DEPARTMENT OF BIOMEDICAL ENGINEERING

Unit III

Cardiac Pacemakers • Defibrillators • Ventilators • Infusion Pumps • Dialysis Machines

No.	Topic	Main subtopics
1	Cardiac Pacemakers	Need for pacing, components, fixed-rate and demand pacing, NBG code, parameters, special pacemakers, safety
2	Defibrillators	Principle, block diagram, waveforms, types, electrodes, synchronised cardioversion, safety
3	Ventilators	Respiratory mechanics, block diagram, breath cycle, modes, settings, alarms, complications
4	Infusion Pumps	Types, block diagram, flow calculations, safety features, errors and maintenance
5	Dialysis Machines	Principles, machine block diagram, dialyzer, safety monitoring, other therapies

TOPIC 1
Cardiac Pacemakers

A **cardiac pacemaker** is an electronic device that delivers small, timed electrical pulses to the heart muscle when the heart's own rhythm is too slow or unreliable. In a healthy heart the **sino-atrial (SA) node** generates about 60–100 impulses per minute; the impulse spreads through the atria, is delayed at the **atrio-ventricular (AV) node** and then travels along the bundle of His and the Purkinje fibres to the ventricles. A pacemaker takes over, wholly or partly, when this natural pacemaker or conduction pathway fails.

1.1 Need for pacing

- **Sick sinus syndrome / symptomatic bradycardia:** the SA node fires too slowly or pauses, causing dizziness, fatigue or fainting (syncope).
- **AV block:** impulses from the atria do not reach the ventricles. Complete (third-degree) block and advanced second-degree block are the commonest reasons for a permanent pacemaker.
- **Slow ventricular rate in atrial fibrillation** and conduction block after a heart attack or heart surgery.
- **Heart failure with delayed ventricular activation:** a biventricular pacemaker (cardiac resynchronisation therapy, CRT) paces both ventricles together to improve pumping.

Pacing may be **temporary** (external or transvenous pacing in emergencies or after surgery) or **permanent** (a pulse generator implanted under the skin below the collar bone).

1.2 Components of a pacemaker system

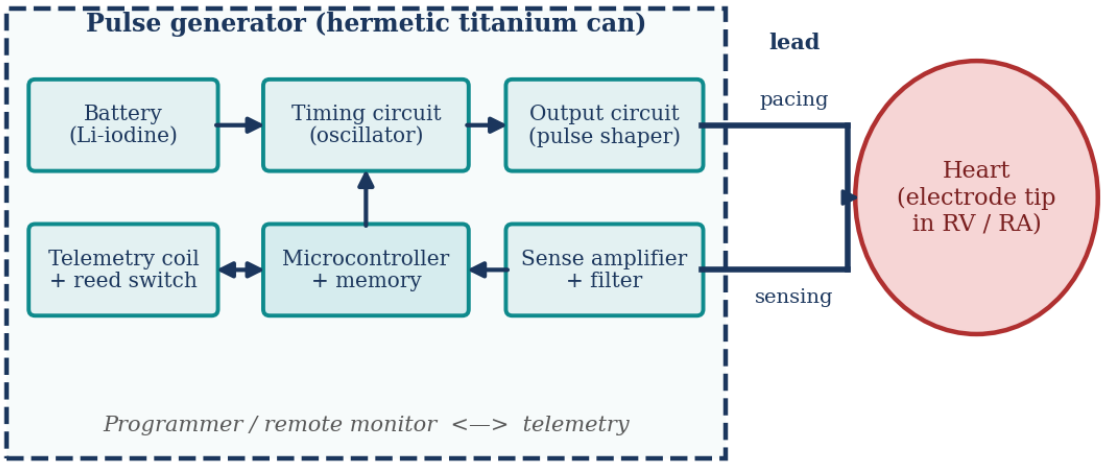


Fig. 1.1 *Block diagram of an implantable pacemaker: pulse generator, leads and heart.*

- **Pulse generator:** a hermetically sealed titanium can holding the battery and electronics. The battery is usually lithium-iodine (or another lithium chemistry) and lasts roughly 7–12 years, depending on pacing output and how often the device paces.
- **Electronic circuit:** the timing (oscillator) circuit sets the pacing rate; the output circuit shapes the pulse; the **sense amplifier** detects the heart's own P or R waves; a microcontroller with memory runs the programme, stores diagnostic data and manages telemetry.
- **Leads:** insulated wires (silicone or polyurethane) that carry pulses to the heart and signals back. They are passed through a vein into the right atrium and/or right ventricle and held by passive-fixation tines or an active-fixation screw-in helix. **Unipolar** leads use the metal can as the

second electrode; **bipolar** leads have both electrodes at the tip, so they are less prone to interference and do not stimulate the pocket muscle.

- **Programmer and telemetry:** a programming wand lets the clinician read and change settings without surgery; many devices also send data to a remote-monitoring system. Placing a magnet over the device closes a reed switch and forces fixed-rate pacing for testing.

1.3 Fixed-rate and demand pacing

Asynchronous (fixed-rate) pacemakers deliver pulses at a constant rate whatever the heart is doing. They are simple, but they compete with natural beats and a pulse that falls on the T wave (the vulnerable period) can trigger ventricular fibrillation. **Demand (inhibited)** pacemakers sense each natural beat: if a beat occurs within the escape interval, the pulse is inhibited and the timer restarts, so the device paces only when it is needed (Fig. 1.2). **Triggered** pacemakers deliver a pulse in response to a sensed event.

