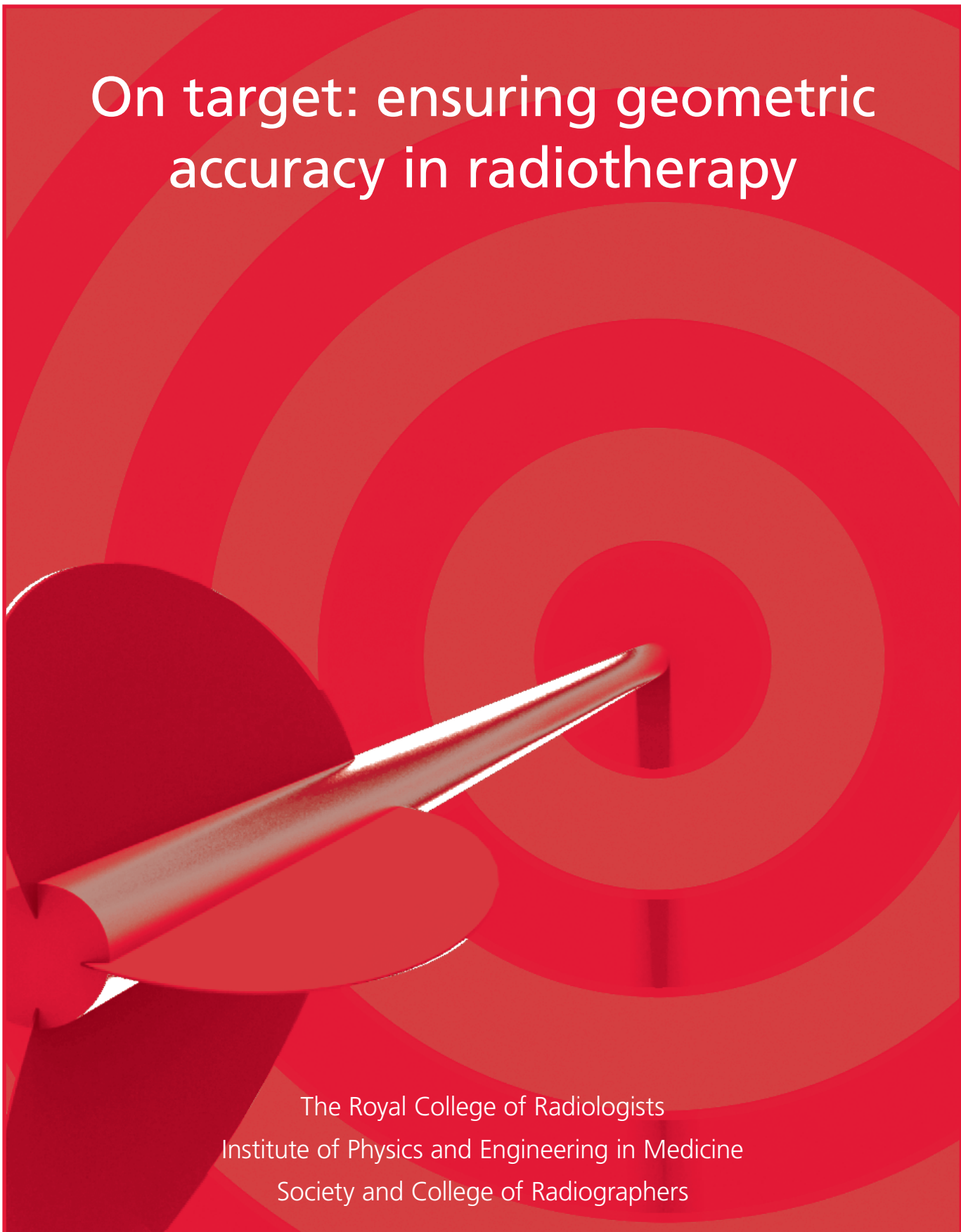# On target: ensuring geometric accuracy in radiotherapy

The Royal College of Radiologists

Institute of Physics and Engineering in Medicine

Society and College of Radiographers

Contents

Foreword

This report provides guidance on how to improve the accuracy of radiotherapy. It explains the significance of the systematic and random errors present in even the best-run departments and lays out methodologies for measuring and minimising such errors. By providing clear guidance it will assist in accurate and reproducible radiotherapy delivery.

Clinicians and radiographers should ensure that for each patient the random uncertainties of set-up are minimised by attention to immobilisation procedures. Systematic error (in the same direction on all fractions) should be identified and then eliminated, by the use of an agreed correction strategy.

Department heads will need to ensure that these processes are in place – not only for individual patients but also for every radiotherapy technique in use in their department. In this way, population-based random and systematic errors can be identified and minimised by changing departmental practices. Measurement can be used to provide the basis for calculating the correct margin between the clinical target volume (CTV) and the planning target volume (PTV).

Completion of this cycle of individual and population-based measures to address random and systematic errors will allow each of us in our own departments to be certain of treating our patients with the minimum margin required without missing the target.

I would like to thank Peter Hoskin (Chair), Mark Gaze, Tony Greener, Mike Kirby, Helen McNair, Melanie Powell, Donna Routsis and Diana Tait for their work in producing this document. Thanks also go to Dr Michael Williams who initiated this project during his time as Dean of the College. I would also like to thank Karen Selby for her assistance.

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Executive summary

Treatment verification is an important component of radiotherapy.

The role of verification is primarily to detect treatment delivery errors and secondly, to assess the suitability of the size of the margins planned around the clinical target volume that allow for the uncertainties in the radiotherapy process.

This document describes and recommends the best evidence-based practices for geometric treatment verification. It also provides guidelines as to how individual centres may implement geometric verification processes locally.

Summary of main recommendations

- Geometric verification is mandatory for all megavoltage X-ray external beam radiotherapy.

- The geometric verification process must be carried out within a clearly defined structure, adhering to locally defined protocols.

- Each radiotherapy department should determine the verification protocols and planning margins required for their own practice. This is because the frequency of imaging, the tolerances and action levels used, and the planning margins will vary according to local use of techniques, processes, anatomical site, equipment and immobilisation.

- Clinical implementation of geometric verification protocols should be co-ordinated by a designated multiprofessional team.

- Training and competency assessment must be undertaken by all professional groups involved in verification.

- A gross error is an unacceptably large set-up error. Methods must be in place in each radiotherapy department to detect and act on gross errors for each patient at the start of each radiotherapy treatment course.

- Set-up errors have both systematic and random components. Verification protocols are necessary to identify each component.

- Systematic errors must be identified and minimised using correction protocols for every patient having a multi-fraction course of radiotherapy.

- Random errors should be minimised by careful attention to immobilisation and patient preparation techniques.

- Population random and systematic errors should be determined for all techniques in use and all anatomical sites treated within individual departments. These data should be used to inform the clinical target volume (CTV) to planning target volume (PTV) margin for each technique.

