BIOMEDICAL INSTRUMENTATION

(24BM502)

UNIT IV

MEDICAL IMAGING AND DIAGNOSTIC TECHNOLOGIES

Topics Covered

4. Magnetic Resonance Imaging (MRI)
5. Ultrasound Imaging
6. Positron Emission Tomography (PET)

4. Magnetic Resonance Imaging (MRI)

MRI produces detailed cross-sectional images of the body using a strong magnetic field and radiofrequency (RF) pulses, without ionising radiation. Its signal comes from hydrogen nuclei (protons), which are abundant in the water and fat that make up most body tissue.

4.1 From Random Alignment to a Net Magnetic Vector

- **The natural state:** outside a magnetic field, the hydrogen nuclei in the body behave like tiny, randomly oriented magnets; their magnetic forces cancel out, so the body has no net magnetic vector
- **Entering the magnetic field (B0):** when a patient enters the MRI bore, the powerful external magnetic field forces the nuclei to align with it; most align parallel to B0, a smaller number align anti-parallel, and this imbalance creates a net magnetic vector along the main field direction (the Z-axis)
- **Precession:** the aligned nuclei do not sit still — they wobble, or precess, around the axis of the magnetic field, much like a spinning top; the speed of this wobble is the precessional frequency, given by the Larmor equation, and it is this frequency that must be matched for resonance to occur

4.2 Excitation and Resonance

Before exciting the hydrogen nuclei, the scanner must know their natural precessional frequency, calculated from the Larmor equation. An RF pulse is then applied at exactly this frequency. When the RF frequency matches the Larmor frequency, resonance occurs, and the hydrogen nuclei absorb the RF energy — the fundamental principle behind RF excitation in MRI (B0 → Larmor frequency → RF pulse → resonance → excitation).

During excitation, the absorbed energy causes the net magnetic vector to flip out of the longitudinal plane (Z-axis) and into the transverse plane (XY-plane).

4.3 Relaxation: T1 and T2

Once the RF pulse is switched off, the nuclei begin to relax back toward equilibrium. This happens through two simultaneous but distinct processes, and it is the RF signal emitted during relaxation that forms the MRI image.

Feature	T1 Relaxation	T2 Relaxation
Alternate name	Spin-Lattice	Spin-Spin
Axis of action	Longitudinal (Z-axis)	Transverse (XY-plane)
Physical process	Regain of longitudinal magnetization	Loss of transverse magnetization (dephasing)
Time constant	Time for 63% of magnetization to be regained	Time for 63% of magnetization to be lost (to 37% of initial value)
Relative speed	Slower process	Faster process

T1 relaxation describes the net magnetic vector returning to its original alignment along the Z-axis; different tissues have different T1 times, which is what allows them to be distinguished on T1-weighted

images. T2 relaxation occurs in the XY-plane: immediately after the RF pulse all nuclei spin together ("in-phase"), but they quickly begin to spin at slightly different speeds and fall out of sync ("dephasing"), causing the net transverse magnetization to decay.

4.4 From Signal to Image

As the nuclei relax through both T1 and T2 processes, they emit the energy they had absorbed as faint radiofrequency signals. These signals are picked up by receiver coils in the MRI machine. A powerful computer then processes the raw signals, using differences in relaxation times across tissues to differentiate them and construct a detailed cross-sectional image.

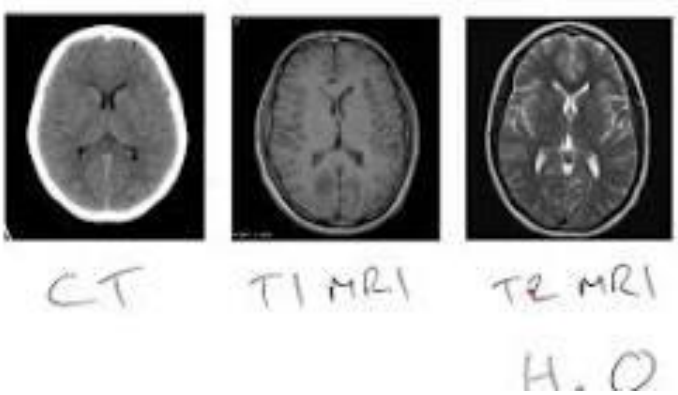


Fig. 4.1 The same brain level imaged by CT, T1-weighted MRI, and T2-weighted MRI — note how soft-tissue contrast differs sharply between modalities

4.5 Components of an MRI System

- **Main magnet (B0):** a very strong, usually superconducting magnet (typically 1.5 T or 3 T) kept cold with liquid helium; it is always switched on, which is the origin of most MRI safety rules.
- **Gradient coils:** three sets of coils that add a small, controlled variation to the field along X, Y and Z; they select the slice and encode position into the signal, and their rapid switching causes the loud knocking noise.
- **RF coils:** transmit the RF pulse at the Larmor frequency and receive the returning signal; head, knee, spine and surface coils are placed close to the anatomy for higher signal.
- **Shim coils:** small correction coils that keep the main field uniform across the imaging volume.
- **Computer and shielding:** the computer converts the raw signal into an image using the Fourier transform; the room is enclosed in an RF-shielded cage to keep outside radio noise out.