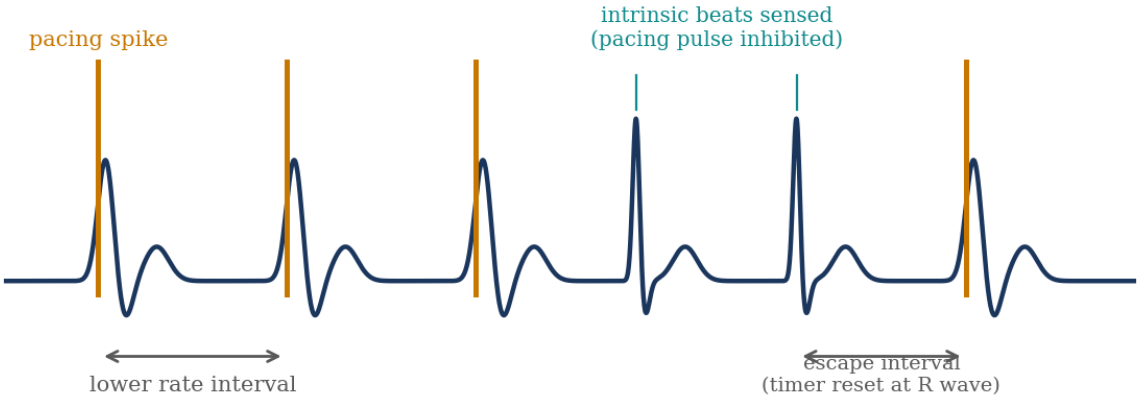


Fig. 1.2 *Demand (VVI) pacing: pulses at the lower rate, inhibited when intrinsic R waves are sensed.*

Feature	Fixed-rate (asynchronous)	Demand (synchronous)
Sensing	None	Senses P or R waves
Pulse delivery	Constant rate	Only when a natural beat is missing
Battery drain	Higher	Lower
Main risk	Competition with natural rhythm; R-on-T	Over-sensing or under-sensing (interference)
Use	Emergency use, magnet testing	Almost all modern pacemakers

1.4 The pacemaker (NBG) code

Pacing modes are named with a letter code of three to five positions; the first three are used most often.

Position	Meaning	Letters
I	Chamber paced	O = none, A = atrium, V = ventricle, D = dual (A + V)
II	Chamber sensed	O, A, V, D
III	Response to sensing	O = none, T = triggered, I = inhibited, D = dual (T + I)

Position	Meaning	Letters
IV	Rate modulation	R = rate-responsive (O = none)
V	Multisite pacing	O, A, V, D

Mode	Description	Typical use
AAI	Atrium paced, atrium sensed, inhibited by a sensed P wave	Sinus-node disease with normal AV conduction
VVI	Ventricle paced and sensed, inhibited by a sensed R wave	Atrial fibrillation with slow ventricular rate; simple back-up pacing
DDD	Both chambers paced and sensed; inhibited and triggered responses	AV block with a normal sinus rate; keeps AV synchrony
VOO / DOO	Asynchronous pacing, no sensing	Magnet mode; surgery with electrocautery
VVIR / DDDR	Rate-responsive form of VVI / DDD	Patients whose heart rate does not rise with exercise

Exam tip: read the code as chamber paced – chamber sensed – response to sensing. For example, VVI means ventricle paced, ventricle sensed, inhibited.

1.5 Pacing threshold and programmable parameters

The **pacing threshold** is the smallest pulse energy that reliably captures (depolarises) the heart. It rises for some weeks after implantation because of tissue reaction around the electrode tip; steroid-eluting tips reduce this rise. The output is therefore set with a safety margin above the threshold, commonly about twice the voltage threshold. The energy of one pulse is $E = V \times I \times t = V^2t / R$, where R is the lead-tissue impedance (typically 400–1000 Ω). For example, a 2.5 V pulse of 0.4 ms into 500 Ω delivers $(2.5)^2 \times 0.4 \times 10^{-3} / 500 = 5$ µJ.

Parameter	Meaning	Typical value
Lower rate	Minimum pacing rate	50–70 pulses/min (60 is common)
Pulse amplitude	Output voltage of each pulse	About 2–5 V
Pulse width	Duration of each pulse	About 0.4–0.5 ms
Sensitivity	Smallest signal that is sensed	Atrium about 0.5 mV; ventricle about 2–3 mV
Refractory period	Interval after an event during which sensing is ignored	About 250 ms (ventricle)
AV delay	Atrial-to-ventricular delay in dual-chamber pacing	About 120–200 ms
Upper tracking rate	Highest ventricular rate that follows the atrial rate	About 120–150 per min

1.6 Rate-responsive and special pacemakers

- **Rate-responsive (R) pacemakers** use a sensor, such as an accelerometer (body motion), minute-ventilation (impedance) or QT-interval sensor, to raise the pacing rate during activity.
- **Biventricular (CRT) pacemakers** have an extra lead on the left ventricle so that both ventricles contract together in heart failure.

- **Leadless pacemakers** are capsule-sized devices placed in the right ventricle through a catheter; they need no lead and no chest pocket.
- **Implantable cardioverter-defibrillators** combine pacing with shock therapy (see Topic 2).

1.7 Complications, interference and follow-up

- **Complications:** lead dislodgement or fracture, failure to capture or to sense, infection or haematoma at the pocket, pacemaker syndrome (loss of AV synchrony in single-chamber ventricular pacing) and battery depletion (flagged by the elective replacement indicator).
- **Electromagnetic interference:** electrosurgery (Topic 6, Part 2), MRI scanners (use MRI-conditional devices only), strong magnets and induction heating. Keep mobile phones at least 15 cm from the device; a brief pass through an airport metal detector is safe.
- **Follow-up:** the device is interrogated every 3–12 months to check battery, thresholds, lead impedance and recorded arrhythmias; remote monitoring can shorten the interval.

EXAM FOCUS

Short answer (2 marks)

1. Define a cardiac pacemaker and list two indications for pacing.
2. Distinguish fixed-rate and demand pacemakers.
3. Decode the pacemaker codes VVI and DDD.
4. What is pacing threshold? Why is a safety margin kept?
5. Name two sources of electromagnetic interference for a pacemaker.

Long answer (13 / 16 marks)

6. With a neat block diagram explain the working of an implantable demand pacemaker and state the function of each block.
7. Describe the pacing modes using the NBG code and discuss the programmable parameters of a pacemaker.
8. Discuss the complications of pacemaker therapy and the follow-up of a patient with a pacemaker.

