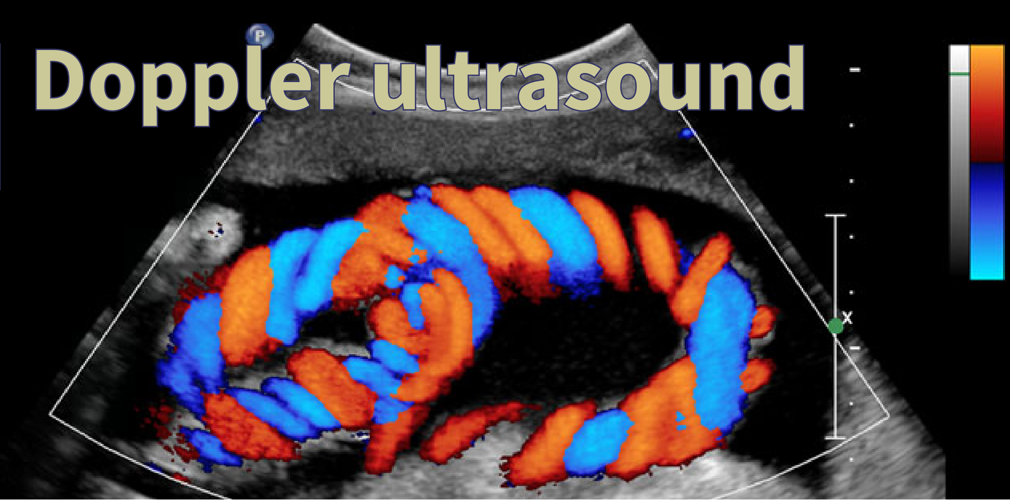
NZASE resource

Doppler ultrasound

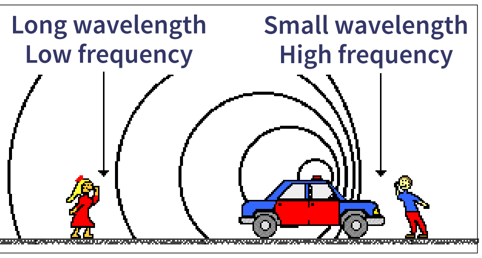


Colour Doppler image of an umbilical cord showing the main artery and vein. VAK Hospital, Thailand.

Doppler ultrasound uses the changing frequency of sound waves as they are reflected by moving blood cells to give diagnostic information for a range of medical conditions. Science Communicator Mike Stone investigates this interesting application of physics.

The change in sound of a fire engine's siren as it comes towards you and moves away has long been used to illustrate the Doppler effect. The frequency of sound waves increases as the source moves towards the observer and decreases as it moves away, changing the sound from a high to a low pitch.

Austrian physicist Christian Johann Doppler discovered the effect in 1842. It is used by police to check the speed of oncoming vehicles, and by meteorologists to track storms. This effect has major applications in astronomy, acoustics, and medical imaging.



Waves emitted by a source travelling towards an observer get compressed. Waves emitted by a source travelling away from an observer get stretched out. From The Physics Classroom.

Sound and ultrasound

Sound waves are caused by the vibration of matter which moves particles in the air back and forwards, carrying energy forwards. These longitudinal waves can be represented by areas of compression and expansion and can be described by their speed, frequency and amplitude.

Ultrasound is a high-frequency sound wave used to produce images of internal organs and tissues. The technique is similar to the echolocation used by bats, whales and dolphins, or SONAR used in submarines. Ultrasonic waves have a frequency of between 20 kHz and 5 MHz; above the range humans can hear.

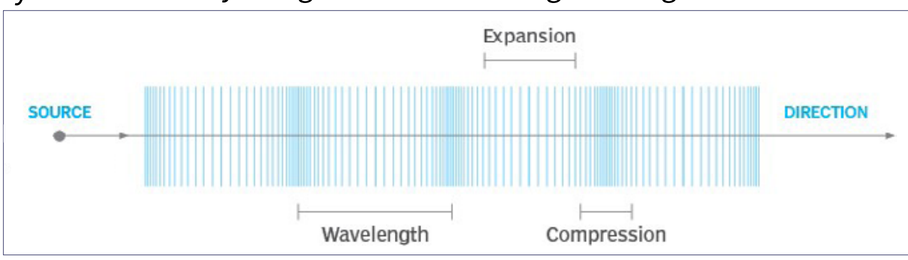
An ultrasound machine consists of a probe and probe-controller, computer, screen, disc storage and printer.

The probe or transducer contains a piezoelectric crystal. An AC current will cause these crystals to change shape rapidly, which generates sound waves, at 1-5 MHz. Incoming sound waves hitting the crystals will also transduce an AC current. This piezoelectric effect was discovered by Pierre and Jacques Curie in 1880.