- Additional exposure for verification must be justified within the Ionising Radiation (Medical Exposure) Regulations (IR(ME)R).

1 Introduction

1.1 Purpose

The purpose of this report is to recommend best practices for geometric treatment verification within megavoltage external beam radiotherapy and to provide guidelines for the local clinical implementation of these practices.

The scope of this report includes all current and emerging treatment verification methods in UK departments, for all treatment sites, complexities and intents.

1.2 Objectives

This report aims to:

- Provide evidence-based guidelines for implementing geometric verification into clinical practice
- Provide guidance for each radiotherapy centre to create local management structures, processes and protocols that would aid the implementation of geometric verification practices. This includes describing methods by which each centre can determine:
    — The local verification protocols required
    — Site-specific and individual patient systematic and random set-up errors, which can be used in defining treatment planning margins.

1.3 Background

An audit of UK verification practice carried out in 2004,[1] identified a wide diversity in practice across the UK; as a result, the need for guidance to direct verification in practice was identified.

This report details the implementation process; additional information to support this is covered in other radiotherapy publications, specifically:

- *Development and Implementation of Conformal Radiotherapy in the United Kingdom*[2]
- International Commission on Radiation Units and Measurements (ICRU) Reports 50[3] and 62[4]
- *Geometric Uncertainties in Radiotherapy*[5]
- *Guidance for the Clinical Implementation of Intensity Modulated Radiation Therapy*[6]
- *Balancing Costs and Benefits of Checking in Radiotherapy*[7]
- *Towards Safer Radiotherapy.*[8]

Image-guided radiation therapy (IGRT) is the latest development for increasing the precision and accuracy in radiation delivery. Many of the concepts detailed in this publication are immediately transferable to these new technologies. The main procedural recommendations, such as the use of specialised, multiprofessional teams for co-ordinating geometric verification, standardising methods of training and authorisation, and the use of clearly defined protocols, are essential for IGRT.[9,10] The acquisition of volume image data throughout a course of treatment introduces other areas of verification (for example, soft tissue verification and adaptive radiation therapy), which need to be considered. These are beyond the scope of this publication, but readers may be interested in recent publications highlighting the new problems being uncovered by IGRT and their potential solutions.[9–16]

2 Principles of geometric verification

2.1 What is verification?

Radiotherapy verification is the process that enables us to be certain we are treating the tumour volume as planned. In ensuring that the right radiation dose has been given to the right place, two measures are needed – geometric and dosimetric verification. This report concentrates on geometric verification. A typical example of a flowchart for the process is shown in Figure 1.

The aim of geometric verification is to ensure that the geometric accuracy of the radiotherapy delivered is within the limits set by the uncertainty margin allowed in the treatment plan. This is achieved by comparing information from the delivery against that planned. Verification is only one component of the treatment process. Accurate and reproducible planning procedures, including the acquisition of good quality reference images, are essential to successful verification.

Figure 1. An example of a typical flowchart for the process of geometric verification
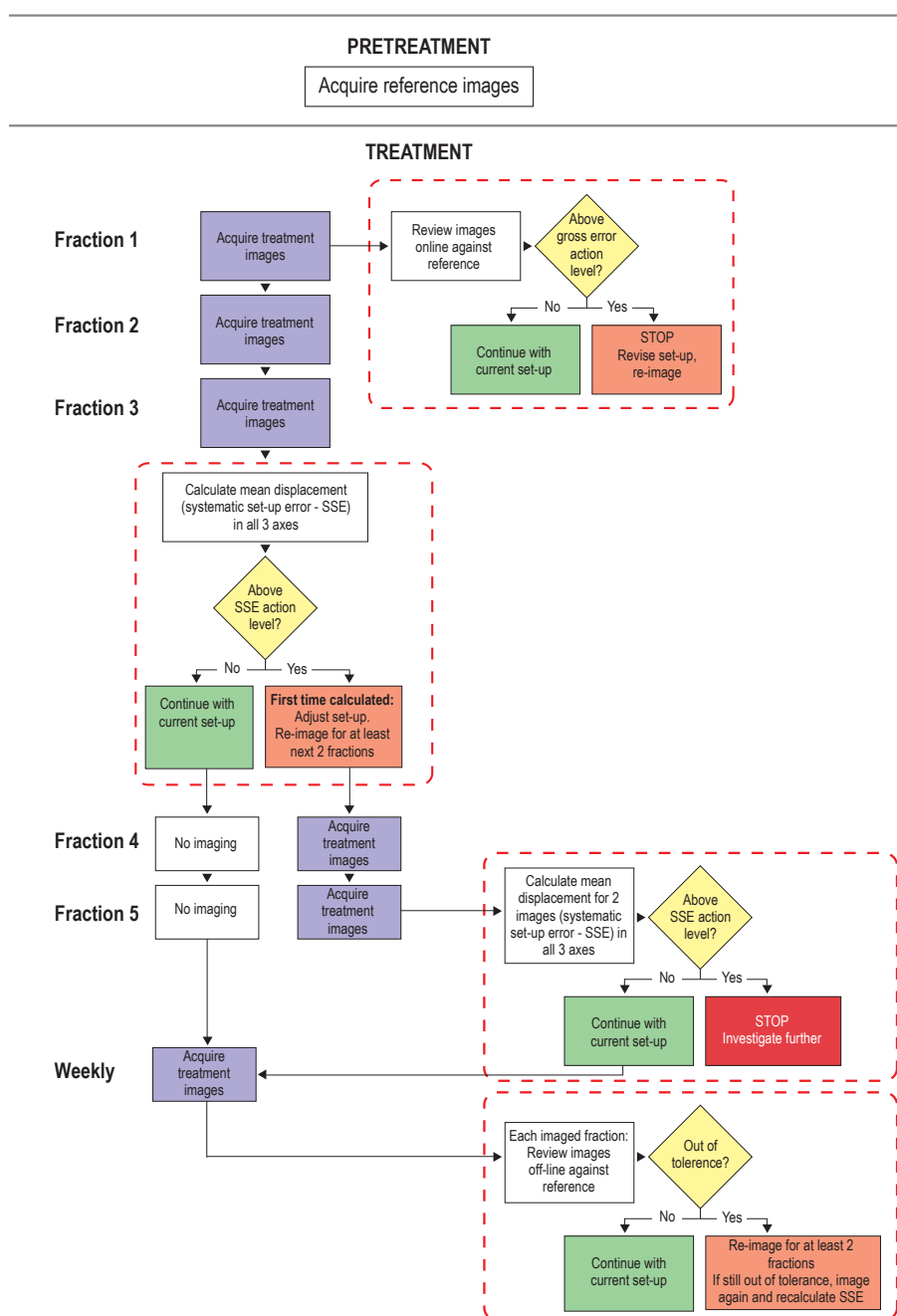
2.2 Verification definitions

Many verification terms are used in this report. The following section describes their specific meanings to set the common language used for the report. Other definitions used in this report are given in the Glossary (page 64).

