Diagnostic and therapeutic imaging in oncology

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Abstract

Medical imaging techniques are an important element in early detection for many cancers. They are also essential for determining the location, extension and stage of the lesion in diagnosis, for guiding treatment and therapeutic interventions, and for assessing tumour response during and after treatment. Imaging methods range from anatomically based methods (ultrasound, conventional plain X-rays, fluoroscopy, computed tomography, magnetic resonance imaging) to more functionally based methods (functional magnetic resonance imaging, magnetic resonance spectroscopy, single-photon emission computed tomography, positron emission tomography). The principles of these image acquisition methods with examples of clinical indications are described. Advances in medical imaging have also been widely applied in the field of radiation oncology, often referred to as 'therapeutic imaging'. A wide range of imaging techniques is employed at almost every step of the radiation treatment process: from diagnosis, treatment planning, dose calculations and simulation of treatment, through to irradiation on the linear accelerator. The most notable recent technical developments have led to more accurate treatment plan calculations and more precise administration of radiation to target tissue.

Keywords Cancer; diagnostic imaging; medical imaging; radiation oncology; therapeutic imaging

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Imaging in modern oncology

Imaging plays an essential and fundamental role in the management of the cancer patient. This includes:

- **screening** in non-symptomatic patients
- **detection and diagnosis** – tumour characterization and anatomical localization, distinguishing between malignant and benign disease, defining sites for biopsy and pathological assessment
- **cancer staging** – determining lesion size and extent (local, loco-regional, metastatic)
- **guiding treatment and management decisions** – determining suitability for treatment options
- **guiding and verifying precise therapies** – such as stereotactic irradiation, external beam radiotherapy, brachytherapy, particle therapy, intraluminal treatment delivery and tissue ablation therapies
- **enabling interventional placement** – tumour fiducial markers, stents, catheters and intravenous devices
- **assessing treatment response** – including complications.

The majority of imaging methods are non-invasive, but invasive 'interventional radiology' methods are widely used in oncology to direct minimally invasive procedures with diagnostic or treatment aims:

- **endoscopic methods** – bronchoscopy, oesophagogastroscopy, colonoscopy and sigmoidoscopy, primarily used for cancer diagnosis and staging, allowing direct tumour visualization and facilitating specimen sampling for pathological review
- **other common interventional radiology procedures** – used to facilitate placement of stents, catheters and intravenous devices, and tumour fiducial markers; guide intraluminal treatment delivery (radioactive isotopes, therapeutic drugs); enable transarterial chemo/radio-embolization therapies (delivering treatment directly to a tumour through its blood supply, then blocking the artery to prevent 'washout'); and monitor the delivery of localized tissue ablation therapies.

Imaging methods can be classified as anatomically based or functionally based, depending on their acquisition technique and type of information produced.

Major anatomical imaging modalities

Ultrasonography (US) uses reflected beams of high-frequency sound to generate images. It is widely available but limited in its applications. This is due to the trade-off between image spatial resolution and imaging depth, which depends on the sound frequency used. The sound waves are also attenuated by fat and bowel gas. As a result, the diagnostic and staging roles of US are confined. It may be used for detecting lesions (e.g. breast, neck), broad definition of nature (e.g. cystic, solid) and sizing and estimation of the extent of disease. It is commonly used to assess liver or bladder masses and to distinguish testicular cancer from benign masses. The staging accuracy of US is reduced with deep-seated lesions, so this application is mainly limited to organs such as the breast, neck, thyroid, and superficial lymph nodes. However, endoscopic US has an important role in staging oesophageal cancer and mediastinal metastases in lung cancer.[1] US can also be used to provide real-time image guidance for biopsies and treatment, for example transrectal US in prostate cancer to guide diagnostic biopsies, place markers to guide external beam radiotherapy and a guide for optimal insertion of radioactive 'seeds' in brachytherapy. Doppler US, which measures and visualizes blood flow, may additionally be used in some cancers to aid diagnosis and determination of treatment options.

