BIOMEDICAL INSTRUMENTATION

(24BM502)

UNIT IV

MEDICAL IMAGING AND DIAGNOSTIC TECHNOLOGIES

Topics Covered

7. Digital Image Acquisition and Processing
8. AI-Based Medical Image Analysis
9. Computer-Aided Diagnosis (CAD)
10. Augmented Reality in Medical Imaging

7. Digital Image Acquisition and Processing

7.1 What Is Digital Image Processing?

Digital Image Processing (DIP) is the use of computers and algorithms to modify or analyse images, replacing traditional film-based methods. It enables improvements such as removing blurriness, sharpening images, or recognising objects (for example, facial recognition on smartphones). DIP operates pixel by pixel to generate clearer, more useful images, and supports applications ranging from tumour detection to robotic vision.

- **Medicine:** CT scans, MRIs, and X-rays are processed to help detect abnormalities such as tumours
- **Robot vision:** enables robots and self-driving cars to navigate their environment
- **Pattern recognition:** used in facial recognition, fingerprint analysis, and handwriting detection
- **Video processing:** supports editing, motion tracking, and surveillance analysis
- **Remote sensing:** used by satellites for weather monitoring and disaster assessment

7.2 Fundamental Steps of Digital Image Processing

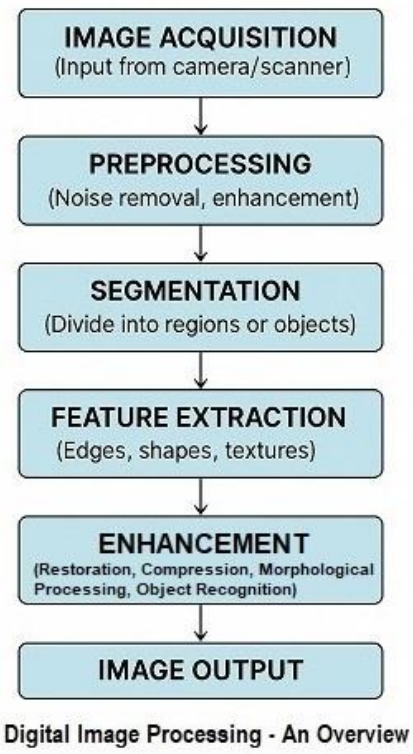


Fig. 7.1 The fundamental steps of digital image processing

- Image acquisition — capturing images using cameras or scanners; the first step, since no processing is possible without an image.
- Preprocessing — enhancing image quality by removing noise or adjusting contrast.
- Segmentation — dividing the image into meaningful regions.
- Feature extraction — identifying important attributes such as edges and shapes.
- Enhancement — making the image visually appealing (e.g., sharpening or brightening).
- Restoration — correcting image defects such as blurriness.

- Compression — reducing file size for storage and transmission.
- Morphological processing — refining image shapes and structures.
- Object recognition — identifying and labelling objects within the image.
- Output — saving or further analysing the processed image.

7.3 Image Acquisition Methods

Image acquisition is the first step in the DIP workflow. Incoming energy is transformed into a voltage by the combination of input electrical power and a sensor material responsive to the type of energy being detected; the output voltage waveform is then digitized to give a digital quantity from each sensor.

- **Single sensor:** for example, a photodiode; obtaining a 2-D image needs motion in both x and y directions — rotation provides motion in one direction and linear motion provides the perpendicular direction; inexpensive with high-precision, high-resolution results, but slow
- **Line sensor (sensor strip):** provides imaging in one direction directly from the strip, with motion perpendicular to the strip providing the other direction
- **Array sensor:** a 2-D grid of individual sensing elements that captures the full image at once, without requiring mechanical motion — the approach used in modern digital cameras and detectors

7.4 Digitisation: Sampling and Quantisation

A real image is continuous in both space and brightness. To store it in a computer it must be digitised in two separate steps.

- **Sampling:** measuring the image at regular spatial positions to form a grid of pixels (for example, a 512 × 512 matrix for a CT slice). More samples give finer spatial detail.
- **Quantisation:** assigning each sample one of a fixed number of grey levels. The bit depth sets the number of levels: 8 bits give 256 levels, while medical images typically use 12–16 bits (4,096 to 65,536 levels) to preserve subtle contrast differences.

Storage required = rows × columns × bits per pixel ÷ 8 bytes. For example, a 512 × 512 CT slice at 12 bits per pixel needs 512 × 512 × 12 ÷ 8 = 393,216 bytes, about 384 KB, before compression.