2.2.1 Verification

This is the process by which the accuracy of radiotherapy is assessed. It is achieved by comparing images (or data) of the treatment delivered with that planned. This will use information from either 2D or 3D systems to give different degrees of translational and rotational set-up accuracy data.

2.2.2 Reference image

The reference image obtained shows the planned geometry of the treatment field placement relative to internal anatomy or anatomical surrogate such as bone or markers. This is used as the standard against which treatment images are assessed. Reference images are produced in numerous ways including: digitally reconstructed radiographs (DRRs), digitally composited radiographs (DCRs), simulator images, digitised films, ultrasound, or the entire volumetric planning data set. In this document, 'image' is used to encompass all of these modalities.

2.2.3 Pretreatment verification

This is the process that compares the reference images with the planned treatment *before the course of radiotherapy is started*. It usually occurs away from the treatment delivery room.

2.2.4 Image-guided radiotherapy (IGRT)

In its broadest definition, this applies to all parts of the radiotherapy process from using imaging to define and delineate the target volume to evaluating treatment response.

The most widely used concept of IGRT is using imaging in the treatment room either immediately before or during treatment to evaluate and correct set-up errors.

For online treatment verification, IGRT uses images obtained *immediately before treatment delivery and intervention to correct set-up before delivery*. Images may be acquired using computed tomography (CT) (kilovoltage [kV] and megavoltage [MV]), portal images (MV), kV planar radiographs, ultrasound or other methods.

Despite improved imaging, it is not possible to correct for all components of geometric error in radiotherapy. There are inevitably residual errors (to be accounted for in margin calculations), which may arise from sources such as:

- Target delineation uncertainty (cannot be detected by imaging)
- Movement of the patient or internal motion of organs as the treatment is being delivered. Intrafractional verification may be needed to quantify this.

2.2.5 Off-line treatment verification

This compares the reference images with the images taken in the treatment delivery room, and analyses the set-up accuracy at some time *after the treatment* has been given. The set-up data are not acted on until the next treatment.

2.2.6 Online treatment verification

This compares the reference images with images taken in the treatment delivery room, *immediately prior to the treatment* being delivered. Any necessary *corrections are applied before the treatment is delivered*.

Ideally, the time taken between online verification and treatment delivery should be as short as possible (a few minutes), to reduce the variation that may occur from patient movement during this time. Beyond this timescale, the information may no longer represent the patient's true position during the therapy.

2.2.7 Interfractional verification

This compares the set-up accuracy *between different treatment fractions*.

2.2.8 Intrafractional verification

This compares the set-up accuracy *during a single treatment fraction* and may be assessed over the course of a single beam being delivered or over a single fraction.

The effect of intrafractional movement can be compensated for when planning treatment margins, or reduced by the following methods:

- Terminating the treatment beam if movement occurs outside predefined tolerances
- Timing the treatment beam (pulse) to ensure delivery of radiation coincides with a known position of the patient's internal anatomy (gating)
- Restricting variation in the position of internal anatomy.

2.2.9 Real-time treatment verification

This is where comparisons are made between the reference images and images taken in the treatment delivery room, as the radiation is being delivered.

Most real-time verification methods detect displacements over a predetermined level, so that the operator or automated system can stop, or gate, the treatment.

Other real-time systems use the relationship between external references and internal anatomy. Optical surface detection systems work on a similar principle, by stopping treatment if the patient's external skin contours or reference points move outside a set tolerance level. This non-radiation method of real-time verification relies on the assumption that the relationship between external reference points and internal anatomy remains constant.

2.3 Set-up error definitions

The term 'set-up error' is used in this document to describe the discrepancy between intended and actual treatment position. It comprises a systematic and random component.

It is normally calculated as a shift in treatment field position when a treatment image is compared against its corresponding reference. The set-up error may be determined relative to the isocentre, the field borders or both and can contain translational and rotational information.

2.3.1 Gross error

A gross error is an unacceptably large set-up error that could underdose part of the clinical target volume (CTV) or overdose an organ at risk. CTV to planning target volume (PTV) treatment margins do not account for errors of such magnitude and therefore gross errors must be corrected before any treatment commences.

Mechanisms to detect gross errors must be in place before any treatment course starts. The usual way of achieving this is to perform imaging after treatment planning, but before the start of treatment. The methods which can be used are detailed in Section 3.4.1. The preferred method is to take and assess an electronic image on the first treatment fraction, immediately prior to treatment delivery.

Possible causes of gross error would include:

- Incorrect patient, anatomical site or patient orientation
- Incorrect field size, shape or orientation
- Incorrect isocentre position of unacceptable magnitude.

Each department must decide on an appropriate magnitude for gross error and this may differ between treatment sites. The chosen value must exceed any that could occur from expected day to day fluctuation in treatment position. In practice a gross error action level of 10 mm is appropriate for a wide range of sites and techniques.

2.3.2 Systematic error

The systematic component of any error is a deviation that occurs in the same direction and is of a similar magnitude for each fraction throughout the treatment course.

When considering geometric uncertainties in radiotherapy, the term systematic error may be used when referring to the individual patient, or to the treatment population, and this distinction needs to be clarified to avoid confusion.

- **Individual** – the systematic error for an individual patient is the mean error over the course of treatment.
- **Population** – the systematic error for a group of patients is an indication of the spread of individual mean errors. It is calculated as the standard deviation (SD) of the distribution of mean errors for each individual patient and is usually given the capital sigma symbol Σ_{error} where the subscript 'error' refers to the particular error considered (for example, Σ_{set-up} for the measured systematic set-up error).

Systematic errors may be introduced into a patient's treatment at the localisation, planning or treatment delivery phases. For this reason these types of errors are often referred to as treatment preparation errors.[17] Once 'frozen' into the process, systematic errors will occur in each treatment fraction. Possible treatment preparation errors[5] are summarised below.

- **Target delineation error** – this may be introduced when the CTV is first delineated and represents the difference between the defined and 'ideal' CTV.
- **Target position and shape** – this is a change in target position and shape between delineation and treatment. Possible causes include tumour regression or growth, bladder filling and rectal distension.
- **Phantom transfer error** – this is the error that accumulates when transferring image data from initial localisation through the treatment planning system to the linear accelerator. It is measured using a test phantom and may be sub-divided into geometric imaging, treatment planning system and linac geometry errors.[18] Possible causes include differences in laser alignment between CT and linear accelerator, CT couch longitudinal position indication, image resolution, margin growing algorithm, field edge and multileaf collimator (MLC) leaf position, isocentre location, source to surface distance indication, gantry and collimator angle accuracy.

  Many of these parameters are subject to routine checks as part of a machine quality control programme and this should ensure that any differences lie within allowed tolerances such as ± 2 mm for a distance and $\pm 1°$ for an angle indication.

  Phantom transfer errors are classed as systematic because their causes either do not change (image resolution, margin algorithm) or are assumed to vary slowly (isocentre position, leaf position accuracy) and are therefore taken as constant over the typical treatment duration.