TOPIC 2
Defibrillators

A **defibrillator** delivers a controlled, high-energy electric shock to the heart to stop a life-threatening arrhythmia so that the natural pacemaker can restart a normal rhythm. In **ventricular fibrillation (VF)** the ventricles quiver chaotically and pump no blood; unless a shock is given within minutes the patient dies, and the chance of survival falls by roughly 7–10% for every minute of delay.

2.1 Principle: defibrillation and cardioversion

The shock depolarises a large part of the myocardium at the same moment. All the cells then enter their refractory period together, the chaotic activity stops and the SA node can regain control. The energy is stored in a capacitor, $E = \frac{1}{2}CV^2$. For example, a 16 µF capacitor charged to 5 kV stores $\frac{1}{2} \times 16 \times 10^{-6} \times (5000)^2 = 200$ J. Only part of this reaches the patient, because some is lost in the inductor and internal resistance and the chest has a transthoracic impedance of roughly 50–150 Ω (about 75 Ω on average).

Feature	Defibrillation	Cardioversion
Shock timing	Asynchronous (delivered at once)	Synchronised with the R wave
Rhythms treated	Ventricular fibrillation, pulseless ventricular tachycardia	Atrial fibrillation, atrial flutter, SVT, ventricular tachycardia with a pulse
Patient	Unconscious, no pulse	Usually conscious and sedated
Energy (adult)	Biphasic 120–200 J (monophasic 360 J)	Lower, about 50–200 J

2.2 Block diagram and components

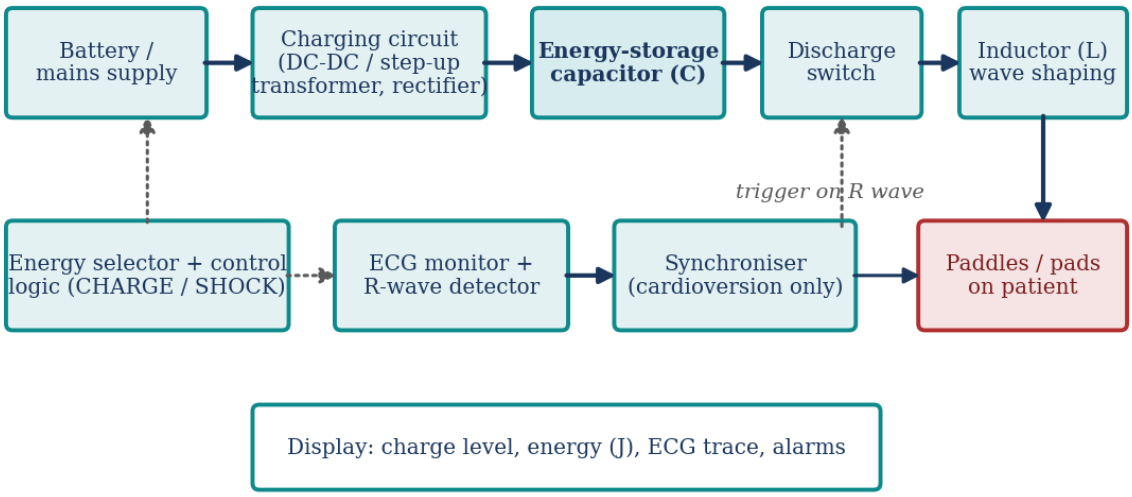


Fig. 2.1 *Block diagram of a defibrillator: charging circuit, capacitor, discharge switch, inductor and paddles.*

- **Power supply and charging circuit:** a battery or mains supply feeds a DC–DC converter or step-up transformer and rectifier that raises the voltage to several kilovolts and charges the capacitor.
- **Energy-storage capacitor:** stores the shock energy; the operator selects the energy in joules and presses CHARGE.
- **Discharge switch and inductor:** when SHOCK is pressed the switch connects the capacitor to the paddles through an inductor of tens of millihenries. The capacitor, inductor and patient

resistance form a series RLC circuit that shapes a smooth pulse lasting about 5–10 ms and limits the peak current.

- **ECG monitor and synchroniser:** the ECG is monitored through the paddles or separate electrodes; for cardioversion the R-wave detector triggers the discharge at the right moment.
- **Safety and display:** a charge indicator, energy display and alarms; an internal dump load safely discharges the capacitor if the shock is cancelled.

2.3 Defibrillator waveforms

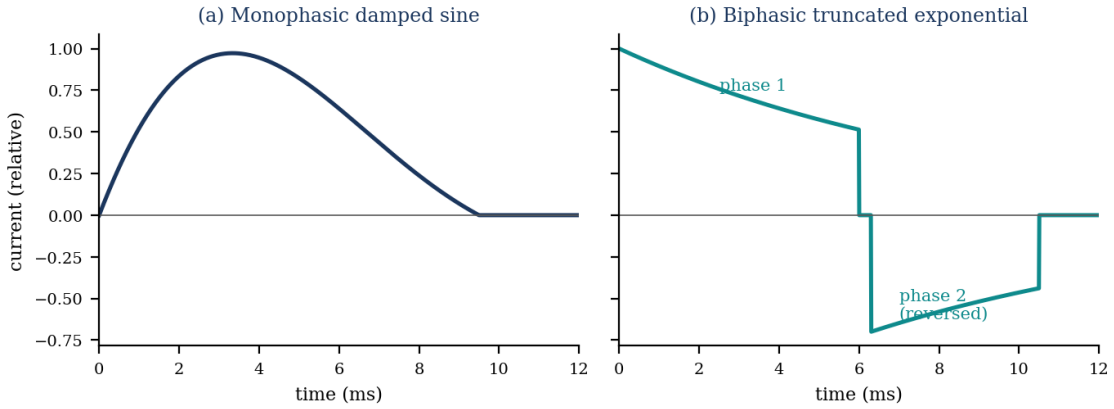


Fig. 2.2 *(a) Monophasic damped sine and (b) biphasic truncated exponential waveforms.*

Waveform	Description	Typical adult energy
Monophasic damped sine	Current in one direction, decaying slowly	360 J
Monophasic truncated exponential	One direction, cut off abruptly	360 J
Biphasic truncated exponential	Current flows one way, then reverses; truncated	120–200 J
Rectilinear biphasic	Near-constant current in each phase	Per manufacturer, about 120–200 J

Biphasic shocks defibrillate as effectively as monophasic shocks at lower energy, so they cause less myocardial damage and fewer skin burns; most modern defibrillators are biphasic. For children the usual starting dose is about 2 J/kg, increased to about 4 J/kg if needed.