7.5 Image Enhancement Techniques

Technique	What it does	Typical use
Contrast stretching / windowing	Expands the range of grey levels of interest to fill the display	Viewing soft tissue vs. bone in CT
Histogram equalisation	Redistributes grey levels to flatten the histogram and increase contrast	Low-contrast radiographs
Smoothing (mean, Gaussian, median)	Averages neighbouring pixels to reduce noise; median filter removes “salt-and-pepper” spikes	Noisy ultrasound and low-dose CT
Sharpening (Laplacian, unsharp mask)	Boosts high-frequency detail at edges	Fine bone and vessel detail
Edge detection (Sobel, Canny)	Highlights boundaries where intensity changes sharply	Preparing images for segmentation

7.6 Segmentation and Compression

Segmentation Methods

- **Thresholding:** pixels above or below an intensity value are assigned to a region; simple and fast.
- **Region growing:** starts from a seed point and grows by adding neighbouring pixels of similar intensity.
- **Clustering:** groups pixels by similarity, for example with k-means clustering.
- **Deep-learning segmentation:** networks such as U-Net learn to outline organs and lesions directly from labelled examples.

Compression

- **Lossless:** the original image is recovered exactly; preferred for primary diagnosis but gives modest size reduction.
- **Lossy:** achieves much smaller files by discarding some information; acceptable only at controlled levels, where diagnostic quality is shown to be retained.

7.7 DICOM and PACS

- **DICOM:** Digital Imaging and Communications in Medicine, the universal standard for storing and exchanging medical images. A DICOM file holds the pixel data together with a header containing patient identity, modality, acquisition settings, and study details.
- **PACS:** Picture Archiving and Communication System: stores images from every modality, retrieves them on demand, and distributes them to radiologists and clinicians across the hospital network, linked to the hospital and radiology information systems.

Key Takeaways

- Digital image processing converts, enhances and analyses images pixel by pixel; acquisition is always the first step.
- Digitisation involves sampling (pixel grid) and quantisation (bit depth); both affect quality and file size.
- Enhancement improves visibility, segmentation isolates regions of interest, and compression reduces storage while lossless methods preserve diagnostic data.
- DICOM standardises image files and metadata, and PACS handles their storage and distribution.

8. AI-Based Medical Image Analysis

8.1 What Is AI in Medical Imaging?

Artificial intelligence (AI) in medical imaging refers to the use of machine learning, deep learning, and computer vision systems to analyse imaging data — including radiology scans, ultrasound images, and multispectral wound images — with greater speed, consistency, and reproducibility than traditional visual interpretation alone. AI enhances diagnostic accuracy, accelerates workflows, and supports more objective decision-making across radiology, wound care, pathology, and cardiology.

8.2 Why AI Matters in Modern Diagnostics

AI plays a central role in modern diagnostics because clinicians must interpret an expanding volume of imaging data under increasing time pressure. Tools that extract patterns, highlight abnormalities, and quantify findings help reduce variability between clinicians and improve diagnostic confidence.

Core Applications

- **Medical imaging analysis:** AI algorithms analyse X-rays, CT scans, MRI datasets, ultrasound, and multispectral imaging to identify subtle abnormalities — including pulmonary findings, oncologic changes, and tissue-viability patterns — that may be difficult to detect visually
- **Predictive analytics:** AI models integrate imaging data with patient history, biomarkers, and demographic factors to forecast risks and outcomes
- **Electronic Health Records (EHRs):** AI automates data extraction, classification, and documentation, and supports population-health surveillance, reducing administrative burden and improving longitudinal tracking of imaging trends
- **Virtual health assistants:** chatbots and virtual agents help patients self-screen symptoms, schedule imaging appointments, and understand preparation instructions

8.3 Clinical Benefits

- Faster interpretation, especially in high-volume radiology departments.
- More consistent findings across clinicians and across shifts.
- Detection of faint or early abnormalities that are often missed during rapid reads.

8.4 AI-Powered Medical Imaging Tools

Modern AI systems use convolutional neural networks (CNNs), generative models, and image segmentation algorithms to detect anomalies, classify tissues, and support diagnostic decisions. These tools now match or exceed human-level performance in several imaging domains.