- **Patient set-up error** – this describes all causes of treatment set-up error not accounted for by the phantom transfer error and includes all the errors listed under gross error. Possible causes include changes in the patient's position, shape or size (for example, weight change, hair loss). It also encompasses more subtle effects such as the displacement of the target relative to skin set-up marks caused by the CT scan and treatment being performed on different couches.

  Patient set-up error is only one possible component of the overall measured systematic set-up error. The chosen method of treatment verification will determine how many of the above sources of systematic error will be incorporated into the measured set-up error.

2.3.3 Random error

The random component of any error is a deviation that can vary in direction and magnitude for each delivered treatment fraction.

When considering geometric uncertainties in radiotherapy, the term 'random error' may be used to refer to the individual patient or to the treatment population and, as for systematic errors above, this distinction needs to be clarified to avoid confusion.

- **Individual** – the random error for an individual patient is the standard deviation (SD) of the measured errors over the course of treatment and quantifies the spread of errors.
- **Population** – the random error for a group of patients is calculated as the mean of the individual random errors and is given the lower case sigma symbol σ_{error} where the subscript 'error' refers to the particular error considered (for example, σ_{set-up} for the measured random set-up error).

Random errors occur at the treatment delivery stage and for this reason are often referred to as treatment (or daily) execution errors.[18] They are summarised below.

- **Patient set-up error** – these are varying, unpredictable changes arising from change in a patient's position, treatment equipment or set-up methodology between each delivered fraction.[19]

- **Target position and shape** – the change in target position and shape <u>between</u> fractions. This error is essentially the same as that described above for systematic errors but accounts for motion between fractions rather than from delineation to treatment.

- **Intrafraction errors** – this describes changes in the patient's position and internal anatomy arising during the delivery of a single fraction, for example, due to breathing.

Random errors are influenced by the immobilisation system, patient compliance and department protocols. If a new immobilisation device is introduced, it is likely that the random error will be affected. An off-line correction strategy cannot predict the random error component in subsequent fractions and so treatment margins must be calculated to include these variations. Online correction strategies can be used to control random errors.

Figure 2 shows the difference between systematic and random errors. The daily set-up errors plotted (in millimetres) from anterior-posterior images acquired for two patients over the course of their treatment. Patient 1 exhibits a small systematic (mean) set-up error compared to Patient 2. Patient 1 has a larger, random spread of errors than Patient 2. Although Patient 1 has an overall treatment accuracy close to that intended, any individual image taken is a poor indicator of this mean position. Action on any individual image must therefore be undertaken with caution as it can lead to overcorrection.
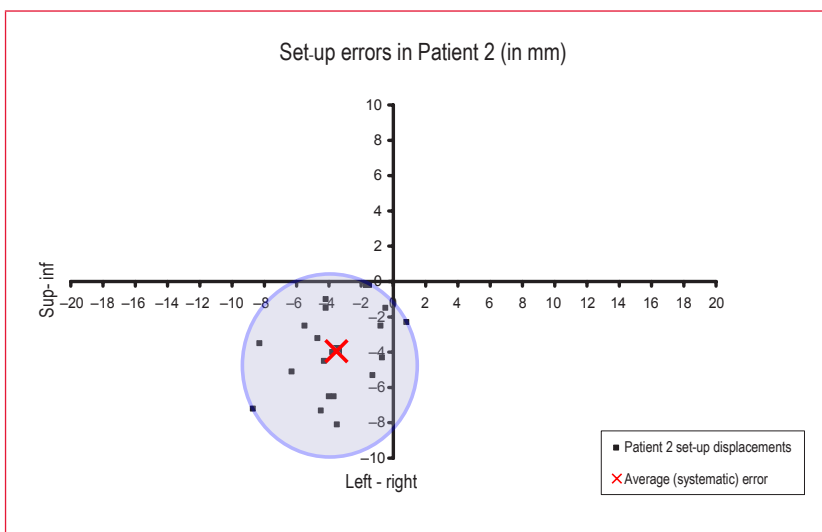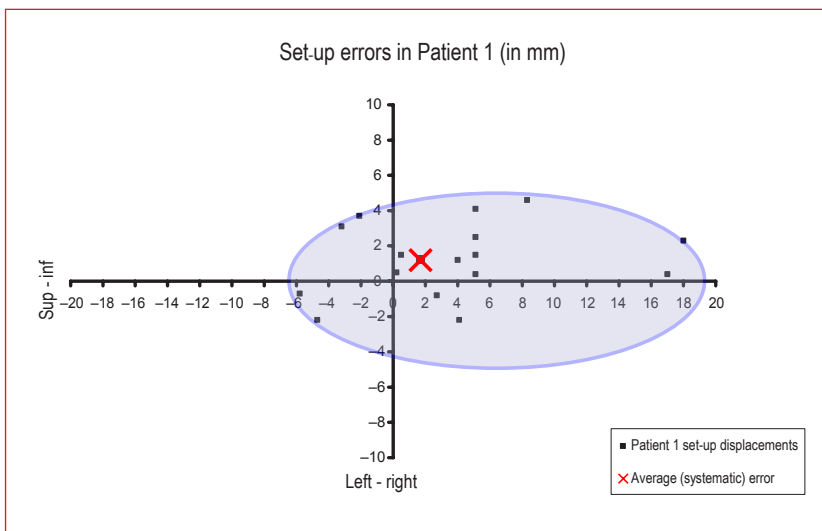
2.3.4 Set-up error measurement

The set-up error measured from a single image will contain both systematic and random components. As outlined above, the systematic part of the measurement will nominally be constant from one fraction to the next whereas the random part will vary in an unpredictable way.

The difference between systematic and random error is demonstrated in Figure 2, where the daily treatment verification data have been plotted for two patients. The information shows that each patient has different systematic and random errors occurring during their treatment; Patient 1 has a small systematic error but larger random errors, while Patient 2 has a larger systematic error but smaller random errors. The random error for Patient 2 is characterised by the individual points being grouped more closely around the mean (systematic error) position.

These examples also demonstrate that more than one image must be acquired to distinguish between the systematic and random components and provide a good 'estimate' of any correction to be applied. Actions based on a single image must be undertaken with caution as it can lead to magnification of errors. For example, if the image of Patient 1 associated with the set-up error of 8 mm right and 5 mm inferior was used in isolation to correct subsequent treatments, a considerable overcorrection would be made. Further images taken and acted on independently would also be subject to the same outcome leading to a series of unnecessary corrections around the mean position. For this reason, most off-line portal imaging correction strategies acquire images over the first few fractions to provide a more accurate estimate of the mean.