2.4 Types of defibrillator

Type	Features	Use
Manual external defibrillator	Clinician reads the ECG, selects energy, charges and delivers the shock	Hospitals, ambulances
Automated external defibrillator (AED)	Analyses the rhythm, gives voice prompts and advises a shock; self-adhesive pads	Public places, lay rescuers
Implantable cardioverter-defibrillator (ICD)	Implanted unit that monitors continuously and gives anti-tachycardia pacing, cardioversion or a shock (up to about 30–40 J)	Patients at high risk of sudden cardiac death
Wearable cardioverter-defibrillator	Vest with dry electrodes and a shock unit	Temporary cover while waiting for an ICD

2.5 Electrodes and placement

- **External paddles or adhesive pads** are placed anterolateral (below the right collar bone and over the left lower ribs) or anteroposterior. Conductive gel or gel pads lower the skin impedance and prevent burns; pads also allow hands-free use.
- **Internal paddles** (spoon-shaped) are applied directly to the heart during open-chest surgery and need much less energy, typically about 10–20 J.
- **Paediatric paddles** are smaller; adult paddles should not be used on infants because the current density would be wrongly distributed.

2.6 Synchronised cardioversion

If a shock falls on the T wave (the vulnerable period) it can itself cause VF. In cardioversion the synchroniser therefore detects the R wave and delays the discharge by a few milliseconds so that the shock lands within the QRS complex, away from the T wave. The ECG monitor must show clear R waves and the **SYNC** marker for the shock to be delivered.

2.7 Safety precautions

- Call “clear” and make sure no one touches the patient, the bed or any conductive attachment during the shock.
- Keep oxygen flow away from the chest, remove any medicinal patch from the shock path and keep pads at least 8 cm from an implanted pacemaker or ICD.
- Test the unit regularly by discharging into a test load and check battery, pads and cables at the start of every shift.
- Use only the energy and paddle size recommended for the patient; apply firm, even pressure with external paddles to reduce impedance.

EXAM FOCUS

Short answer (2 marks)

1. Define defibrillation. Why is the energy stored in a capacitor?
2. Calculate the energy stored in a 32 µF capacitor charged to 5 kV.
3. Distinguish monophasic and biphasic waveforms.
4. What is synchronised cardioversion and why is it needed?
5. State two safety precautions when using a defibrillator.

Long answer (13 / 16 marks)

6. Explain with a block diagram the working of a DC defibrillator. State the role of the inductor.
7. Compare the types of defibrillator (manual, AED, ICD) and discuss electrode placement.
8. Discuss defibrillator waveforms and their effect on the energy required and on patient safety.

TOPIC 3
Ventilators

A **mechanical ventilator** moves breathable gas into and out of the lungs when a patient cannot breathe adequately. It provides **ventilation** (removal of CO_2) and **oxygenation**. In a normal adult the tidal volume is about 500 mL at 12–20 breaths per minute, so the minute ventilation (tidal volume × respiratory rate) is about 6–8 L/min.

3.1 Respiratory mechanics

The lungs behave like an elastic balloon with some airway resistance. **Compliance** $C = \Delta V / \Delta P$ (volume change per unit pressure) describes stiffness; **resistance** $R = \Delta P$ / flow describes the opposition of the airways. During inspiration the pressure the ventilator must produce is Paw = PEEP + V/C + R × flow, where PEEP is the positive pressure kept at the end of expiration. Stiff lungs (low compliance, as in ARDS) and narrow airways (high resistance, as in asthma) both need higher pressures.

3.2 Indications and types

- **Indications:** respiratory failure, apnoea, general anaesthesia, neuromuscular disease, chest injury, acute respiratory distress syndrome (ARDS), severe pneumonia.
- **Negative-pressure ventilators** (iron lung, cuirass) draw air in by lowering the pressure around the chest; they are now rare. **Positive-pressure ventilators** push gas into the lungs and are used almost everywhere.
- **Invasive ventilation** uses an endotracheal or tracheostomy tube; **non-invasive ventilation (NIV)** uses a face or nasal mask (CPAP, BiPAP).
- By use: intensive-care, transport, home-care, anaesthesia and neonatal ventilators. Modern machines are microprocessor controlled; simple ones are pneumatically controlled.

