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COLLEGE OF ENGINEERING & TECHNOLOGY
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Near Anjugramam - Kanyakumari Main Road, Palkulam, Variyoor P.O.-629401, Kanyakumari Dist, Tamil Nadu.

DEPARTMENT OF BIOMEDICAL ENGINEERING

VI Semester

BIOMEDICAL DEVICE DESIGN

2.2 Physiological Signal Measurement

This section explains how five of the most important physiological parameters – **ECG, EEG, EMG, SpO_2 and blood pressure** – are sensed, conditioned and displayed. For each one the origin of the signal, the sensor, the block diagram and the working are discussed, followed by key specifications.

➢A. Electrocardiogram (ECG)

Origin of the ECG signal

The heart contracts because of a wave of electrical depolarisation that begins at the **sino-atrial (SA) node**, spreads through the atria, pauses at the **atrio-ventricular (AV) node**, and then passes down the **bundle of His and Purkinje fibres** into the ventricles. The summed electrical activity of millions of cardiac cells produces potential differences on the body surface of about 0.5–4 mV. Recording these potentials against time gives the ECG.

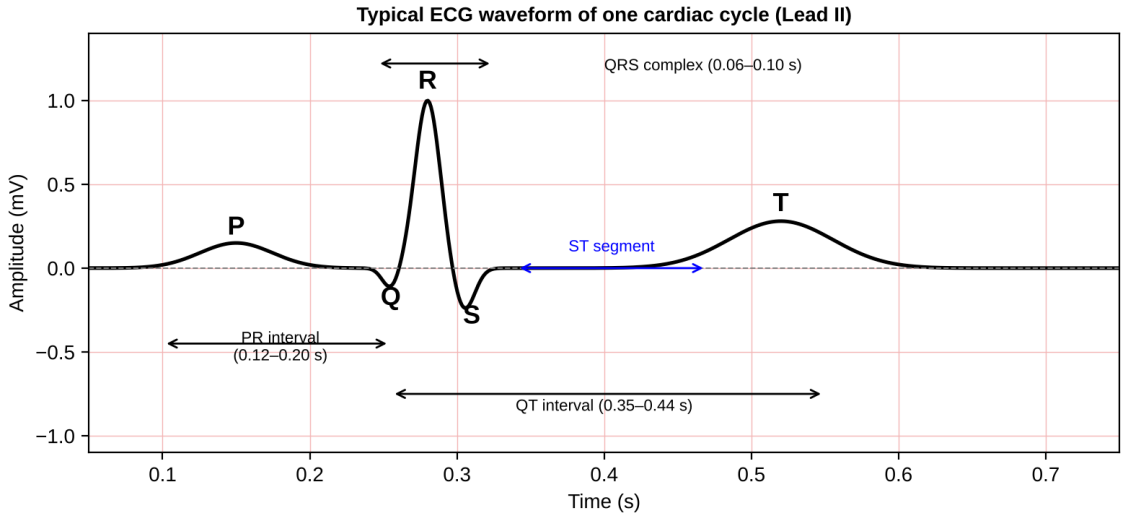

Fig. 2.3 Normal ECG waveform and its intervals

Wave / Interval	Represents	Normal value
P wave	Atrial depolarisation	0.08–0.10 s; < 0.25 mV
PR interval	Conduction from SA node to ventricles (AV delay)	0.12–0.20 s

Wave / Interval	Represents	Normal value
QRS complex	Ventricular depolarisation (atrial repolarisation is hidden)	0.06–0.10 s
ST segment	Early ventricular repolarisation; elevated in myocardial infarction	Isoelectric
T wave	Ventricular repolarisation	0.16 s
QT interval	Total ventricular depolarisation + repolarisation	0.35–0.44 s

ECG lead systems

A **lead** is a particular pair of electrode positions (or a combination) from which the potential difference is recorded. In **Einthoven's bipolar limb-lead system** the electrodes are placed on the right arm (RA), left arm (LA) and left leg (LL), forming an equilateral triangle with the heart at the centre. A right-leg electrode serves as the ground/reference.