Ideally, all departments should determine their own population systematic and random set-up error components for each site-specific group. Section 4 of this report describes a practical method of performing this along with worked examples.[20]

2.3.5 Set-up error and treatment margin

Set-up errors and CTV-PTV geometric margins are interlinked. Figure 3 (page 15) demonstrates the impact of systematic and random errors on CTV coverage. It demonstrates that random errors, which vary from day to day, lead to a blurring of the cumulative dose distribution around the CTV, whereas systematic errors could lead to a cumulative underdose to a portion of the CTV. Because of this latter effect, most of the CTV-PTV margin is needed to ensure adequate coverage from the various sources of systematic error. The CTV-PTV margin may be modified depending on the number of contributing errors that can be detected and corrected during the course of treatment. This will be dependent on the treatment verification method used and which contributing error can be imaged. These may be summarised as follows.

- **Off-line imaging of bony anatomy**   Detects phantom transfer and patient set-up errors.
- **Off-line imaging of target**   As above plus the systematic error associated with target position and shape that can occur between delineation and first treatment.
- **Online imaging of bony anatomy**   Detects phantom transfer and patient set-up errors.
- **Online imaging of target**   As above plus the random and systematic errors associated with target position and shape.

Although online and off-line imaging of bony anatomy measure the same parameters, an online approach measures the set-up error before treatment and enables correction of the total set-up error for that treatment; that is, systematic plus that day's random error.

The target delineation error cannot be measured for an individual patient and is present for the treatment course. This and any other uncorrected errors should be incorporated into the geometric CTV-PTV treatment margin. These concepts are described in more detail in Section 4 along with worked examples.

Figure 3. The impact of geometric deviations on the dose distribution relative to the CTV. Random (treatment execution) deviations lead to a blurring of the dose distribution. Systematic (treatment preparation) deviations lead to an unknown shift in the cumulative dose distribution relative to the CTV,[17] as shown in Figure 3, below. The normal situation comprises a combination of systematic and random components. If left uncorrected, the systematic error will remain throughout the course of treatment potentially compromising dose coverage to the CTV. Treatment verification concerns quantifying this unknown systematic deviation and ensuring it lies within acceptable tolerances. An off-line correction strategy aims to quantify and correct for the systematic errors occurring over a course of treatment, so that only random errors remain.
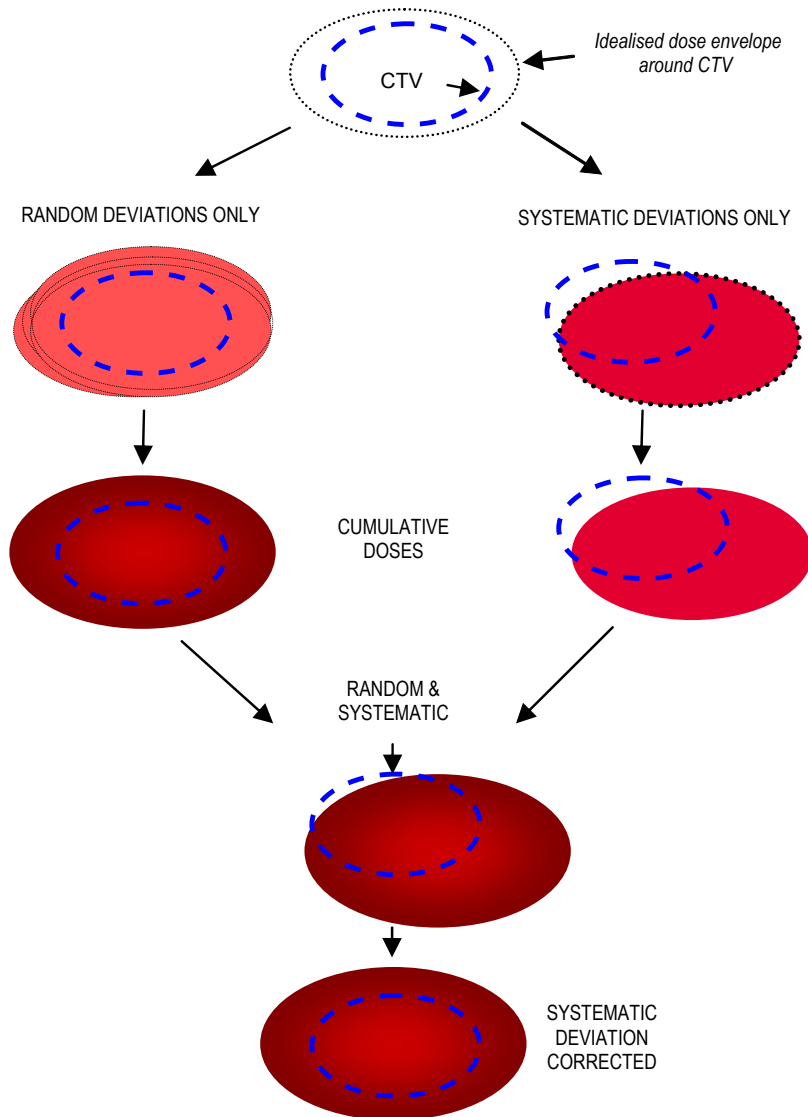
3 How to verify: creating geometric verification processes

This section outlines an evidence-based implementation process that can be adapted according to the needs of the individual radiotherapy department.

When starting this process, the first step is to identify the scope of the verification practice needed for the local clinical service. The equipment, management and protocols chosen will vary according to the verification systems available within the department.

With certain verification processes, the clinical workload for the department may increase, and it is essential that the resource implications are considered at an early stage. Services can be planned to optimise the balance between best verification practices and workload.

The verification process chosen should consider the following:

- Equipment and technical infrastructure
- Personnel, responsibilities and training
- Imaging protocols
  - Image acquisition
  - Frequency and timing of imaging
- Measurement of set-up errors
  - Gross error
  - Systematic and random error
- Tolerances, action levels and correction strategies
- Dose considerations – concomitant exposure
- Audit.

3.1 Equipment and technical infrastructure

A clear method for verification should be decided by each department. This should start with identifying the equipment needed for verification (for reference image acquisition, treatment image acquisition, image matching and data storage), establishing the connectivity methods between the equipment, and determining the quality levels and tests needed to maintain verification standards.

3.1.1 Generation of reference and treatment images

Good quality images are essential.

- CT image quality is related to slice width. These should be 5 mm or less. The optimal image quality will vary with different systems and should be chosen accordingly.[21]
- Where the DRR is of poor quality, X-ray simulator reference images should be obtained. However, the risk of introducing a further source of systematic error by using this additional step needs to be considered.
- Treatment image quality should ideally have fine spatial resolution and high contrast with a high contrast-to-noise ratio. Acquisition methods should be optimised to produce the quality required and may involve the use of image-processing software.

The images should be of sufficient quality to identify the following on both the reference and treatment image:

- Isocentre and/or field edge
- Tumour surrogate (bone, soft tissue, implanted markers).

3.1.2 Data transfer and storage

Image storage and distribution should be considered before implementing verification processes as image file sizes from electronic systems can be large. Transfer of data between the planning system, CT scanner, simulator, CT

simulator and treatment machine should be:

- Secure and maintain integrity of reference and verification data
- Efficient and reliable – transferred data should be available within a few minutes.