3.3 Block diagram and components

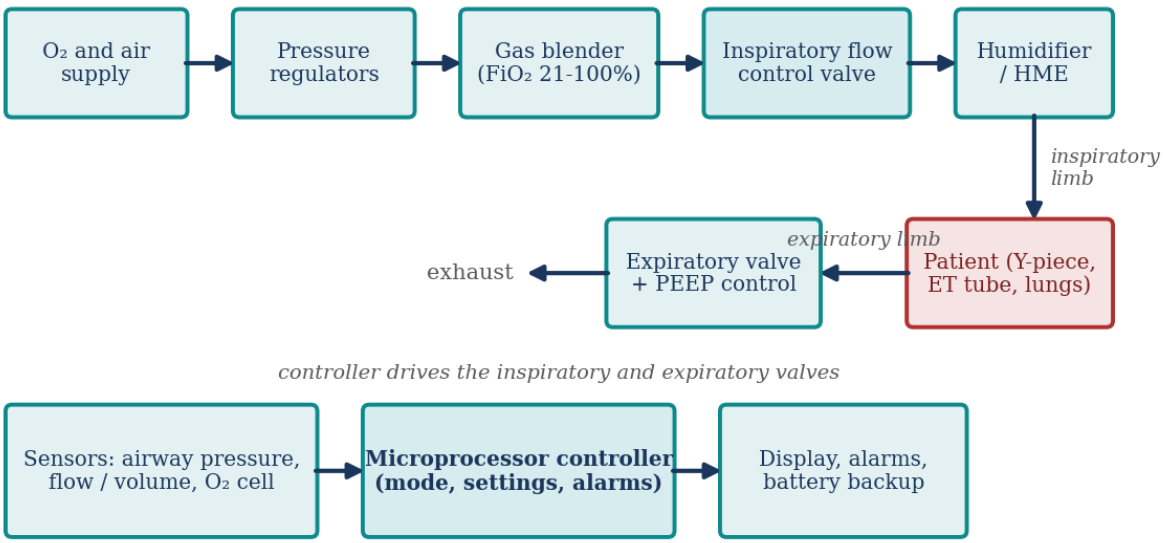


Fig. 3.1 *Block diagram of a positive-pressure ventilator.*

- **Gas supply:** high-pressure oxygen and air (about 3.5–4 bar from the hospital pipeline) or a compressor/turbine, reduced by **pressure regulators**.
- **Blender:** mixes air and oxygen to give the set **FiO_2** (21–100%).

- **Inspiratory flow control valve:** the controller opens it to deliver the set flow or pressure during inspiration.
- **Patient circuit:** inspiratory limb, humidifier or heat-and-moisture exchanger (HME), a Y-piece to the endotracheal tube and an expiratory limb.
- **Expiratory valve with PEEP control:** closes during inspiration and then opens to let the patient exhale down to the PEEP level.
- **Sensors, controller and alarms:** pressure, flow/volume and oxygen sensors feed the microprocessor, which controls the valves, displays waveforms and sounds alarms; a battery gives back-up during power failure.

3.4 The breath cycle

Every ventilator breath is defined by four events: what **triggers** inspiration (the patient's effort or a timer), what **limits** the gas delivery (a set flow, volume or pressure), what **cycles** the breath from inspiration to expiration (time, flow or volume) and the **baseline** pressure during expiration (PEEP). In **volume-controlled** ventilation the volume and flow are fixed and the pressure varies with the lungs; in **pressure-controlled** ventilation the pressure is fixed and the volume varies (Fig. 3.2).

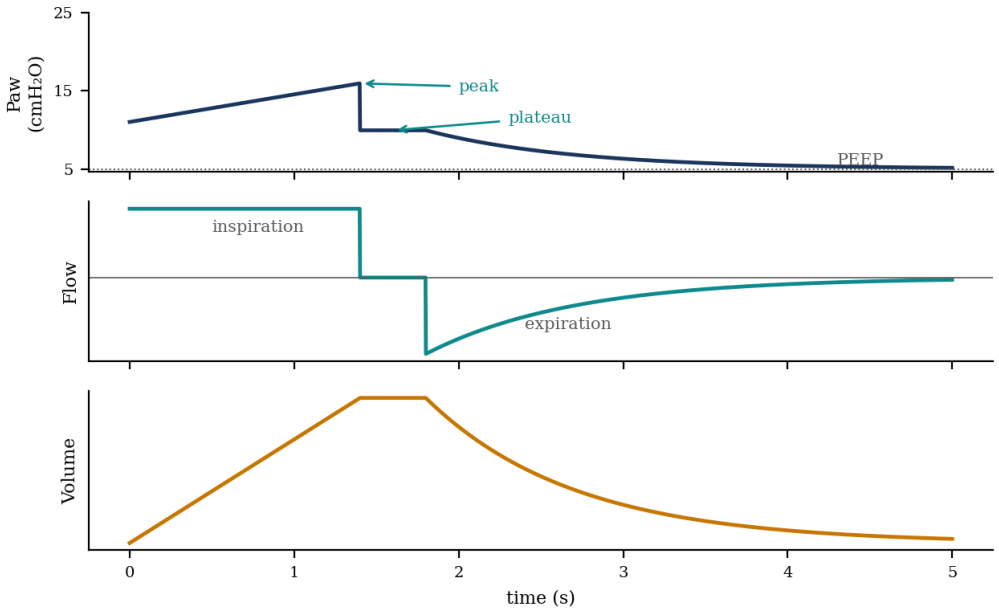


Fig. 3.2 *Pressure, flow and volume against time for a volume-controlled breath with an inspiratory pause.*

3.5 Ventilation modes

Mode	How it works	Typical use
Volume assist-control (VC-AC)	Every breath, machine- or patient-triggered, delivers the set tidal volume	Sedated or weak patients
Pressure assist-control (PC-AC)	Every breath is delivered to a set pressure for a set time	Lung protection; neonates
SIMV	Set number of mandatory breaths synchronised with the patient; extra spontaneous breaths are allowed	Weaning
Pressure support (PSV)	Each patient-triggered breath is assisted to a set pressure; the patient controls rate and timing	Weaning, spontaneously breathing patients

Mode	How it works	Typical use
CPAP	Constant positive pressure through the whole breath; no mandatory breaths	Sleep apnoea, mild respiratory failure
BiPAP (NIV)	Two pressure levels (higher on inspiration, lower on expiration) through a mask	COPD exacerbation, avoiding intubation

3.6 Typical settings

- **Tidal volume:** about 6–8 mL per kg of ideal body weight (lower values protect the lungs); **respiratory rate:** 12–20 per minute.
- **FiO_2:** the lowest value that keeps oxygen saturation adequate; **PEEP:** about 5–10 cmH_2O to keep alveoli open.
- **I:E ratio:** usually 1:2; **trigger sensitivity:** about −1 to −2 cmH_2O (pressure trigger) or 1–3 L/min (flow trigger).
- **Plateau pressure:** keep below about 30 cmH_2O to avoid lung injury.