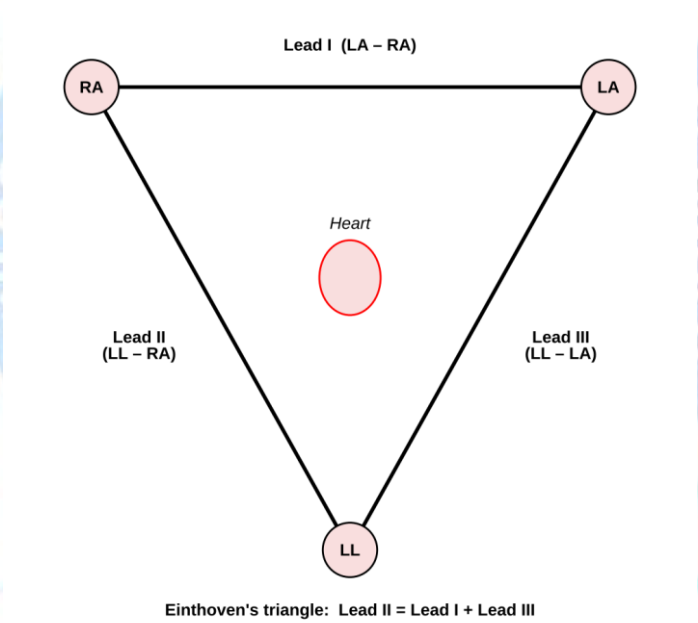

Fig. 2.4 Einthoven's triangle and bipolar limb leads

Lead I = V(LA) – V(RA); Lead II = V(LL) – V(RA); Lead III = V(LL) – V(LA); Lead II = Lead I + Lead III

In addition to the three bipolar leads, the standard **12-lead ECG** uses three **augmented unipolar limb leads** (aVR, aVL, aVF) and six **chest (precordial) leads** V1–V6. Together they view the heart from the frontal plane and the horizontal plane, allowing localisation of infarcts and arrhythmias.

Block diagram and working of an ECG machine

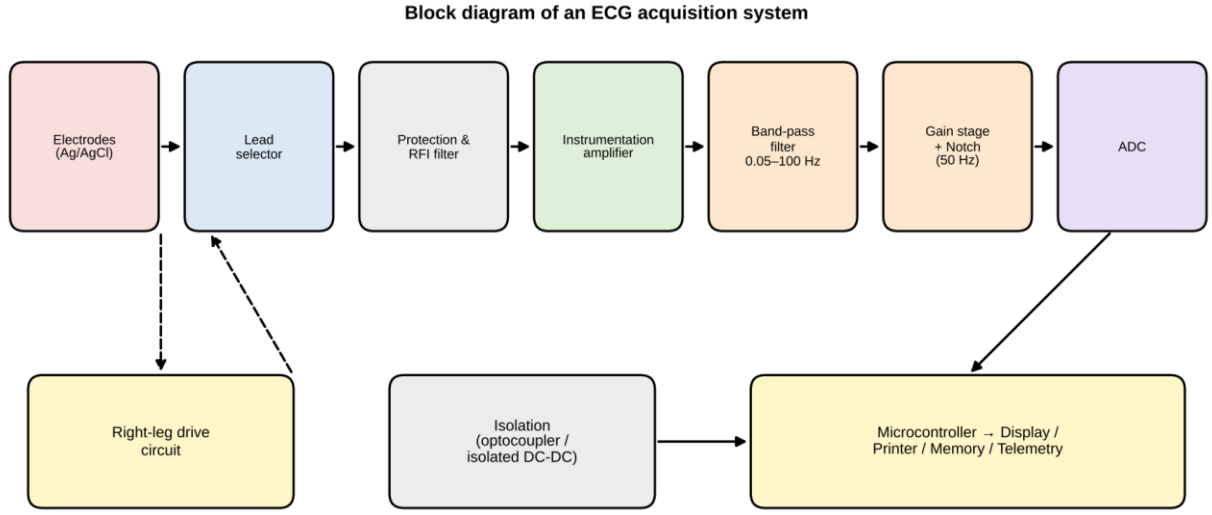

Fig. 2.5 Block diagram of an ECG acquisition system

1. **Electrodes (Ag/AgCl):** pick up the potential from the limbs/chest through conductive gel.
2. **Lead selector:** a switching network that selects Lead I, II, III, aVR, aVL, aVF or V1–V6 for display.
3. **Protection circuit:** limits the input voltage during defibrillation (neon lamps / diodes / series resistors) and an RFI filter removes high-frequency interference.
4. **Instrumentation (pre-)amplifier:** a differential amplifier with very high input impedance and CMRR > 100 dB amplifies the millivolt-level signal and rejects 50 Hz common-mode noise.
5. **Right-leg drive (RLD) circuit:** it senses the common-mode voltage, inverts and amplifies it, and feeds it back to the right-leg electrode. This actively cancels common-mode interference and also limits patient leakage current.
6. **Band-pass filter (0.05–100 Hz) and 50 Hz notch filter:** remove baseline wander, muscle noise and mains hum.
7. **Main amplifier / gain stage:** raises the signal to about 1–2 V for the ADC.
8. **Isolation stage:** an optocoupler or isolated DC–DC converter separates the patient from mains to satisfy safety limits.
9. **ADC and microcontroller:** digitise (typically 250–1000 samples/s, 12–24 bit), perform QRS detection and heart-rate calculation, then send data to display, printer, memory or wireless link.