4.6 Image Weighting and Pulse Sequences

By choosing when the RF pulse is repeated (repetition time, TR) and when the echo is measured (echo time, TE), the operator decides whether T1, T2 or proton-density differences dominate the image contrast.

Weighting	TR	TE	Appearance	Best used for
T1-weighted	Short	Short	Fluid dark; fat bright	Anatomical detail, post-contrast imaging
T2-weighted	Long	Long	Fluid bright	Oedema, inflammation, tumours, cysts

Weighting	TR	TE	Appearance	Best used for
Proton density	Long	Short	Contrast reflects hydrogen density	Joints, cartilage, menisci

Common pulse-sequence families include spin echo (robust, the standard for T1 and T2), gradient echo (faster, used in angiography and functional MRI) and inversion recovery (such as FLAIR, which suppresses the bright cerebrospinal-fluid signal so that lesions near the ventricles stand out).

4.7 Clinical Applications, Advantages and Safety

- **Applications:** brain and spinal cord, joints and soft tissue, heart, liver and pelvic organs, MR angiography of blood vessels, and functional MRI (fMRI) for mapping brain activity.
- **Advantages:** no ionising radiation, superb soft-tissue contrast, any imaging plane without moving the patient, and the ability to image function and flow.
- **Limitations:** long scan times, high cost, loud noise, claustrophobia in the narrow bore, and image degradation from patient motion.
- **Safety:** the magnet attracts ferromagnetic objects, which can become dangerous projectiles. Patients and staff are screened for pacemakers, cochlear implants, certain aneurysm clips, and metal fragments, and no loose metal may enter the scanner room. Gadolinium-based contrast agents are used when needed, with kidney function checked first.

Key Takeaways

- MRI signal comes from hydrogen nuclei aligning with a strong external magnetic field (B0) and precessing at the Larmor frequency.
- An RF pulse at the Larmor frequency causes resonance, flipping the net magnetic vector from the Z-axis into the XY-plane.
- T1 (spin-lattice) relaxation is the regain of longitudinal magnetization; T2 (spin-spin) relaxation is the loss of transverse magnetization through dephasing — both happen simultaneously but at different rates.
- Different tissues have different T1 and T2 times, which is the basis of MRI's excellent soft-tissue contrast.
- No ionising radiation is used, making MRI safe for repeated or long-duration studies, though scan times are longer than CT.

5. Ultrasound Imaging

5.1 What Is Ultrasound?

Ultrasound (US) is a form of non-ionising radiation — mechanical sound energy propagated through a medium (tissue, fluid) by particle collision, without permanently displacing the particles themselves. Human hearing spans roughly 20 Hz to 20 kHz; diagnostic medical ultrasound uses much higher frequencies, typically 2–15 MHz.

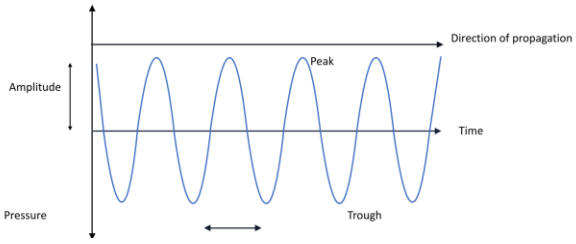


Fig. 5.1 Anatomy of a sound wave — amplitude, wavelength, peak and trough

- **Frequency vs. depth trade-off:** higher frequency gives better resolution but less penetration (e.g., ~7.5 MHz for intraoperative US); lower frequency gives deeper penetration but lower resolution (e.g., ~3.5 MHz for transabdominal US); wavelength is inversely proportional to frequency

5.2 The Pulse-Echo Principle

Image formation is driven by the piezoelectric effect inside the transducer, through five linked steps:

- Electrical pulse — the generator sends an electrical pulse to piezoelectric crystals in the probe.
- Sound emitted — the crystals convert electrical energy into sound energy (the piezoelectric effect), and waves travel into the tissue.
- Tissue interaction — sound is reflected, scattered, refracted, or absorbed at different tissue interfaces.
- Echo received — reflected waves return to the probe, and the crystals reconvert sound energy back into an electrical signal.
- Image displayed — the processor uses echo timing (speed of sound ≈ 1540 m/s in soft tissue) and amplitude to build a real-time greyscale image.