The data collected (images and match analysis) should be:

- Backed up and archived
- Stored so that historical data is readily retrievable.

3.1.3   Quality assurance and image-matching accuracy

Quality assurance programmes should be created to ensure image qualities and verification data collection standards are regularly assessed and maintained.

Each component of the verification process – from the acquisition of planning data to the subjectivity in decision-making by individuals – may have a certain level of error or uncertainty within it. Ideally, these should be measured so that the overall accuracy of the verification process is known. This can be taken into consideration when assessing the validity of the image match data. This is an important measure when determining planning margins.[5]

Verification systems should be assessed in terms of:

- Absolute accuracy – how accurate is the displacement information given from a particular measuring system? This is tested by analysing data containing a known displacement
- User accuracy – how do the measured results vary between users?
- Registration technique – how is the accuracy of registration affected by the different algorithms available, such as template, fiducial and chamfer automated matches?
- Image processing – some processing may affect the measured displacement
- Consistency of output – how accurate is the conversion of 2D data to 3D movements, and how limiting is the accuracy of couch movements?

3.1.4   Consistency of co-ordinate systems, error reporting and corrective actions

It is essential within a department to develop clear and consistent conventions for the reporting and correction of set-up errors. Consideration should be given to each of the possible patient orientations on the treatment couch, ensuring that this information is displayed on the images and incorporated into the offset measurements.

- Ideally, a single co-ordinate system should be used across the department, specifying the isocentre position relative to a set-up point, stating x, y, z, translational directions and rotation (pitch, roll, and yaw) around these axes. If such consistency between different systems that specify movement within a department is not possible, other co-ordinate systems used in the verification pathway should be clearly documented, along with the conversion process from one to another.
- Specify direction of movement.
- Specify what is moving, treatment field or couch.

3.1.5   Verification data management software

Software plays an important role in automating the verification process. It must address the specific requirements of a department.[22,23] A recommended list of functions that such software should provide is given below:

- Enable the design and implementation of imaging protocols that deal with the full range of possible outcomes
- Incorporate a patient-based database that allows a chosen protocol to be applied to an individual patient. This includes highlighting on the treatment unit when and which images are required for each treatment
- Allow the input of measured set-up errors
- Calculate any required shifts based on the chosen protocol and convert to new isocentric co-ordinates (table positions)

- Incorporate any shifts correctly into the ongoing analysis
- Calculate population statistics
- Generate reports
- Analyse trends
- Enable audit.

This functionality lies somewhere between that of an electronic portal imaging and a record and verify (R&V) system and could be incorporated within either. Ideally there should be a link both to the imaging system for automated recording of set-up errors and to the record and verify system to use the patient management database.

Summary. Equipment and technical infrastructure
- Images used should be of sufficient quality to be able to determine information required.
- Good connectivity is required.
- Clear conventions needed for co-ordinate system and error reporting.
- Quality assurance (QA) is important for ensuring accuracy of data.
- The contribution of uncertainties in the verification pathway should be measured.
- The software packages used must be suitable for managing the complete verification process.

3.2 Personnel, responsibilities and training

Responsibility for verification should be carefully assigned within each department. The following components should be considered.

3.2.1 Managerial responsibilities

A verification team comprising senior experienced physicists, radiographers and clinicians, should undertake responsibility for managing the verification process. It may be appropriate to have either one dedicated team or several tumour site-specific teams.

The following areas of responsibilities should be included:

- Design of the overall structure and process which includes:
    — Verification protocols
    — Set-up error action levels
    — Timescales for action on verification anomalies
    — Personnel responsibilities and authorities
    — Pathways for referral
    — Action to take outside the protocol
- Implementation of training programmes
- Instigation of quality control programme
- Implementation of audit programmes.

3.2.2 Clinical responsibilities

Day-to-day responsibility for acquisition and approval of verification data will rest with individuals and is based on training and competency assessments. Treatment delivery staff, usually radiographers, are often considered best placed to make these decisions and, in particular, online corrections, as they have all the information regarding patient set-up and compliance at their disposal.[24]

However, different skills are required for each aspect of the verification process and different personnel may be used for all or part of it. These disciplines could include: radiographers, physicists, clinical oncologists and also perhaps nonregistered staff (for example, assistant practitioners, clinical technologists, dosimetrists), provided that they are

suitably trained and authorised in accordance with locally agreed protocols and any published guidance.[25-27] An individual may be permitted to undertake all or only some of the tasks required, based on their competencies.

The following areas of responsibilities should be included:

- Image acquisition
- Gross error detection and management
- Set-up error detection and correction
- Image manipulation and processing
- Making clinical decisions using the verification data.

The number of independent checks needed when analysing and making clinical decisions on verification data is dependent on the local levels of training and competency assessment. This may vary between local clinical settings and take into account changing roles and differing models of service delivery. A risk analysis is recommended to determine that the local practices used are safe.[8] There must be agreement across the service as to who is responsible for image approval and actioning. Specific recommendations are:

- If the procedure is carried out by a single operator, s/he must be fully trained to the level required locally and assessed as competent
- Two independent checks are required for technique audit.

3.2.3 Training and competency programmes

A competency programme requires:

- Identification of each task in the verification process
- Determination of the knowledge and skills necessary for each task
- A formal training programme
- Assessment of competencies.

The frequency of repeating competency assessments should be stated. Generally a maximum time interval of one year is required. However, it has been suggested that accuracy of quantitative analysis depends on the amount undertaken[28] and refresher training may be required within this time.

An outline programme is shown in Section 5 of this report.

Summary. Personnel, responsibilities and training
- Verification team required to set guidelines on structure, process and responsibilities.
- Training and competency assessments are necessary.
- Action to take outside protocol to be clear.
- The number of independent checks needed for making clinical decisions is dependent on the levels of training and competence. A risk analysis is recommended for each local setting.

3.3 Imaging protocols

An imaging protocol is simply a series of instructions (or preferably a flow diagram) that gives the user guidance on the appropriate images and action to be taken at all stages of the treatment course. It should identify and manage all possible scenarios (what to image, when and how often) and will normally include one or more correction strategies. The protocol required will vary between centres based on local needs and practices and may differ with each anatomical site or technique or patient preparation method used.

An imaging protocol should clearly indicate:

- The need to act immediately for gross error
- The number of fractions allowed before action is taken on non-gross errors.

3.3.1 Image acquisition

- If planar MV images are used in the geometric verification process, they can be acquired using various modes such as single exposures (short or long), double exposures or movie loops, as described in Section 6.

- The method of image acquisition (for example, interfractional or intrafractional) will vary for different anatomical sites and verification purposes. It is dependent on the anatomy visible within a treatment field and by how much that anatomy moves during irradiation.

- The need for irradiating normal tissue in order to make a decision on the accuracy of field placement should be balanced against the radiation dose given to these tissues.

- Where double exposures are required, care should be taken to avoid unnecessary exposure to critical structures. This is outlined further in the site-specific protocols in Section 7.