Specifications of a typical diagnostic ECG

Parameter	Typical value
Input impedance	> 10 MΩ
CMRR	> 100 dB (at 50 Hz)
Frequency response	0.05 Hz – 100 Hz (diagnostic), 0.5–40 Hz (monitor)
Sensitivity / gain	5, 10, 20 mm/mV
Chart speed	25 and 50 mm/s

Parameter	Typical value
Patient leakage current	< 10 µA (CF type)
Noise	< 30 µV peak-to-peak

➢B. Electroencephalogram (EEG)

Origin and nature

The EEG records the electrical activity of the cerebral cortex. It is generated mainly by the summed **post-synaptic potentials** of large groups of pyramidal neurons that fire in synchrony. Because the signal must pass through the cerebrospinal fluid, skull and scalp, only 5–300 µV reaches the electrodes, i.e. it is about 100 times smaller than the ECG. EEG is used to diagnose epilepsy, sleep disorders, brain tumours, coma and brain death, and in brain–computer interfaces.

Electrode placement – International 10–20 system

The 10–20 system places 19 electrodes at distances of 10 % and 20 % of the nasion–inion and left–right preauricular distances. Odd numbers denote the left hemisphere, even numbers the right hemisphere and "z" the mid-line. The letters represent the underlying lobe: **Fp** – frontopolar, **F** – frontal, **C** – central, **P** – parietal, **T** – temporal, **O** – occipital.

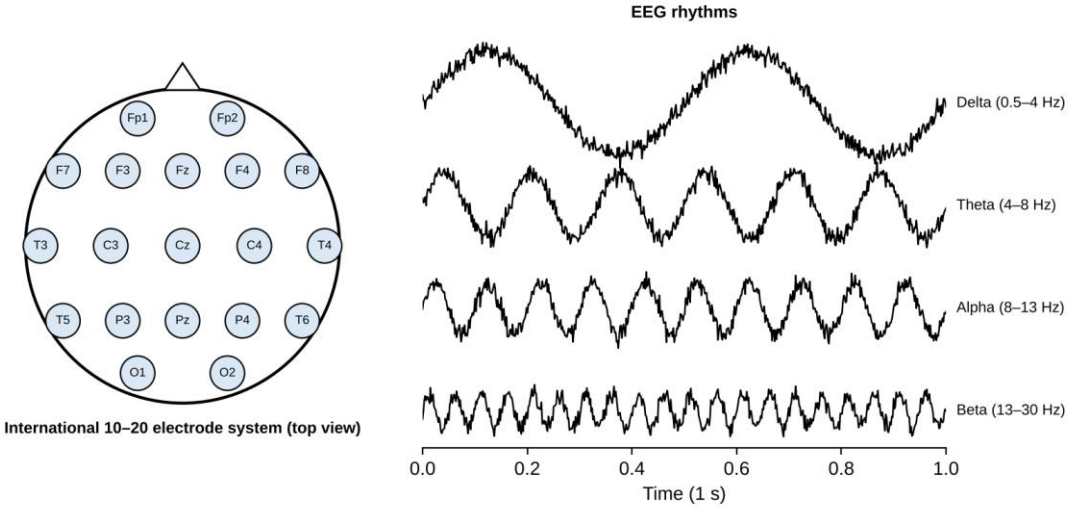

Fig. 2.6 10–20 electrode system and the four main EEG rhythms

Rhythm	Frequency	Amplitude	State of the person
Delta (δ)	0.5 – 4 Hz	100 – 200 µV	Deep sleep, brain damage
Theta (θ)	4 – 8 Hz	50 – 100 µV	Drowsiness, light sleep
Alpha (α)	8 – 13 Hz	20 – 60 µV	Relaxed with eyes closed; occipital region
Beta (β)	13 – 30 Hz	5 – 30 µV	Alert, active thinking, anxiety
Gamma (γ)	> 30 Hz	< 5 µV	High-level cognition