X-ray-based techniques remain widely used in oncology. *Traditional X-rays* are commonly used as a first-line method in the detection of primary or secondary (metastatic) lung and bone cancer. *Digital mammography*, which uses static low dose-amplitude X-rays for breast cancer detection is now used in most UK screening centres. *Digital breast tomosynthesis*, which builds three-dimensional (3D) tomographic images from limited rotation angle X-rays, is currently under evaluation for improved diagnostic accuracy in National Health Service breast screening programmes. *Digital fluoroscopy*, which consists of an X-ray source and a fluorescent detection system coupled to an image digitization and recording device, is commonly used to obtain real-time moving images of internal structures. '*Barium swallow*' *fluoroscopy* is of particular benefit in examination of the upper gastrointestinal tract. It involves taking fluoroscopic images while the patient is drinking a suspension of barium sulphate, and provides important diagnostic and localization information for oesophageal cancer. Fluoroscopy may also used to track implanted tumour markers for on-treatment radiotherapy target monitoring.

Computed tomography (CT), whereby a 3D high-contrast resolution anatomical image is generated from a large series of two-dimensional X-ray slice data, is recognized as the current mainstay in oncology for diagnostic, staging and treatment guidance. It is also used to guide many interventional procedures and assess response to treatment. For helical scanning, an X-ray source and opposite sensor rotate in an 'imaging circle' around the patient, while the patient is slowly slid through the imaging circle. This enables multi-planar and virtual reconstructive imaging when combined with advanced computing to generate real-time volumetric images. Some of the current key applications of diagnostic CT scanning include:

- **chest** – presence and extent of lung, pleural and mediastinal abnormalities
- **liver and biliary tree** – lesion classification with vascularity details (benign versus, primary cancer versus metastases)
- **pancreas** – tumour detection and staging
- **kidney and adrenal glands** – tumour detection, classification and staging
- **small bowel and colon** – extent of the disease and lymph node involvement.

In radiotherapy, CT plays a principal role in treatment planning and delivery, as outlined in 'Therapeutic imaging in radiation oncology' below. (See also *Radiotherapy: Technical Aspects* on pages 10–14 of this issue.)

Magnetic resonance imaging (MRI) is based on the differences in absorption and emission of energy within tissues in the radiofrequency range of the electromagnetic spectrum. MRI offers several advantages over CT, including unmatched soft tissue resolution, superior tissue contrast and no radiation dose. There are also disadvantages, including longer scan time, increased motion artefact challenges and difficulties in detecting calcification or delineating tumour invasion of bone. MRI is the imaging technique of choice in evaluating neoplasms of the brain,[2] spinal cord region and musculoskeletal tumours, particularly sarcomas of the extremities. MRI, usually with gadolinium contrast enhancement, can also be useful in assessing and staging head and neck, breast, prostate, adrenal gland and female pelvic tumours. MRI is less useful for imaging the upper abdomen and liver because of respiratory motion. Fast-breathhold scanning may be used in this situation, although other methods to compensate (e.g. gating) or correct (e.g. modelling) for respiratory motion are becoming more available. Similar to CT, multiplanar reconstruction allows MRI to create virtual endoscopy, angiography and lymphography. MRI is also used in image-guided brain surgery to locate tumours and key structural components of the brain. More recently, MRI-based methods have been developed to support radiation therapy systems, with the introduction of fully integrated MRI-guided radiotherapy systems compatible with advanced radiotherapy methods, including intensity-modulated radiotherapy, and four-dimensional (4D) real-time tracking and delivery technologies. The expected advantages of the approach are superior soft tissue monitoring and targeting without additional radiation dose.

Functional/metabolic imaging modalities in oncology

Functional imaging allows for enhanced or earlier detection of tumour and provision of tumour biological information to improve treatment decisions, as well as prediction of the treatment response.[3,4] These advantages, and the recent focus of research activity on the potential uses of functional imaging methodologies in oncology, are likely to result in expanded clinical use of functional imaging. The use of functional and metabolic imaging in current oncology covers:

- **tumour detection** – especially in cases of metastatic disease with an unknown primary
- **disease staging** – especially in locations where anatomical imaging is limited
- **differential diagnosis** – by providing supplementary data in addition to anatomical methods
- **optimal treatment decisions and management planning** – by providing supplementary information
- **target volume delineation** (TVD) – as an aid to CT in radiotherapy planning
- **optimal dosimetry planning** – by delineating resistant regions requiring radiation boost
- **treatment response assessment**
- **detection of tumour recurrence and disease monitoring**.

Radionuclide imaging methods require administration of a radiolabelled agent (intravenously, orally). As the radionuclide isotope decays, it emits γ rays that are detected by a gamma camera. The resulting images reflect the distribution of the isotope. These methods usually provide functional information with only limited anatomical resolution, depending on the type of process