Key relationship: Distance = (speed of sound × time) / 2. The go-and-return time of the echo tells the machine how deep the reflecting surface lies.

5.3 Acoustic Impedance and Attenuation

Acoustic impedance describes a tissue's opposition to the propagation of sound. The difference in impedance between two adjacent tissues at an interface determines how much sound is reflected back to the probe. A high impedance mismatch (e.g., muscle–bone) produces strong reflection and a bright echo, while minimal mismatch (e.g., liver–kidney) produces few reflected echoes and the tissues blend together. Because air has very high impedance and would reflect almost all sound at the skin surface, coupling gel is used between the probe and skin to displace air and create a favourable low-impedance path into the body.

As sound travels to its target and back, energy is progressively lost — attenuation — through four mechanisms: reflection (the wave bounces back to the probe — the main principle behind US imaging), refraction (the wave is deflected from its path at an interface), scattering (the wave bounces in many directions off a small particle), and absorption (wave energy is converted to heat).

5.4 Ultrasound Artifacts

Artifacts are elements in the image that do not correlate with real anatomy, though some of them reveal useful tissue clues.

- **Reverberation:** bouncing between two reflective interfaces (or the probe itself) produces multiple, equally spaced lines, of which only the first is real
- **Comet tail / ring-down:** reverberation from a small particle such as a gas bubble, appearing as a bright cone or parallel lines distal to the gas
- **Acoustic enhancement:** increased brightness deep to a low-attenuation structure — helps identify cysts and fluid collections
- **Acoustic shadowing:** loss of brightness distal to a high-impedance structure, seen behind gallstones, calcifications, or bone
- **Mirror image:** a strong reflector (e.g., the diaphragm) creates a false duplicate image deeper in the tissue

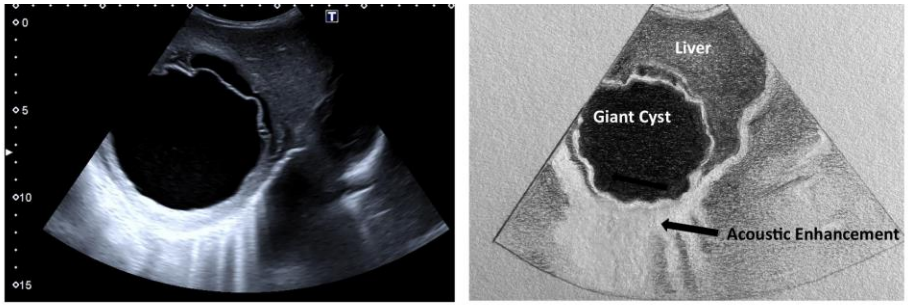


Fig. 5.2 Acoustic enhancement behind a giant liver cyst (left) and acoustic shadowing behind a gallstone (right)

5.5 The Doppler Effect

Described by Christian Doppler in 1842, the Doppler effect is a change in frequency when a sound wave reflects off a moving interface, such as blood cells flowing through a vessel. When flow moves toward the probe, frequency increases (shown as red on a Doppler display); when flow moves away from the probe, frequency decreases (shown as blue).

Angle matters: at 90° (perpendicular) to the vessel, no Doppler shift is detected. An insonation angle of 60° or less is recommended to reliably capture the flow signal. Doppler is used clinically to assess the presence, direction, and speed of blood flow within vessels.

5.6 Imaging Modes and Instrumentation

Mode	Name	What It Shows
A	Amplitude Mode	Echo amplitude over time — conceptual basis for B mode, not used directly today

Mode	Name	What It Shows
B	Brightness Mode	Echo amplitude converted to greyscale — the familiar real-time 2-D image
M	Motion Mode	Movement over time — ideal for the diaphragm, cardiac valves, vascular walls
D	Doppler Mode	Flow presence, direction, and speed within a vessel, as a colour overlay

Duplex imaging combines B mode and Doppler mode to show anatomy and flow together; triplex imaging adds spectral flow quantification on top of duplex.