Block diagram and working

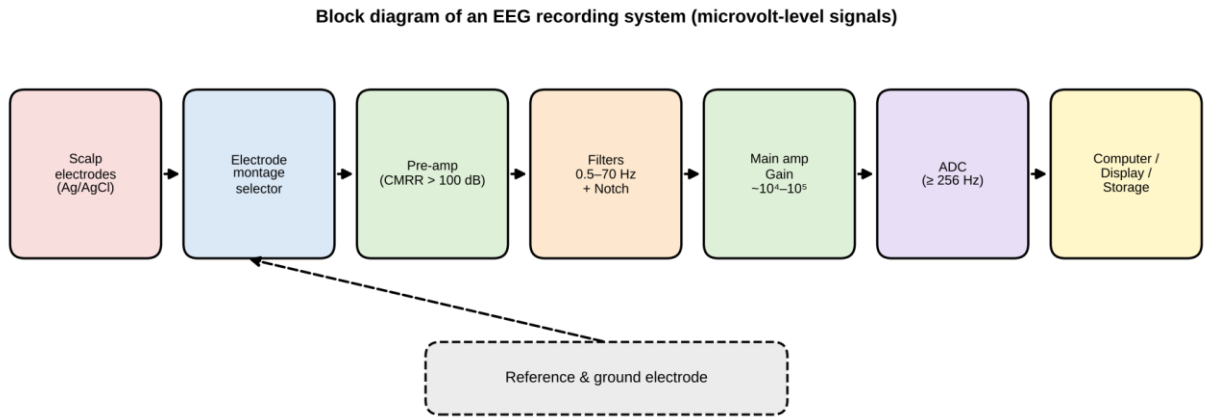

Fig. 2.7 Block diagram of an EEG recording system

Scalp electrodes (usually 21 channels) are connected through a **montage selector** to a high-gain differential **pre-amplifier** with CMRR above 100 dB and input impedance above 100 MΩ. Because the electrode–skin impedance must be below 5 kΩ for EEG, the skin is cleaned and abraded and conductive paste is used. The signal is then passed through filters (high-pass 0.5 Hz to remove drift, low-pass 70 Hz to remove EMG, and a 50 Hz notch). A **main amplifier** with a gain of 10^4–10^5 brings the signal to ADC level; the ADC samples at 256 Hz or more per channel, and the computer displays, stores and analyses the waveform (e.g. spectral analysis, seizure detection). Reference and ground electrodes are placed on the ear lobes or mastoid.

- ✓ **Recording modes:** *bipolar* (difference between adjacent electrodes) and *referential/monopolar* (each electrode versus a common reference).
- ✓ **Activation procedures:** hyperventilation and photic stimulation are used to provoke abnormalities.
- ✓ **Special care:** isolation from mains, shielded room, and impedance checking are mandatory.

➢C. Electromyogram (EMG)

Origin of EMG

The EMG measures the electrical activity produced by skeletal muscles when they contract. A single **motor unit** consists of one motor neuron and all the muscle fibres it innervates. The summation of the **motor-unit action potentials (MUAPs)** gives the interference pattern recorded by the electrodes. Amplitude is between 0.1 and 5 mV and the useful bandwidth is 10–500 Hz (surface) and up to 10 kHz (needle).

Types of EMG electrodes

- ✓ **Surface electrodes:** non-invasive, record the global activity of superficial muscles; used in kinesiology, prosthetics and biofeedback.
- ✓ **Needle / fine-wire electrodes:** inserted into the muscle; record individual motor units; used for neuromuscular diagnosis (e.g. neuropathy, myopathy).