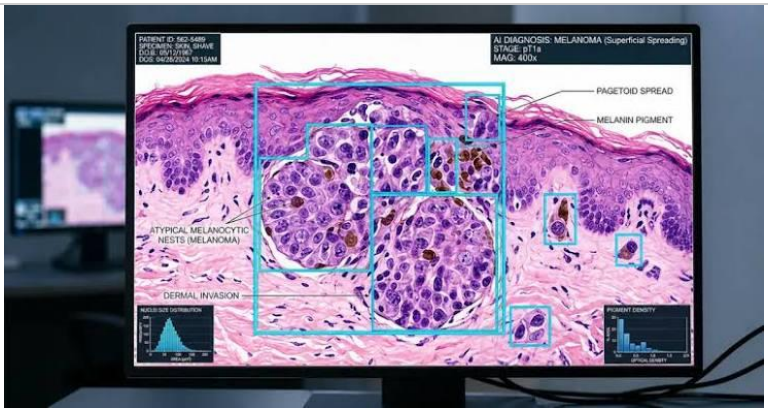


Fig. 8.1 AI-assisted digital pathology — automated detection and annotation of malignant cell patterns in a tissue sample

- **AI in pathology:** aids pathologists by digitally scanning slides and identifying micro-patterns associated with malignancy, inflammation, or tissue damage
- **AI in cardiology:** interprets echocardiograms, CT angiography, and cardiac MRI to detect structural defects, perfusion deficits, or early signs of cardiomyopathy

8.5 How Deep-Learning Models Analyse Images

A convolutional neural network (CNN) passes the image through successive layers. Early convolution layers detect simple features such as edges; deeper layers combine them into textures and then into whole structures such as nodules or organs. Pooling layers shrink the data, and a final output layer produces a result, such as the probability that an abnormality is present.

Typical Development Workflow

- **Data collection and labelling:** collect a large set of images and have experts annotate them with the correct diagnosis or outline.
- **Preprocessing:** normalise intensities and augment the data (rotations, flips, brightness changes) to improve robustness.
- **Training:** split the data into training, validation, and test sets; the network adjusts its weights on the training set while the validation set guides tuning.
- **Evaluation:** measure sensitivity, specificity, and area under the ROC curve (AUC) on unseen test data, preferably from other hospitals.
- **Deployment:** integrate the model into the reporting workflow and monitor its performance over time.

8.6 Main Tasks of AI in Imaging

Task	What the AI does	Example
Classification	Assigns a label to the whole image	Normal vs. pneumonia on a chest X-ray
Detection	Locates and marks abnormal findings	Lung nodules, fractures, breast lesions
Segmentation	Outlines organs or lesions pixel by pixel	Tumour volume for radiotherapy planning

Task	What the AI does	Example
Reconstruction / denoising	Improves image quality from limited data	Low-dose CT, accelerated MRI
Triage	Reorders the worklist so urgent cases are read first	Alerting on suspected intracranial haemorrhage

8.7 Challenges and Ethical Considerations

- **Data quality and bias:** models trained on limited or unrepresentative data may perform poorly on other populations or on images from different scanners.
- **Explainability:** many deep networks behave as "black boxes"; clinicians need to understand why a finding was flagged before trusting it.
- **Privacy and security:** patient images must be de-identified and protected under data-protection rules.
- **Regulation:** AI software used for diagnosis is regulated as a medical device and requires clinical validation.
- **Automation bias:** over-reliance on AI output can cause errors to go unchallenged, so the clinician must remain the final decision-maker.

Key Takeaways

- AI in imaging uses machine learning and deep learning, mainly CNNs, to detect, classify, segment, and quantify findings.
- Its main benefits are speed, consistency, and detection of subtle abnormalities, especially in high-volume departments.
- Models depend on good annotated data and must be validated on independent data before clinical use.
- Bias, explainability, privacy, and regulation are the central challenges; AI supports, but does not replace, the clinician.

9. Computer-Aided Diagnosis (CAD)

9.1 What Is CAD?

Computer-aided detection (CADe) and computer-aided diagnosis (CADx) are systems that assist doctors in interpreting medical images. X-ray, MRI, endoscopy, and ultrasound produce a huge amount of information that a radiologist must analyse in a short time. CAD systems process digital images or videos for typical appearances and highlight conspicuous sections, such as possible disease, to support the professional's decision. CAD is interdisciplinary, combining artificial intelligence and computer vision with radiological and pathology image processing. A typical application is tumour detection — for example, mammography for breast cancer, colonoscopy for polyps, and lung cancer screening.



Fig. 9.1 CAD software overlay on a hand X-ray, automatically annotating skeletal landmarks

9.2 The Family of CAD Systems

- **CADe — Computer-Aided Detection:** confined to marking conspicuous structures and sections in an image
- **CADx — Computer-Aided Diagnosis:** evaluates the conspicuous structures — for example, highlighting microcalcification clusters and hyperdense structures in mammography — so the radiologist can draw conclusions about the pathology
- **CADq — Computer-Aided Quantification:** quantifies findings, such as the size of a tumour or its behaviour under contrast-medium uptake
- **CAST — Computer-Aided Simple Triage:** performs a fully automatic first interpretation, sorting studies into categories such as negative and positive — useful for emergency imaging

CAD has been used clinically for over 40 years but usually supports, rather than replaces, the professional's final interpretation.