- Where possible, field placement information should be acquired in all three translational dimensions (x, y, z). If using planar images, acquiring an orthogonal pair of images will give displacements that can easily be used to calculate the corrective couch movements required to reposition the patient. If using planar images obtained at non-orthogonal angles, the corrective couch movements may still be determined following appropriate correction.[29]

- Where software allows, information on in-plane rotations may also be gained.

- If planar images are acquired from a single direction, or opposing directions, the accuracy of the field placement can be assessed in two dimensions only.

- Ideally when using planar imaging, the two images should be acquired simultaneously to be truly representative of the patient's position. In practice, there is usually a few minutes' delay. This should be minimised wherever possible.

3.3.2 Frequency and timing of imaging

- Images should be taken over a sufficient number of fractions to determine the set-up error.[30] The number required for each disease site/technique will vary. Accuracy increases with the number of images obtained, but image acquisition over the entire treatment course is resource-intense[31] and may increase concomitant radiation exposure.

- The best distribution of image acquisition over the treatment course is unclear. The value of first day images has been debated since patient anxiety may give an unrepresentative picture.[32] One study has recommended that isocentre correction decisions should not be based on the first day except in the case of gross errors.[33] Other studies have suggested the worth of first day images depends on the efficacy of the immobilisation technique.

- Optimal correction and imaging strategies are discussed below and are summarised for individual site-specific protocols in Section 7.

- All exposures must be justified by a practitioner under The Ionising Radiation (Medical Exposure) Regulations (IR(ME)R).[34]

Summary. Imaging protocols

- The image acquisition method to use will depend on the quantity of stable anatomy seen within the field.
- Critical structures should be avoided when exposing normal tissue for data gathering.
- The timing of the image acquisition changes the information gathered.
- For planar imaging, an imaging set (minimum two orthogonal images) acquired in as small a time frame as possible, is needed to verify accuracies in all three directions.
- The accuracy of assessing the systematic error increases with the number of image sets acquired. In general for radical treatments, three to five imaging sets are needed to assess the systematic error.
- The number of imaging fractions will depend on site and treatment technique. The actual number of images will also be influenced by perceived risk of additional radiation exposure and resources.

3.4 Measurement of set-up errors

3.4.1 Identification of gross error

Gross error determination **must** be undertaken in all centres before the first treatment fraction is delivered. Ideally, this should be on the treatment unit as set-up errors may go undetected when using pretreatment simulation alone.

Gross error must be determined by one of the following methods, in order of preference.

- Undertaking a rapid estimate of gross error on the first treatment fraction, immediately prior to treatment delivery. A quick check for gross error can be made by interrupting the treatment as soon as an electronic image has been acquired and reviewing it for field size and orientation, shielding and approximate position accuracy.

- Using the first treatment unit session for verification alone.

- Using the simulator or CT scanner to provide pretreatment verification. Images must still be taken on the first fraction on the treatment unit and reviewed before the next fraction.

- Where a beam arrangement cannot be accurately visualised on imaging, gross error can be investigated by reviewing the light field in relation to surface anatomy. This is often used for electron or skin treatments and vertex fields.

3.4.2 Determining systematic and random errors for individual patients

The systematic component of the set-up error of all individual patients should be determined for all multi-fraction courses (>5 fractions) so that it can be minimised for the rest of the treatment.

For three-dimensional treatment plans, verification data should be obtained from two imaging planes. Where possible, verification data should be acquired from an orthogonal image pair. This enables corrections to be easily resolved into the required treatment couch adjustments (Section 3.3.1).

Anatomy, to which comparisons can be made, can be identified on the reference images and contoured using drawing tools. At least three features are required for most automatic image registration software. These same features or measurements can then be compared with each treatment image. These anatomical or surrogate reference points should be defined and be constant for any given site.

If port films are used, these images should be digitised and compared electronically. If a digitisation method is not available, film and reference images can be marked and measured manually, but the data will contain a greater error component. The level of observer error should be determined to assist decision-making.

Out-of-plane rotations are difficult to measure and require the use of specialist software. These measure the discrepancy in magnification in different parts of the image. Currently, software gives an indication of the presence of an out-of-plane rotation but is unable to quantify it, although it is possible to create algorithms to do so. This is of importance as out-of plane rotations affect the accuracy of the two dimensional translational displacement.[35] Further developments are to be expected in this area.

> **Summary. Measurement of set-up errors**
> - Gross error detection on the treatment unit is an essential requirement prior to first treatment.
> - Individual patient systematic set-up error should be measured and minimised.

3.5 Tolerances, action levels and correction strategies

3.5.1 Tolerances

The 'tolerance' of any measurement or parameter may be defined as the permitted observed variation in that measurement or parameter. Tolerance levels set the optimum conditions based on a therapeutically desired value, although these may not be enforceable or achievable in all circumstances.

In the case of treatment verification, the tolerance will be the permitted range of set-up error from the reference point. For example, we might allow a 5 mm left/right tolerance for a measured set-up. This will mean that the measured set-up error in the left/right direction may range from –5 (left) to +5 mm (right) from the reference (desired) position.

For treatment verification, the chosen tolerance of a particular measure of set-up error is related to the margins used for treatment planning, the aim being to always maintain adequate dose coverage of the CTV (Section 4). Input data to calculate both CTV-PTV margins and set-up tolerances may be derived from a portal imaging study undertaken for the particular treatment site and technique.[5] For radiotherapy centres that are still developing their treatment verification protocols, or are commissioning new treatment techniques (including equipment), data summarised by Hurkmans[36] and in Section 7 should form a good starting point.

The tolerances used in practice will take into account several other factors,[5] including:

- Immobilisation method
- Tolerances in equipment movement and set-up
- Internal organ motion.

Each radiotherapy centre should define tolerances for each anatomical site and treatment technique used. Information on how these studies may be conducted is presented in Section 4.

Individual patients may require special consideration; for example, those in pain, the anxious or the obese.

The tolerance to be used in an imaging protocol therefore depends on:

- Anatomical site
- Treatment technique
- CTV-PTV margin
- Patient compliance.

3.5.2 Action levels

An action level for a measurement or parameter is the point at which action is necessary. Action levels set minimum conditions, beyond which performance is deemed unacceptable.

The action to be taken depends on the importance of the parameter and the risk of not making any alteration. For instance, one may set a series of action levels whereby for a small deviation from the tolerance, observation is recommended. For a larger deviation, immediate amendment is required.

Actions in treatment verification will include:

- Further imaging (in case the result was simply random)
- Re-assessment of any systematic error
- Immediate modification such as stopping and adjusting the patient's position if the measurement is at a level which may be regarded as a gross error.

The magnitude of the chosen action level is related to planning margin, frequency of imaging, the random (daily set-up) error, and the chosen strategy used to constrain the set-up error over the treatment course. For example, in the case of a single acquired image, an action level of twice the standard deviation of the random set-up uncertainty may be used.[5] The action level for immediate intervention (that is, a gross error) may be set at three times the random set-up uncertainty that will typically come to around 1 cm for a wide range of treatment techniques.