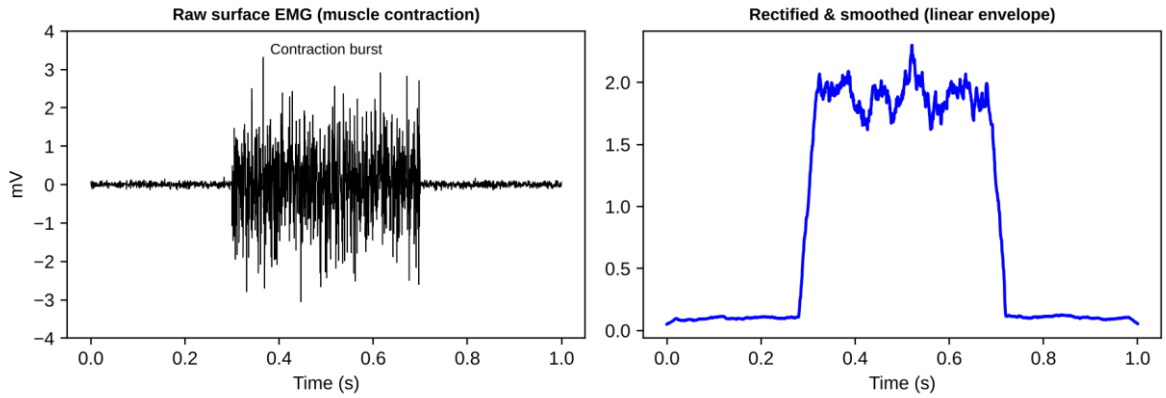

Fig. 2.8 Raw EMG signal and its processed envelope

Block diagram and working

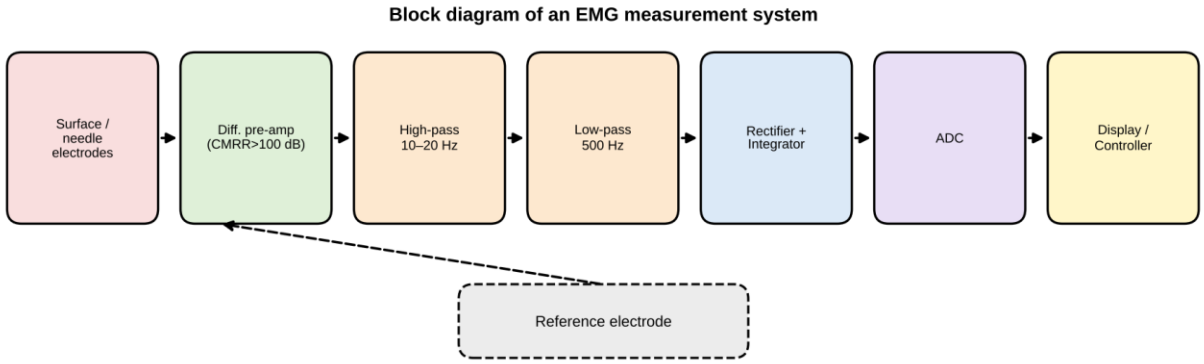

Fig. 2.9 Block diagram of an EMG measurement system

Two recording electrodes are placed over the muscle belly and a third reference electrode is placed over electrically neutral tissue (bone). The differential **pre-amplifier** (gain 100–1000, CMRR > 100 dB) amplifies the difference signal and rejects common-mode noise. The signal then passes through a **high-pass filter (10–20 Hz)** that removes motion artefact and a **low-pass filter (≈ 500 Hz)** that prevents aliasing. For quantification the signal is **full-wave rectified** and **integrated / low-pass filtered** to obtain the linear envelope, which is proportional to muscle force. Finally the ADC digitises the signal for the display, loudspeaker (audio feedback) or controller (e.g. to drive a myoelectric prosthetic hand).

Parameter	EMG	ECG
Source	Skeletal muscle	Heart muscle
Amplitude	0.1–5 mV	0.5–4 mV
Frequency	10–500 Hz	0.05–100 Hz
Nature	Random, interference pattern	Quasi-periodic

Applications of EMG

- ✓ Diagnosis of neuromuscular diseases, nerve injury and muscle fatigue
- ✓ Control of myoelectric prostheses and robotic exoskeletons
- ✓ Rehabilitation biofeedback, ergonomics and sports science

✓ Gesture recognition in human–machine interfaces

➢D. Pulse Oximetry (SpO_2)

Principle

Oxygen saturation (SpO_2) is the percentage of haemoglobin in arterial blood that is carrying oxygen. Oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (Hb) absorb red and infrared light differently: **Hb absorbs more red light (660 nm)** while **HbO_2 absorbs more infrared light (940 nm)**. The pulse oximeter works on the **Beer–Lambert law** and **photoplethysmography (PPG)**: with each heartbeat the volume of arterial blood in the finger increases, so the light absorption has a small pulsatile **AC** component superimposed on a large steady **DC** component caused by tissue, bone and venous blood.