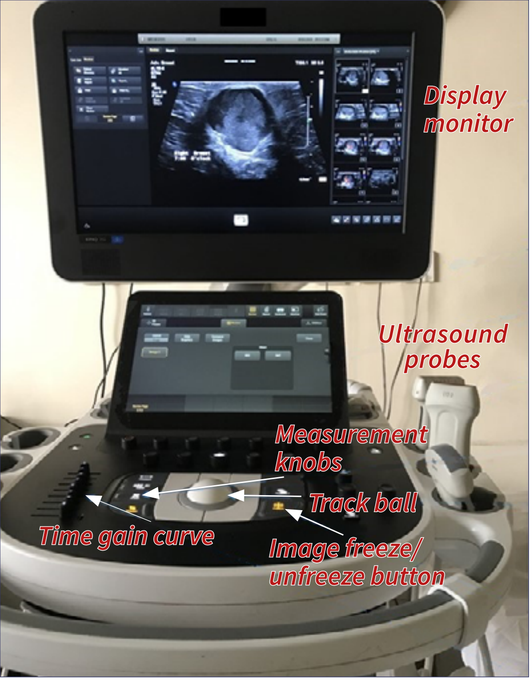
The ultrasound waves travel from the probe into the body and hit a boundary between tissues (eg, between fluid and soft tissue, or soft tissue and bone). Some of the sound waves get reflected back to the probe, while some travel on further until they reach another boundary in the tissue and get reflected.

The probe detects the reflected waves, producing an electric current, which the computer converts to a 2D diagnostic image or sonogram. Using the speed of sound in tissues (540 ms^{-1}), and the time of each echo's return, the computer can also calculate the distance of the probe to the tissue boundary.

Some probes are designed to be inserted into the body (rectum, vagina or oesophagus) so they can get closer to the organ being



A sound wave. By TechTarget, Whatis.com.



Ultrasound imaging components. International Agency for Research on Cancer, W.H.O.

examined (prostate gland, uterus or stomach) to give a more detailed view.

Ultrasound waves travel at different speeds and with different amplitude loss in different tissues. High frequency pulses can penetrate only to shallow depths as the signal gets weaker with depth (attenuation).

The frequency used for medical imaging must be balanced – high enough to give good resolution, and low enough to ensure adequate penetration of the tissue. For example, a frequency of 3 MHz is normally used to visualise the kidneys, while 20 MHz is used to visualise a needle inserted by a doctor.

Ultrasound can be used to observe and measure various aspects of foetal and placental growth to help prevent problems. It can also be used to detect kidney stones and prostate cancer, and doctors can use ultrasound to guide a needle during a biopsy.

This low-energy, non-ionising wave is considered safer than other types of medical imaging. Ultrasound can generate some heat as tissues absorb the energy, and this can form bubbles as dissolved gases come out of solution. However, extensive research has shown no harmful effects on babies.

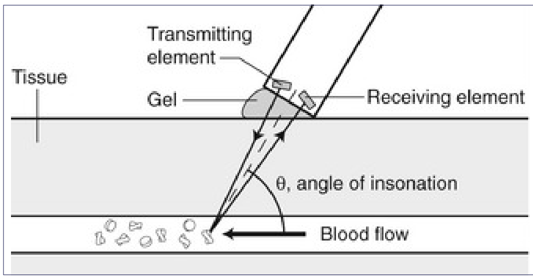
Doppler ultrasound

When the parts of the body we want to observe are moving, such as blood flowing through large vessels, hearts and kidneys, then Doppler ultrasound can be useful to help:

- Detect clots, blockages, and stenosis (narrowing) in blood vessels
- Detect abnormalities in hearts and kidneys
- Detect some cancers – as blood flows differently in tumours from normal tissue
- Check blood flow in mother and foetus for high-risk pregnancies
- Check blood flow to the brain after a stroke
- Annually check the condition of arterial bypass grafts.

The frequency of a wave changes when the source of the wave is moving relative to the observer. In Doppler ultrasound the source of the wave is the transducer, but it is the reflected waves that show the Doppler shift.

When ultrasound waves are sent into the body, they bounce off the moving red blood cells in the blood vessels. If the blood is flowing towards the transducer, the frequency of the reflected wave is higher than the frequency of the emitted wave. Conversely, if the blood is flowing away from the transducer, the frequency of the reflected wave is lower than the frequency of the emitted wave.



Elements of the doppler equation, Radiology Key.

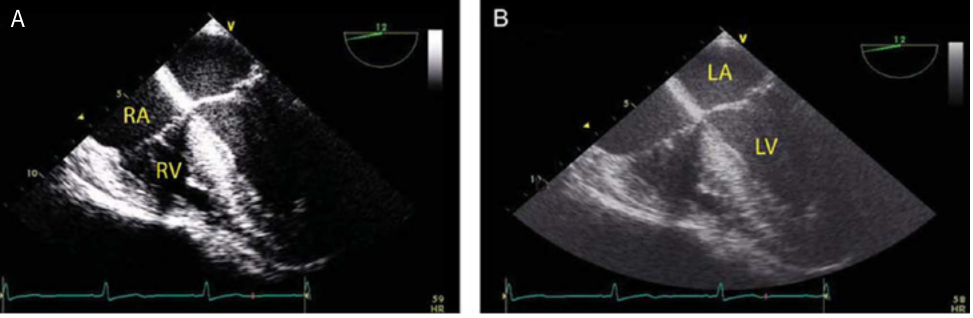
By measuring the change in frequency of the reflected wave, the Doppler effect can be used to determine the velocity and direction of blood flow in the organ being scanned.