- **Core components:** the generator (produces the electrical pulse, regulating frequency, duration, and amplitude), the transducer (contains the piezoelectric crystals; available as linear, curvilinear, and phased-array probes), the processor/computer (amplifies and filters echoes, calculates depth from timing), and the monitor/recorder (displays and stores the study)
- **Transducer selection:** linear probes give a rectangular field, best for superficial structures (7.5–10 MHz); curvilinear probes give a truncated-cone field, standard for transabdominal scanning (3.5–5 MHz); phased-array probes have a small footprint with a wide far-field view, optimised for deep structures through a narrow window
- **Basic machine controls:** presets (auto-configure the machine for a probe/exam type), gain/TGC (amplifies echoes and compensates for depth-dependent attenuation), frequency (trade-off between resolution and penetration), depth (sets the displayed distance range), and focus (sharpens a chosen depth of interest)

5.7 Clinical Applications of Ultrasound

- **Obstetrics and gynaecology:** fetal growth, anatomy, and well-being assessment.
- **Abdomen and pelvis:** liver, gallbladder, kidneys, pancreas, spleen, and bladder.
- **Cardiac:** echocardiography of heart chambers, valves, and wall motion.
- **Vascular:** Doppler assessment of arteries and veins, such as carotid stenosis or deep-vein thrombosis.
- **Other uses:** guidance for needle biopsy and fluid drainage, superficial structures such as thyroid and breast, tendons and muscles, and rapid bedside emergency examination.

5.8 Advantages, Limitations and Safety

Aspect	Advantages	Limitations
Safety	No ionising radiation; safe in pregnancy and for repeated use	Prolonged high-intensity exposure can cause heating, so exposure is kept ALARA
Practicality	Real-time, portable, inexpensive, no contrast needed	Highly operator-dependent; results vary with skill
Image quality	Excellent for fluid and soft tissue, plus blood-flow information	Cannot pass through air or bone, so lungs, bowel gas, and the adult brain are poorly seen

Modern machines display two safety indices: the Thermal Index (TI), which estimates tissue heating, and the Mechanical Index (MI), which estimates the risk of cavitation (bubble formation). The operator keeps both as low as possible while still obtaining a diagnostic image.

Key Takeaways

- Ultrasound uses high-frequency mechanical sound waves (2–15 MHz) and the pulse-echo principle; depth is calculated as (speed of sound × echo time) / 2.
- Higher frequency improves resolution but reduces penetration, so probe choice depends on how deep the target lies.
- Reflection occurs at interfaces with different acoustic impedance; coupling gel removes air so that sound enters the body.
- B mode gives the greyscale anatomy image, M mode shows motion, and Doppler shows direction and speed of blood flow.
- Ultrasound is safe, real-time and portable, but limited by air, bone, and operator skill.

6. Positron Emission Tomography (PET)

6.1 What Is a PET Scan?

PET is a nuclear medicine imaging technique that shows changes at the cellular level. A small amount of radioactive material (a radiotracer) is injected into the patient; the tracer collects in tissues that are chemically very active, and a ring of detectors picks up the gamma rays it emits. A computer converts these signals into images of body function — PET is functional/molecular imaging, not anatomical imaging.

Because disease usually alters tissue chemistry before it alters shape or size, PET can flag illness earlier than CT or MRI alone, and it can also show whether a treatment is actually working. It is non-invasive and, apart from the injection, painless.

6.2 Physics of PET: Positron Annihilation and Coincidence Detection

PET uses radionuclides that decay by emitting a positron (a positively charged electron). The positron travels only a few millimetres before it meets an electron, and the two annihilate, converting their mass into two gamma-ray photons of 511 keV each that leave in almost exactly opposite directions (about 180° apart).

- **Coincidence detection:** a ring of scintillation detectors surrounds the patient. When two detectors register photons within a few nanoseconds of each other, the event is accepted as a coincidence and the annihilation is known to lie somewhere along the line joining them, called the line of response (LOR).
- **Image reconstruction:** millions of LORs are collected and reconstructed (commonly by iterative methods such as OSEM) into a 3-D map of tracer concentration. Attenuation correction, using the CT scan in PET/CT, compensates for photons absorbed in the body.
- **Quantification:** uptake is often expressed as the Standardised Uptake Value (SUV), which relates tracer concentration in a region to the injected dose and body weight, helping to compare lesions and follow treatment response.

The radionuclides used have short half-lives, so they are produced in a cyclotron close to the scanner and used soon after production.

Radionuclide	Half-life	Typical use
Fluorine-18	about 110 min	FDG for cancer, heart and brain metabolism (most common)
Carbon-11	about 20 min	Labelling of biological molecules for brain research
Nitrogen-13	about 10 min	Ammonia for myocardial blood-flow studies
Oxygen-15	about 2 min	Water for blood-flow and brain-activation studies
Gallium-68	about 68 min	Receptor-targeted tracers, such as for neuroendocrine tumours

6.3 The Radiotracer

A radiotracer is a normal biological molecule tagged with a small amount of radioactive material. The most common tracer is F-18 FDG, a molecule very similar to glucose. Cancer cells are more metabolically active and take up glucose faster than normal cells; because FDG resembles glucose to the body, it accumulates in those cells, and that build-up is what the scanner detects as a bright spot. Tracers gather in tumours, inflamed tissue, or bind to particular proteins, and (for PET) are always given by injection.