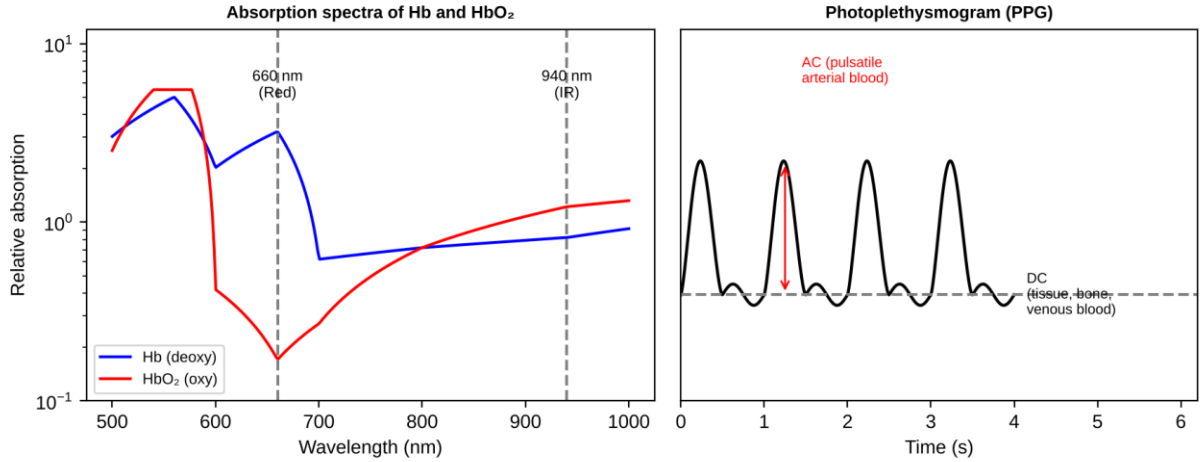

Fig. 2.10 Absorption spectra of Hb and HbO_2 and the photoplethysmogram

$$R = (AC_{660} / DC_{660}) / (AC_{940} / DC_{940}) \qquad SpO_2\ (\%) \approx 110 - 25\,R \quad \textit{(empirical calibration)}$$

The ratio-of-ratios **R** cancels the effect of tissue thickness, skin colour and light intensity; the microcontroller converts R to SpO_2 using a calibration look-up table derived from healthy volunteers. Normal SpO_2 is 95–100 %; below 90 % indicates hypoxaemia.

Block diagram and working

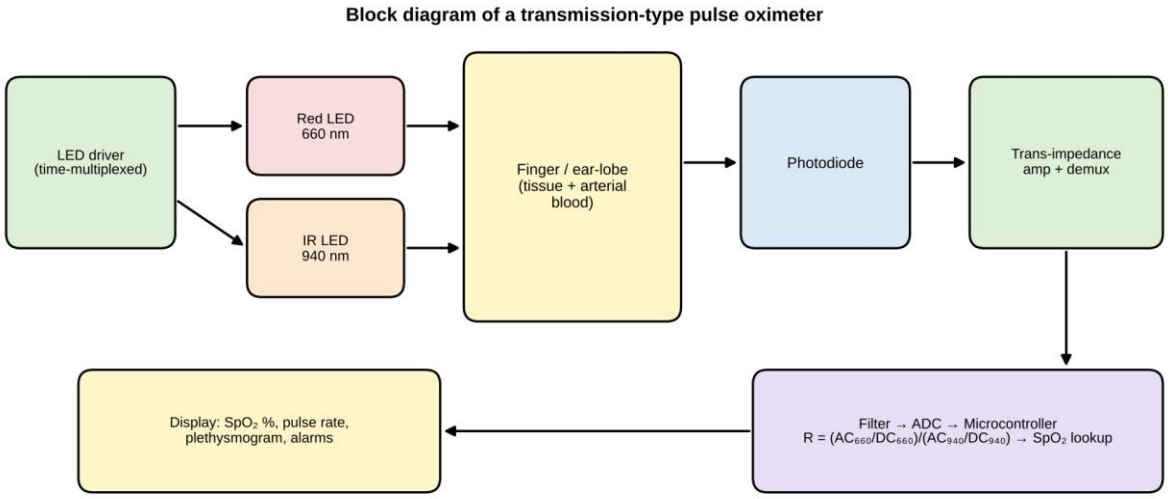

Fig. 2.11 Block diagram of a transmission-type pulse oximeter

1. The **LED driver** switches the red (660 nm) and infrared (940 nm) LEDs on alternately in time-multiplexed fashion (with a dark period to measure ambient light).
2. Light passes through the finger or ear-lobe (**transmission mode**) or is reflected from the forehead/wrist (**reflectance mode**).
3. A single **photodiode** detects the light; its current is converted to voltage by a **trans-impedance amplifier**.
4. A **demultiplexer / sample-and-hold** separates the red and IR channels; band-pass filtering separates AC from DC.
5. The **ADC and microcontroller** compute R, then SpO_2 and the pulse rate and drive the display and alarms.