9.3 How CAD Works: Four Processing Steps

- Preprocessing — reduce artifacts and image noise, level image quality and contrast, and apply filtering.

- Segmentation — differentiate structures in the image (heart, lung, ribcage, blood vessels, possible lesions), matching against an anatomic database and sampling grey values in the volume of interest.
- Structure / ROI analysis — every detected region is analysed for compactness, form, size, location, proximity to nearby structures, and grey-level characteristics.
- Evaluation / classification — each region of interest is scored for the probability of a true finding using a classification algorithm, and threshold-passing structures are highlighted for the radiologist.

CAD is fundamentally based on highly complex pattern recognition, usually trained on a few thousand images in DICOM format.

9.4 Classification Algorithms Used in CAD

Classical Approaches	Learned / Model-Based Approaches
Nearest-neighbour rule (e.g., k-NN)	Artificial neural network
Minimum distance classifier	Radial basis function network (RBF)
Cascade classifier	Support vector machine (SVM)
Naive Bayes classifier	Principal component analysis (PCA)

9.5 Measuring CAD Performance

A correct hit is a True Positive (TP); an incorrect mark on healthy tissue is a False Positive (FP) — fewer FPs mean higher specificity. Today's CAD sensitivity can reach up to 90%, depending on the system and application. Low specificity reduces clinical acceptance, since the user must review every false hit; in CT lung exams the FP rate can be 25 or more, while CAST systems need under 1 FP per exam to be useful for triage. An alternative metric, the absolute detection rate, varies with study design (retrospective vs. prospective), image quality, exam conditions, radiologist experience, and lesion type and size.

Two standard measures describe detection performance: Sensitivity = TP ÷ (TP + FN), the fraction of true abnormalities that are found, and Specificity = TN ÷ (TN + FP), the fraction of normal cases correctly left unmarked. A CAD system must balance the two, because raising sensitivity usually increases false positives.

9.6 Challenges Facing CAD Systems

- **Algorithmic limits:** most algorithms select a single likely diagnosis, giving suboptimal results for patients with multiple concurrent disorders
- **Data source and scale:** input increasingly comes from electronic health records, which must be well designed and analysed; the volume and complexity of often semi-structured or unstructured patient data is a major challenge
- **Standardisation:** a lack of standardised assessment measures complicates regulatory approval (e.g., FDA) and clinical validation
- **Adoption:** negative studies and a lack of clinician training on CAD sometimes lead to incorrect interpretation of its outputs

9.7 Clinical Applications

CAD is used in the diagnosis of breast cancer, lung cancer, colon cancer, prostate cancer, bone metastases, coronary artery disease, congenital heart defects, pathological brain conditions, fractures, Alzheimer's disease, and diabetic retinopathy. Most systems are second-opinion tools — the radiologist remains responsible for the final interpretation.

- **Breast and lung cancer:** CAD helps classify mammographic tumours as malignant or benign; 3-D lung CAD systems analyse CT volumes of thousands of images and can detect round lesions from 1 mm, catching early-stage cancers easily overlooked on plain X-ray
- **Colon and cardiovascular disease:** CAD detects colorectal polyps in CT colonography by their characteristic shape; ultrasound-based markers support early detection of carotid atherosclerosis, and CAD can automatically detect significant coronary stenosis in CT angiography
- **Brain and Alzheimer's disease:** CAD helps distinguish Alzheimer's and mild cognitive impairment from normal ageing, using features from wavelet transforms, neural networks, and PCA-based methods
- **Diabetic retinopathy:** CAD improves accuracy and can safely substitute for some human graders, using preprocessing (normalization, histogram equalization, green-channel filtering) followed by SVM-based vessel and lesion classification

9.8 CAD Compared with Modern Deep-Learning AI

Aspect	Classical CAD	Deep-learning AI
Feature design	Hand-crafted features (shape, size, texture) chosen by engineers	Features learned automatically from data
Algorithms	k-NN, SVM, Bayesian, neural networks with few layers	Deep CNNs and related networks
Data needed	Thousands of images	Often tens of thousands or more
Output	Marked regions or probability scores, usually as a second reader	Detection, segmentation, classification, triage, and prediction
Transparency	Easier to explain	Harder to interpret

Key Takeaways

- CAD systems assist, and do not replace, the radiologist, acting as a second reader that marks suspicious regions.
- The CAD family comprises CADe (detection), CADx (diagnosis), CADq (quantification), and CAST (triage).
- The processing chain is preprocessing, segmentation, region analysis, and classification.
- Sensitivity and specificity (false-positive rate) determine clinical acceptance.
- CAD is widely applied in breast, lung, colon, brain, cardiac and retinal imaging.

