dynamic assessment of joint stability is required. Ligaments share a closely packed linear arrangement of fibres offering isometric stability to joints. The collateral stabilisers of the knee, elbow and the medial and lateral ligamentous complexes of the ankle are
frequently studied with US. A sound knowledge of anatomy is, as always, essential. However oedema, thickening or absence of the ligament can be readily demonstrated with reinforcement of the diagnosis by visualising the joint space opening under gentle dynamic stress.

Joints

Although unable to define the deep internal arrangement of large joints, US provides useful information about the superficial supporting tissues of these joints and has a proven record in assessment of smaller joints such as those of the hands and feet. US is sensitive at detecting the presence of joint fluid, and synovitis, and directing diagnostic needle aspiration especially where blind attempts have failed. Recent advances in near field high-resolution technology have been applied to imaging the relatively accessible metacarpophalangeal and interphalangeal joints of the hands. Early erosion of the articular cartilage and juxta-articular bone can be demonstrated in inflammatory arthropathies where disease-modifying drugs such as anti-TNF agents are being considered. US has practical advantages over MRI for this purpose and has recently become the primary imaging method for such patients.

Soft tissue masses

It is much easier to localise a soft tissue mass with the patient present, able to point out their lump. A brief history also reveals important information such as how long it has been there, whether it is painful or growing, any previous trauma, and whether there are any other lumps or other
relevant medical or surgical history e.g. diabetes or seropositive arthritis.

Ultrasound is then used to define the dimensions and morphology of the mass with respect to its surface contour and definition, internal reflectivity, relationship to surrounding structures, and other specific features such as internal calcifications, and vascularity. This process might yield an easy diagnosis such as a simple cyst: a well-defined, clearly margined lesion containing anechoic fluid (low reflectivity, acoustic enhancement of its deep wall) with no internal vascularity; or a intralipomatous lipoma: a superficial well-defined fat reflectivity mass containing internal striations but no non-fatty solid reflectivity complexity or increased vascularity. The diagnosis may be less obvious in cases with more non-specific features. In these cases, the differential diagnosis may be narrowed by typical location, history or behaviour on follow-up scanning. Correlation with findings of other imaging may be helpful but ultimately a biopsy will be required for tissue diagnosis.

**US guided intervention**

Percutaneous fine needle aspiration, core tissue biopsy or injection of local anaesthetic and corticosteroid are commonly performed interventional musculoskeletal procedures. US is ideally suited to safely guide the needle tip to the correct location for the injection or biopsy, avoiding important vascular or neural tissue. Acquiring the necessary skills requires patience, a respect for anatomy and practice. In US skills courses, chicken fillets are a useful substitute for a volunteer! A common approach to enhance the visualisation of the needle is to keep the angle of the probe surface as near parallel to the long axis of the needle as possible, causing the barrel of the needle to reflect maximum amount of sound.

A careful initial US examination is essential to plan the safest, most effective route to the target. The position of the probe and planned entry site of the needle are marked with indelible pen or the impression of the blunt hub of a needle. The skin is prepared with sterilising fluid and drapes. US is used both to direct the placement of local anaesthetic and the subsequent biopsy or injection.

**Conclusion**

Ultrasound is dynamic and patient centered providing a safe, low-cost, targeted imaging tool for the investigation of disease of the soft tissues of the musculoskeletal system. US has many advantages over other cross-sectional imaging techniques with the best available soft tissue contrast resolution, lack of ionising radiation and the potential for real-time guided intervention. There is increasing recognition of these benefits in many clinical centres and the future will see further development of this exciting imaging field.

**Recommended reading**