Sources of error

- ✓ Motion artefact, poor perfusion (cold fingers) and ambient light
- ✓ Nail polish, dark skin pigmentation (slight overestimation)
- ✓ Carboxyhaemoglobin (CO poisoning) is read as HbO_2, causing falsely high SpO_2
- ✓ Venous pulsation and intravenous dyes (methylene blue)

➢E. Blood Pressure Measurement

Introduction

Blood pressure (BP) is the force exerted by blood on the arterial walls. **Systolic pressure (SBP, ≈ 120 mmHg)** is the peak pressure during ventricular contraction and **diastolic pressure (DBP, ≈ 80 mmHg)** is the minimum during relaxation. Mean arterial pressure is **MAP = DBP + (SBP – DBP)/3**. Methods are classified as **direct (invasive)** and **indirect (non-invasive)**.

1. Direct (invasive) method

A catheter filled with saline is inserted into an artery and connected through a fluid-filled line to an external **strain-gauge or MEMS pressure transducer**. It gives beat-to-beat pressure waveform and is used in ICU and cardiac surgery. It is accurate but carries risks of infection, clotting and bleeding.

2. Indirect auscultatory (Korotkoff) method

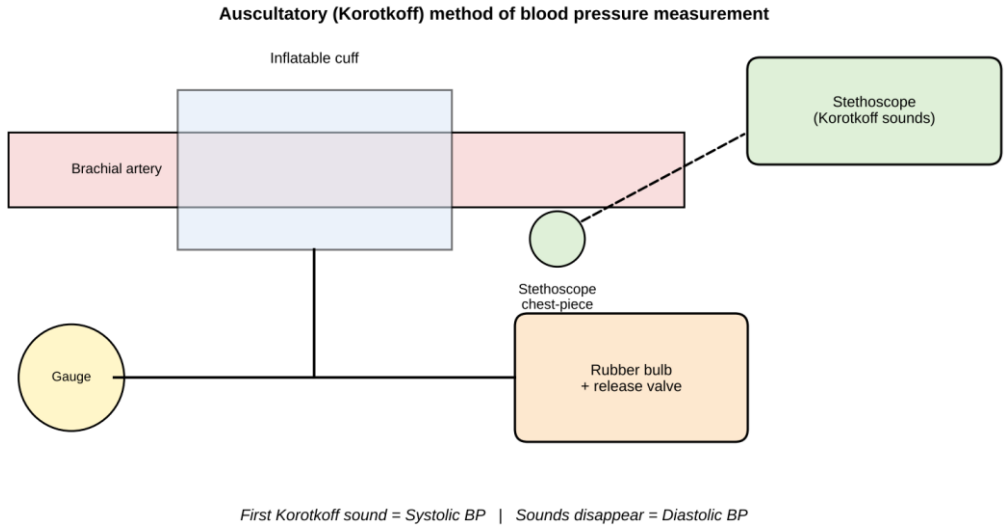

Fig. 2.12 Auscultatory method using a cuff, stethoscope and sphygmomanometer

A cuff placed on the upper arm is inflated above systolic pressure so that the brachial artery is completely occluded. The cuff is then deflated slowly (2–3 mmHg/s). When cuff pressure falls just below systolic pressure, blood spurts through and produces tapping **Korotkoff sounds** heard with the stethoscope; the pressure at the **first sound is SBP**. As the cuff pressure falls further the artery opens fully and the sounds fade; the pressure at which they **disappear is DBP**.

3. Oscillometric method (automatic NIBP)

Automatic and home BP monitors use the oscillometric method. A pressure sensor detects small oscillations caused by arterial wall movement that appear in the cuff pressure while the cuff deflates. The oscillation amplitude rises to a maximum when cuff pressure equals **mean arterial pressure (MAP)** and then declines. The microcontroller determines SBP and DBP from fixed fractions of the maximum amplitude (empirically about 0.5 × max on the high-pressure side and 0.8 × max on the low-pressure side).