3.7 Monitoring and alarms

Alarm	Common causes
High airway pressure	Kinked tube, secretions, coughing, bronchospasm, patient biting the tube
Low pressure / disconnection	Leak, circuit disconnected, cuff leak
Low tidal or minute volume	Leak, weak patient effort, wrong settings
Apnoea	No patient trigger in support modes
High / low FiO_2	Blender or oxygen-supply fault
Power or gas failure	Mains failure, empty cylinder; the machine switches to battery or air

3.8 Complications and care

- **Barotrauma and volutrauma** (pneumothorax from high pressures or volumes), **oxygen toxicity** from long exposure to high FiO_2, **ventilator-associated pneumonia** and reduced venous return from high intrathoracic pressure.
- **Patient–ventilator asynchrony** when the machine breath does not match the patient's effort.
- Use bacterial filters and clean or replace circuits as per protocol; calibrate the flow and oxygen sensors and run a pre-use test before connecting each patient.

EXAM FOCUS

Short answer (2 marks)

1. Define compliance and airway resistance.
2. What is PEEP and why is it used?
3. List the four phases of a ventilator breath.
4. Differentiate volume-controlled and pressure-controlled ventilation.
5. Mention two ventilator alarms and their causes.

Long answer (13 / 16 marks)

6. Explain with a block diagram the working of a positive-pressure ventilator.
7. Describe the common ventilation modes and state a typical use of each.
8. Discuss the complications of mechanical ventilation and the monitoring needed for a ventilated patient.

TOPIC 4
Infusion Pumps

An **infusion pump** delivers fluids, drugs or nutrients into a patient's body in precisely controlled amounts over a set time, usually through a vein but also by the subcutaneous, epidural or enteral route. It is far more accurate and safer than a gravity drip, which changes as the bag empties and the patient moves. Flow rates are set in **mL/h** and accuracy of about ±5% is typical.

4.1 Applications

- Chemotherapy, antibiotics, vasoactive drugs (dopamine, noradrenaline), heparin and insulin infusions.
- Analgesia and patient-controlled analgesia (PCA), anaesthesia and sedation in the operating theatre and ICU.
- Parenteral and enteral nutrition, and neonatal infusions where very small volumes must be given accurately.

4.2 Types of infusion pump

Type	Mechanism	Typical use
Volumetric (large-volume) pump	Peristaltic: rollers or fingers squeeze the IV tube in sequence and push fluid forward	General IV fluids and drugs from a bag
Syringe pump	A stepper motor turns a lead screw that pushes the syringe plunger at a precise speed	Small volumes, slow rates; ICU, neonates, anaesthesia
Ambulatory / PCA pump	Small battery-powered pump worn by the patient; patient presses a button for a bolus within set limits	Pain relief, chemotherapy at home
Insulin pump	Syringe-type pump delivering a basal rate with meal boluses through a subcutaneous cannula	Diabetes
Elastomeric pump	Non-electric: a stretched balloon pushes the drug through a flow-restrictor	Disposable, ambulatory use
Smart pump	Pump with a drug library and dose limits that warns about out-of-range doses	Medication-error prevention

4.3 Block diagram and components

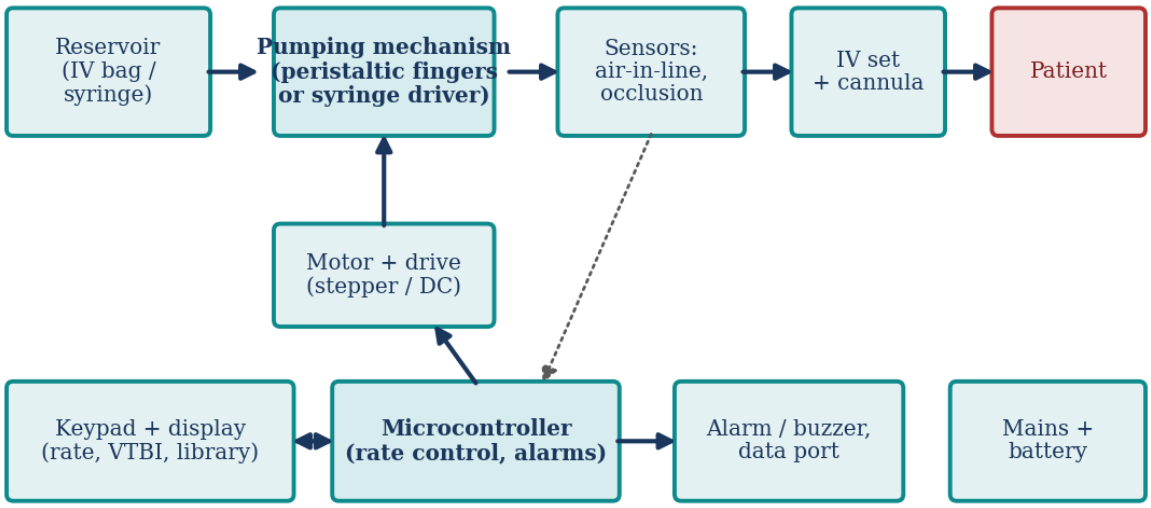


Fig. 4.1 *Block diagram of an electronic infusion pump.*

- **Pumping mechanism and motor:** a stepper or DC motor drives the peristaltic mechanism or the syringe plunger; the motor speed sets the flow rate.
- **Microcontroller:** converts the entered rate and volume to be infused (VTBI) into motor commands, counts the volume delivered and generates alarms.
- **Sensors:** air-in-line (ultrasonic), occlusion (pressure or force sensor on the tube or plunger), drop sensor, door-open and syringe-size detectors.
- **Keypad, display and alarm;** a data port for networking with hospital systems; mains supply with a rechargeable battery.

4.4 Flow rate calculations

For a **peristaltic pump** the flow rate is the volume delivered per stroke multiplied by the number of strokes per hour. For a **syringe pump** the flow is $Q = A \times v$, where $A = \pi d^2/4$ is the inner cross-section of the syringe barrel and v is the plunger speed. For example, a 50 mL syringe with an inner diameter of 26.7 mm has $A \approx 560$ mm². To deliver 10 mL/h (10 000 mm³/h) the plunger must move at $v = 10\,000 / 560 \approx 17.9$ mm/h, or about 0.3 mm per minute.