6.4 Why Combine PET with CT?

PET tells you function — metabolism and chemical activity, with excellent sensitivity but a blurry picture. CT tells you anatomy — sharp structural detail, but limited information on activity. In a combined PET/CT scan, both exams are performed in one session without the patient moving, so the two images line up exactly (image fusion, or co-registration), and the abnormal activity can be located precisely within the body. Almost all PET scans today are done on combined PET/CT scanners; PET/MRI is a newer option, not yet widely available.



Fig. 6.1 A combined PET/CT scanner with the patient table extended

6.5 Clinical Uses

- **Cancer (the largest application):** detect a cancer and help diagnose it, stage it (check whether it has spread), monitor treatment response, follow up for recurrence, estimate prognosis, and assess tissue viability
- **Heart:** assess damage after a heart attack, identify muscle that would benefit from angioplasty or bypass surgery, and map normal heart function
- **Brain:** evaluate brain tumours, investigate memory disorders, study seizures and other CNS disorders, and map normal brain function

6.6 Procedure: Preparation, Equipment, and Scan

Preparation directly affects image quality: patients fast for several hours before a whole-body scan (water only), wear loose comfortable clothing, remove metal objects (jewellery, hairpins, dentures, hearing aids), and must inform staff of pregnancy, breastfeeding, medications, allergies, and recent illness. Diabetic patients receive separate instructions because blood sugar affects tracer uptake, and punctuality matters because the tracer decays quickly.

The equipment resembles a large CT or MRI unit — a doughnut-shaped gantry containing multiple detector rings, with the patient table sliding into a short tunnel; the CT part has an X-ray tube and detectors mounted opposite each other in a rotating gantry.

- **Emission, not transmission:** ordinary X-ray passes radiation through the body, but PET detects radiation coming out of the body — the injected tracer emits gamma rays as it decays
- **Hot spots:** areas of greater intensity, indicating a high concentration of tracer and a high level of metabolic activity
- **Cold spots:** less intense areas, indicating a smaller tracer concentration and less activity

A typical whole-body study: the patient is positioned and an IV line placed, the tracer is injected, the patient waits 30–60 minutes for uptake, oral contrast may be given, CT is acquired first and then PET, and extra images may be taken before the line is removed. Total scanning time on the table is around 30 minutes; some cardiac protocols (imaging before and after stress) can run up to three hours.

6.7 Benefits, Risks, and Limitations

- **Benefits:** combines function and anatomy in one exam; greater accuracy since the patient does not change position between scans; one visit instead of two; often less expensive and more precise than exploratory surgery; may detect disease before it is visible on CT or MRI alone
- **Risks:** the tracer dose is low and exposure is relatively low and acceptable for a diagnostic exam; allergic reactions are extremely rare; patients must always disclose pregnancy or breastfeeding
- **Limitations:** the procedure is slow, with about an hour of uptake time; spatial resolution is lower than CT or MRI, though PET compensates with far greater sensitivity to function; altered blood sugar can spoil results; the short tracer lifetime means appointments must be kept punctually
- Main strength is early, sensitive detection of disease; main weaknesses are scan time, modest spatial resolution, and sensitivity to blood sugar.

6.8 Comparing MRI, Ultrasound and PET

Factor	MRI	Ultrasound	PET
Energy used	Magnetic field + RF waves	Mechanical sound waves	Gamma rays from injected radiotracer
Ionising?	No	No	Yes (low dose)
Main information	Detailed soft-tissue anatomy	Real-time anatomy and blood flow	Function and metabolism
Spatial resolution	High	Moderate to high (depth dependent)	Low
Scan time	30–45 min	5–10 min	About 30 min plus uptake wait
Cost / portability	Expensive, fixed	Cheap, portable	Very expensive, fixed
Main limitation	Metal implants, long scans	Air and bone block sound	Radiotracer needed, poor resolution

Key Takeaways

- PET detects pairs of 511 keV gamma photons from positron–electron annihilation and locates the event along a line of response.

- F-18 FDG, a glucose analogue, accumulates in metabolically active tissue such as tumours, producing “hot spots”.
- PET shows function but has poor spatial detail, so it is combined with CT (PET/CT) to give both function and anatomy in one session.
- MRI, ultrasound and PET are complementary: MRI for soft-tissue detail, ultrasound for real-time and flow, PET for metabolic activity.