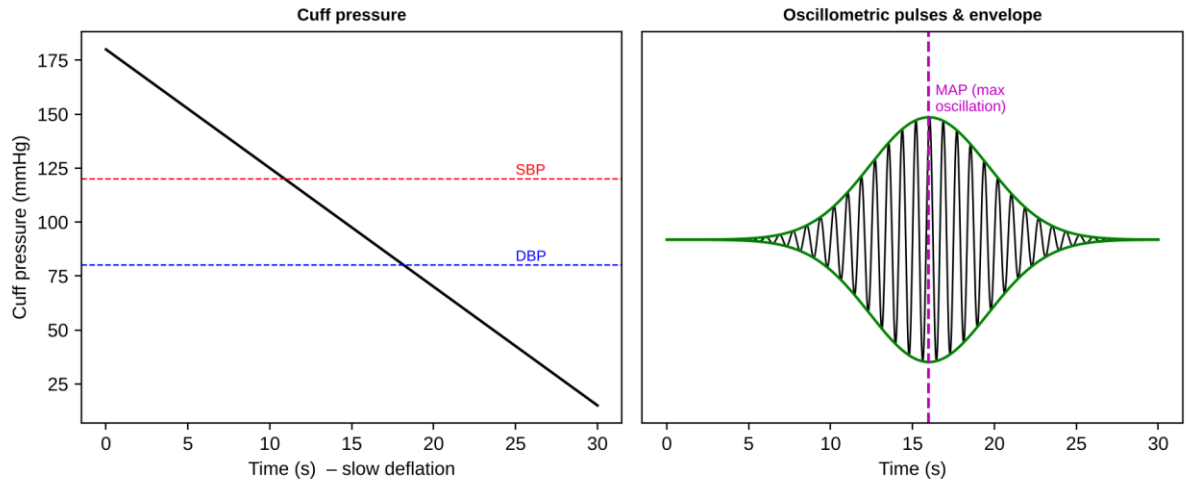

Fig. 2.13 Cuff deflation curve and oscillometric envelope

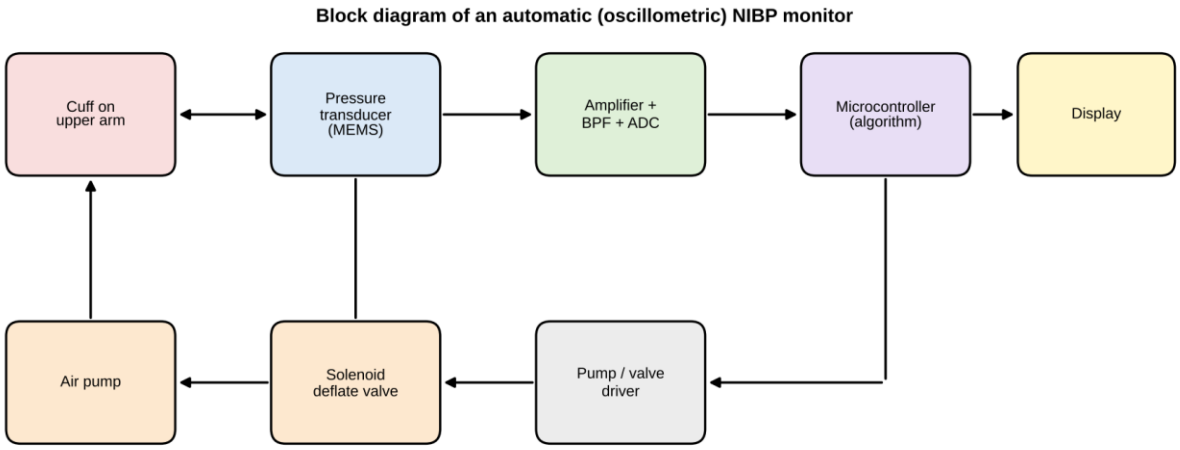

Fig. 2.14 Block diagram of an automatic oscillometric NIBP monitor

1. The **pump** inflates the cuff to about 30 mmHg above the expected systolic pressure; the controller drives the pump through a driver circuit.
2. A **MEMS pressure transducer** continuously measures cuff pressure; the signal is amplified and band-pass filtered (0.5–5 Hz) to extract the small oscillations from the large DC cuff pressure.
3. The **solenoid valve** deflates the cuff in steps or continuously.
4. The **microcontroller** finds the oscillation envelope, locates MAP, calculates SBP and DBP, and shows them with the pulse rate on the display.
5. Safety: an over-pressure relief valve and a watchdog timer prevent injury.

Comparison of BP measuring methods

Feature	Invasive	Auscultatory	Oscillometric
Accuracy	Highest (gold standard)	Good, observer dependent	Good, algorithm dependent
Sensor	Strain gauge / MEMS via catheter	Stethoscope + mercury / aneroid gauge	MEMS pressure sensor
Skill needed	Clinician, sterile	Trained observer	None
Output	Continuous waveform	SBP, DBP	SBP, DBP, MAP, pulse
Use	ICU, surgery	Clinic	Home and wearable devices