For a drug ordered by body weight, rate (mL/h) = dose (µg/kg/min) × weight (kg) × 60 / concentration (µg/mL). For example, dopamine at 5 µg/kg/min for a 70 kg patient from a 1600 µg/mL solution (400 mg in 250 mL) runs at $5 \times 70 \times 60 / 1600 \approx 13$ mL/h.

4.5 Safety features and alarms

Alarm / feature	Purpose
Occlusion alarm	Detects a blocked or kinked line or a closed clamp when the pressure rises above the set limit; stops the pump
Air-in-line alarm	Detects bubbles (above a set size) to prevent air embolism
End-of-infusion / near-end alarm	Warns that the bag or syringe is almost empty
Free-flow protection	Clamps the tube whenever the door is opened so fluid cannot run freely
Drug library with soft / hard limits	Warns (soft) or blocks (hard) doses outside the safe range

Alarm / feature	Purpose
Low-battery and power-failure alarm	Allows the pump to continue on battery and warns the user

Infusion pumps are tested against the standard **IEC 60601-2-24**, which sets requirements for accuracy and protection against incorrect delivery.

4.6 Errors and maintenance

- **Common problems:** wrong rate or concentration entered, wrong syringe size selected, a delay at the start of syringe infusion because of the compliance of the syringe and tubing, siphonage if a syringe pump is placed above the patient, and infiltration or phlebitis at the cannula site.
- **Maintenance:** periodic accuracy testing with an infusion-device analyser or by weighing the delivered fluid, occlusion-pressure checks, battery checks, cleaning and software updates.

EXAM FOCUS

Short answer (2 marks)

1. Define an infusion pump and state two advantages over gravity infusion.
2. Differentiate volumetric and syringe pumps.
3. Calculate the plunger speed needed for 10 mL/h with a syringe of 560 mm² cross-section.
4. List four safety alarms of an infusion pump.
5. What is a smart pump?

Long answer (13 / 16 marks)

6. Explain with a block diagram the working of a microcontroller-based infusion pump.
7. Describe the types of infusion pump with their mechanisms and uses.
8. Discuss the safety features, sources of error and maintenance of infusion pumps.

TOPIC 5
Dialysis Machines

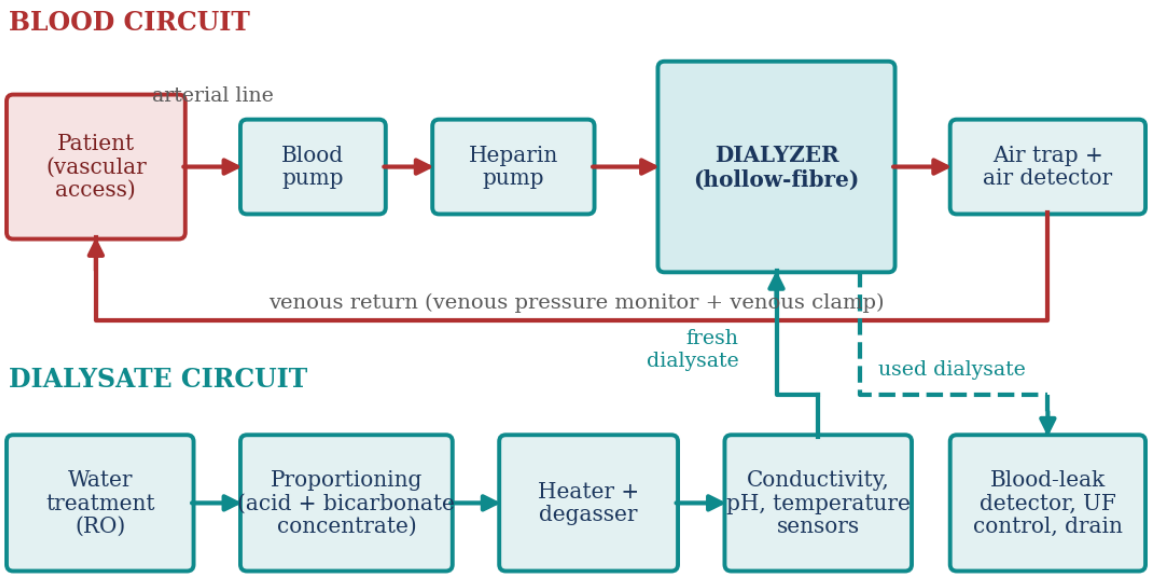
The kidneys remove urea, creatinine and excess water, balance electrolytes (Na^+, K^+, Ca^{2+}) and keep the blood pH steady. When they fail, as in end-stage renal disease (ESRD) or acute kidney injury, **renal replacement therapy** is needed: haemodialysis, peritoneal dialysis, continuous therapies or a kidney transplant. A **haemodialysis machine** pumps the patient's blood outside the body through a **dialyzer** where wastes pass across a semi-permeable membrane into a cleansing fluid called **dialysate**, and the cleaned blood returns to the patient.

5.1 Principles of dialysis

- **Diffusion:** solutes such as urea, creatinine and potassium move from blood (high concentration) to dialysate (low concentration) across the membrane. Blood and dialysate flow in opposite directions (**counter-current**) to keep the concentration gradient high along the whole membrane.
- **Ultrafiltration (UF):** excess water is removed by applying a pressure difference across the membrane. The **transmembrane pressure** is TMP = (Pb,in + Pb,out)/2 − (Pd,in + Pd,out)/2, and the UF rate = UF coefficient × TMP.
- **Convection:** in haemofiltration and haemodiafiltration, water carries dissolved solutes across the membrane (solvent drag).
- **Osmosis:** the driving force in peritoneal dialysis, where a glucose-rich fluid draws water into the peritoneal cavity.

Typical values for haemodialysis are a blood flow of 300–400 mL/min, a dialysate flow of about 500–800 mL/min and a session of 3–4 hours, three times a week. The **clearance** of a dialyzer for a solute is K = Qb (Cb,in − Cb,out) / Cb,in, where Qb is the blood flow rate.