10. Augmented Reality in Medical Imaging

10.1 What Is AR in Medical Imaging?

Medical imaging is central to diagnosing and treating conditions; X-ray, MRI, and CT have already transformed medicine. Augmented Reality (AR) overlays digital data — such as images or sounds — onto real-world objects or locations, in real time. In medicine, AR has become an essential tool across patient examination, surgery, and therapy, and continued advancements are transforming diagnostics and treatment procedures across several domains.

10.2 How AR Works in Medical Imaging

An AR system must know exactly where the patient and the display are in space so that digital information appears in the correct place on the real anatomy. This relies on three core functions:

- **Tracking:** cameras or optical/electromagnetic sensors follow the position of the patient, instruments, and the viewer's head in real time.
- **Registration:** pre-operative CT or MRI data are segmented into a 3-D model and aligned (registered) with the patient's actual position.
- **Display:** the aligned model is shown on a head-mounted display, a tablet or screen, a projector, or inside a surgical microscope or endoscope view.

Feature	Augmented Reality (AR)	Virtual Reality (VR)
Environment	Digital content overlaid on the real world	Fully computer-generated environment
Typical medical use	Surgical guidance, bedside visualisation	Surgical rehearsal, training, pain distraction

10.3 AR-Assisted Surgery

- Surgeons can see 3-D images of the patient's internal organs, tissues, and blood vessels during an operation.
- This offers unparalleled precision, accuracy, and visual assistance compared with traditional methods.
- Surgeries can be performed with minimal invasion, reducing patient recovery time.
- AR also benefits doctors in training, who can learn surgical procedures through virtual reality simulations before operating on real patients.

10.4 Image-Guided Intervention and Therapy

- AR displays real-time images of internal organs during a procedure, allowing precise navigation and guidance.
- In radiation therapy, AR helps clinicians focus radiation beams precisely on the tumour while sparing surrounding healthy tissue.
- This precision is especially valuable in procedures where a small margin of error carries significant risk to the patient.

10.5 Patient Education, Rehabilitation, and Training

- **Patient education and rehabilitation:** patients use AR to view and better understand their own medical conditions; AR can showcase the effects of a treatment plan, give feedback on progress, and support personalised rehabilitation recommendations
- **Medical education and training:** medical students explore the human body in 3-D through virtual reality simulations, gaining hands-on experience with procedures; trainees can learn to use medical equipment through AR simulation without any risk to real patients

10.6 Remote Patient Monitoring

AR has the potential to transform remote patient monitoring. Patients can capture images and videos remotely using AR technology and send them to medical professionals — saving time and resources, particularly for people living in remote areas, and letting them receive diagnoses and advice promptly.

10.7 Challenges and Limitations

- **Registration accuracy:** organs move and deform with breathing and surgical manipulation, so the overlay can drift from the real anatomy.
- **Latency:** delay between movement and display update causes discomfort and positional errors.
- **Depth perception and occlusion:** virtual structures can appear in front of real tissue, confusing depth judgement.
- **Ergonomics and cost:** headset weight, limited field of view, and cost slow adoption and require clinical validation.

10.8 Outlook: CAD and AR Together in Modern Imaging

AR has moved from a novelty to a practical tool across surgery, image-guided intervention, patient education, medical training, and remote monitoring. With continued research and development, AR could significantly transform healthcare delivery, promising more accurate, efficient, and cost-effective procedures, diagnosis, and treatment — and ultimately, better patient outcomes.

CAD and AR complement each other well as the two “intelligent” layers added on top of raw medical images: CAD helps clinicians interpret existing images faster and more consistently, flagging conspicuous findings for review, while AR helps clinicians act on imaging in real time — during surgery, intervention, therapy, training, and remote care. Both technologies keep the professional in the decision-making loop while extending what they can perceive and process, pointing toward a future of medical imaging that is faster, more precise, and more accessible.

Key Takeaways

- AR overlays digital information, such as 3-D organ models from CT or MRI, onto the real view of the patient in real time.
- Tracking, registration, and display are the three technical building blocks.
- Applications include surgery, image-guided therapy, patient education, training, and remote monitoring.
- Accuracy, latency, and validation remain the main barriers; CAD interprets images while AR helps act on them.