The Doppler shift can be determined by the equation: $\Delta f = (2f_0 v\cos\Theta) / c$

where Δf is the Doppler shift, f_0 is the frequency of the emitted sound wave, v is the velocity of the blood cells, Θ is the angle between the direction of motion of the blood cells and the direction of the emitted wave, and c is the speed of sound in the tissue. Note that the Doppler shift is a change in frequency, rather than an absolute frequency.

Doppler ultrasound sonograms indicate the direction and speed of blood flow and the location of blood vessels and other structures in the body. The type of Doppler ultrasound is categorised by how the wave is transmitted:

- **Pulsed wave Doppler** – sends waves in short pulses from a single crystal, and in between detects the reflected wave. It can accurately measure depth and blood flow at lower speeds.
- **Continuous wave Doppler** – gives a continuous real-time image as one crystal sends and one receives. It can more accurately



Images of atria and ventricles showing high resolution (A), and low (B). By M. Smith, Royal Wolverhampton Hospitals NHS Trust.

measure faster blood flow, eg, in the aorta, but depth is unclear.

The image may be represented in different ways, for example –

- **Colour Doppler** – generates colour images: red indicates blood moving towards the transducer, blue away. It can show the speed and direction of blood flow but spatial resolution is unclear. It is used to image the heart and major blood vessels and find blockages.
- **Power Doppler** – uses the power of the return signal to show the blood flow in a single colour. It provides more detail, so is useful for smaller blood vessels, slower flows and tumour imaging. It gives no information on speed or direction.
- **Spectral Doppler** – uses the Doppler shift of the echo signal as a measure of flow velocity and direction. It displays a graph to show how much of a blood vessel is blocked.

One limitation of Doppler ultrasound is that it can measure blood flow only in the direction of the emitted sound waves – it may not be able to detect blood flow in vessels perpendicular to the transducer.

The accuracy of velocity measurements can also be affected by the viscosity of the blood, the presence of turbulence due to obstructions in the vessel, and the angle of incidence (it is best held at a shallow angle relative to the vessel being scanned).

Blood is made up of red and white blood cells and platelets. Red blood cells make up half the volume of blood. They have a biconcave disc shape and a diameter of 7 µm, much smaller than the wavelength of Doppler ultrasound.

This means that groups of red blood cells act to scatter ultrasound. This effect is small and although it increases with transmission frequency, it is offset by the loss of amplitude at higher frequencies (attenuation).

Doppler sonography can show useful information about blood flow in a safer way than some other medical imaging techniques. It is a valuable tool for diagnosing and monitoring a wide range of medical conditions.

Questions

1. Explain the symbols MHz, kHz, µHz; ie, explain M, k and µ, and explain Hz

2. Rearrange the Doppler shift equation to find v. Use $\Delta f = (2f_0 v\cos\Theta) / c$

3. Calculate the speed of blood if a 5 MHz transducer uses an angle of insonation of 60°, the speed of sound in the tissues was 1540 ms^{-1} and the Doppler shift was 1.6 kHz.

4. Why is virtually no Doppler effect detected when the transducer is oriented at right angles to the blood vessel?

5. In the Colour Doppler image of the umbilical cord why are the artery and vein different colours?

6. How might Doppler ultrasound help a doctor:
   a. Find a blockage in a blood vessel
   b. Find out which areas of the brain are affected after a stroke
   c. Find the valves damaged in varicose veins.

Ngā Kupu

Ariari – Resolution (of an image)
Auau (o te ngaru oro) – Frequency of sound wave
Hauoro – Pitch (of sound)
Ngaru oro – Sound wave
Oro ikeike – Ultrasound
Pūtautau – Tissue (of organism).

From Paekupu

References

BYJU'S, 2023, Doppler effect.
P. Magee, 2020, Essential notes on the physics of Doppler ultrasound, *BJA Education*.
C. Freudenrich, 2001, How ultrasound works, *How stuff works*.
CHATGPT (needs a login).
MedlinePlus, 2020, Doppler ultrasound.
ScienceDirect, 2023, Doppler effect.
Radiology Key, 2015, Doppler ultrasound.
Victor Ekpo, 2017, Doppler effect, Slideshare.

Videos

J. T. Nomura, 2017, Ultrasound physics and basic principles.
D. Walker, Doppler effect with an elastic band, NZIP.