5.2 Block diagram of a haemodialysis machine



Blood and dialysate flow in opposite directions (counter-current) inside the dialyzer

Fig. 5.1 *Haemodialysis circuit: blood circuit and dialysate circuit meeting at the dialyzer.*

- **Blood circuit:** vascular access (arteriovenous fistula, graft or catheter), arterial line, **blood pump** (peristaltic roller pump), **heparin pump** (syringe pump that prevents clotting), arterial

and venous pressure monitors, dialyzer, **venous air trap** with an **air detector** and a venous clamp that closes if air is found.

- **Water treatment:** the dialysate is made from water purified by reverse osmosis (RO) because the patient is exposed to 120–150 litres of water in every session.
- **Dialysate preparation:** a proportioning system mixes RO water with acid and bicarbonate concentrates; a heater brings the fluid to body temperature (about 36–37 °C) and a degasser removes dissolved air.
- **Monitors:** conductivity and pH (correct mixing), temperature, a **blood-leak detector** (photometric) on the outgoing dialysate, and UF control with balancing chambers or flow sensors.
- **Bypass and drain:** if any dialysate parameter is out of range the dialysate is routed past the dialyzer (bypass) and used dialysate goes to the drain.

5.3 The dialyzer

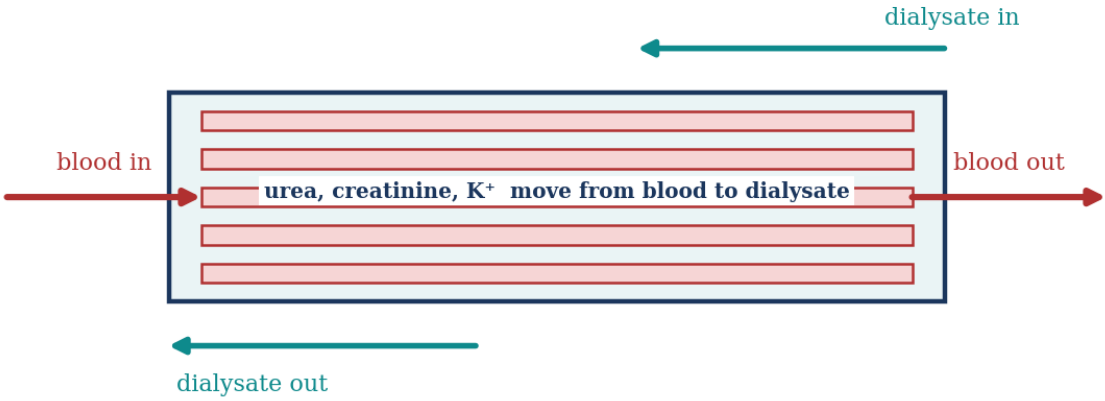


Fig. 5.2 *Hollow-fibre dialyzer: counter-current flow of blood (inside the fibres) and dialysate (outside).*

The commonest dialyzer is the **hollow-fibre (capillary) type**: a bundle of about 10 000 hair-thin fibres in a plastic housing. Blood flows through the fibres and dialysate flows around them in the opposite direction. The membrane is made of cellulose or synthetic polymers such as polysulfone; surface area is about 1.0–2.2 m². **High-flux** membranes have larger pores and remove larger molecules than **low-flux** ones. Older **flat-plate** and coil dialyzers are now rarely used.

Dialysate component	Typical concentration	Purpose
Sodium	About 135–145 mmol/L	Prevents large fluid shifts and cramps
Potassium	About 0–4 mmol/L (often 2)	Removes excess potassium
Calcium	About 1.25–1.75 mmol/L	Calcium balance
Bicarbonate	About 30–38 mmol/L	Corrects acidosis (buffer)
Glucose	About 0–11 mmol/L	Prevents low blood sugar

5.4 Safety monitoring

Parameter	How it is monitored	Machine response
Air in blood line	Ultrasonic air detector in the venous line	Stops the blood pump and closes the venous clamp

Parameter	How it is monitored	Machine response
Venous / arterial pressure	Pressure transducers	Alarm and stop pump on high or low pressure (access problems, clotting)
Blood leak	Photometric detector in dialysate outflow	Alarm; blood pump stopped and dialysate bypassed
Conductivity and pH	Sensors in the dialysate line	Dialysate bypass if outside the set limits
Temperature	Thermistor after the heater	Bypass if too hot or too cold
Ultrafiltration and TMP	Flow balance and pressure sensors	Alarm and correction of UF volume

5.5 Other renal replacement therapies

Therapy	Principle	Notes
Peritoneal dialysis (CAPD / APD)	Dialysis fluid placed in the peritoneal cavity; the peritoneum is the membrane; osmosis removes water	Done at home; no blood access needed
Haemodiafiltration (HDF)	Diffusion and convection combined, with replacement fluid	Better removal of middle-sized molecules
Continuous renal replacement therapy (CRRT)	Slow, continuous haemofiltration or haemodialysis	Critically ill, unstable patients in ICU
Kidney transplant	A donor kidney replaces the failed kidneys	Best long-term option when suitable

5.6 Complications and care

- **Complications:** low blood pressure, muscle cramps, air embolism, haemolysis, clotting in the circuit and infection at the vascular access.
- **Machine care:** disinfect with heat or chemicals between sessions, monitor water quality against standards such as ISO 23500, and test alarms and sensors before each treatment.

Further reading: R. S. Khandpur, Handbook of Biomedical Instrumentation; J. G. Webster (ed.), Medical Instrumentation: Application and Design; J. D. Bronzino, The Biomedical Engineering Handbook.

EXAM FOCUS

Short answer (2 marks)

1. Name the three transport mechanisms involved in dialysis.
2. Why do blood and dialysate flow in opposite directions in a dialyzer?
3. Define transmembrane pressure and write its formula.
4. What is the function of the air detector and the blood-leak detector?
5. List two differences between haemodialysis and peritoneal dialysis.

Long answer (13 / 16 marks)

6. Explain with a block diagram the working of a haemodialysis machine.
7. Describe the construction of a hollow-fibre dialyzer and the composition of dialysate.
8. Discuss the safety monitoring systems of a dialysis machine and the other renal replacement therapies.