3.5.3 Corrective strategies

The key requirement in any imaging protocol, apart from gross error detection, is to provide an accurate estimate of systematic set-up error. Depending on action level, the chosen correction strategy can then be used to remove this error. The protocol must confirm any applied correction is valid and remains so for the duration of the treatment.

Figure 4a (page 23) shows the effect of a poor correction strategy. The blue triangles indicate the set-up error measured from a portal image. The red line indicates the systematic set-up error, calculated as the average

displacement over four days. For this patient, the systematic set-up error (SSE) has been determined as being the largest (or last) value seen over the four days and a correction applied to that value. This method is repeated for the next four sets of images. The result is an exaggerated oscillation in the accuracy of the patient set-up. Figure 4b (page 23) shows the outcome on set-up if the SSE had been correctly calculated and actioned.

Figure 4a. Effect on set-up of poor correction strategy

Set-up error during radiotherapy course – poor correction protocol
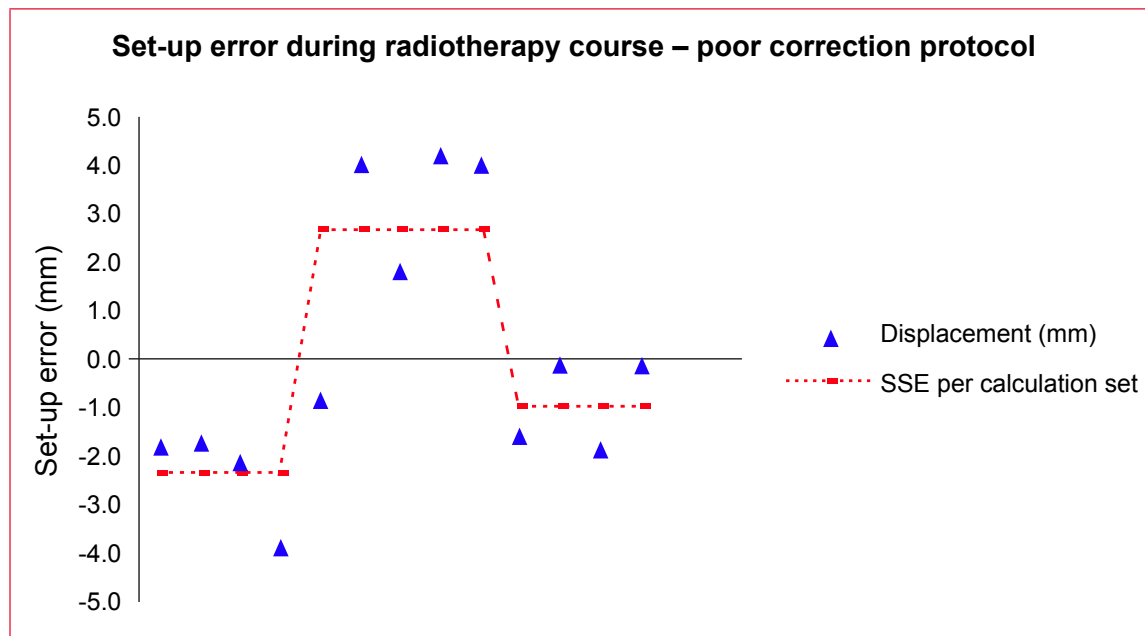
Figure 4b. Outcome on set-up if the SSE is correctly calculated and actioned

Set-up error during radiotherapy course – good correction protocol
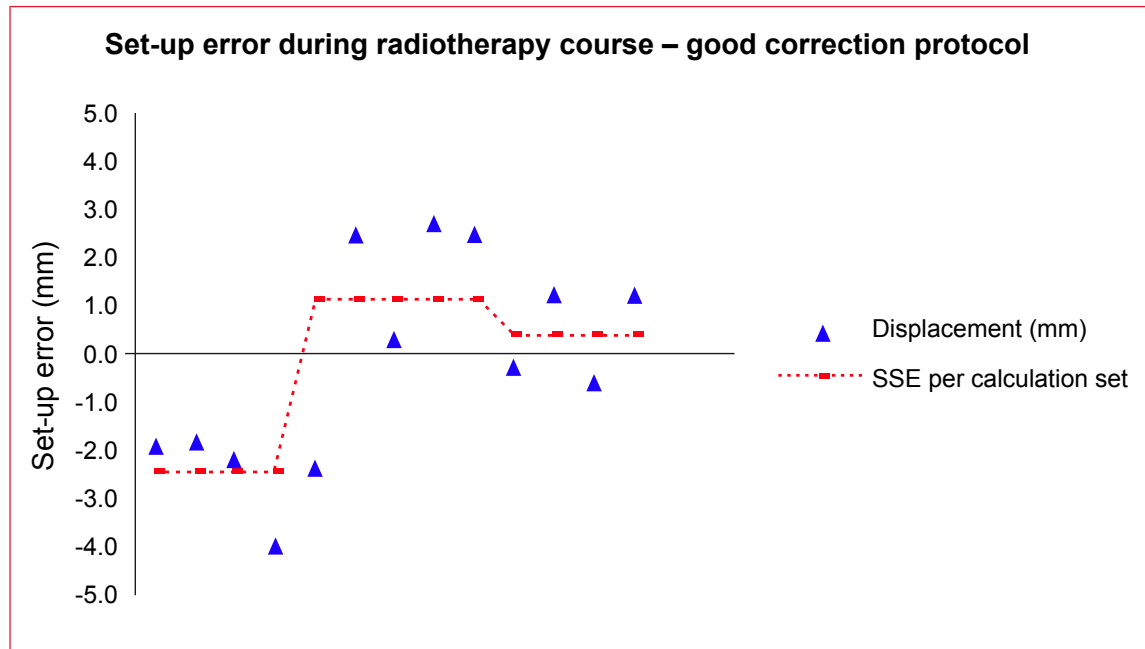
3.5.4   *Assessment and correction of systematic errors*

It is important to assess the SSE accurately within an appropriate number of fractions so that (a) a robust estimate of the true systematic error can be made, while (b) the minimum number of fractions is delivered with the systematic error present.

Two possible approaches are the no action level (NAL) and shrinking action level (SAL) correction strategies.

- The NAL[37,38] is most commonly advocated for radical treatments. It involves the systematic error being

calculated after 3–4 fractions and a correction performed which is the total magnitude of the systematic error, regardless of the tolerance for that treatment site. Since the NAL approach does not define an action level for corrections, there is also a subpopulation of patients in whom the systematic error is so small that applying a correction would be impractical; for example, moving the couch <2 mm. It is suggested that only systematic errors of >2 mm should be corrected. The extended NAL protocol (eNAL) includes once-weekly imaging in addition to imaging in the first 3–4 fractions if the result is within tolerance there is no action. If out of tolerance, further images are obtained to determine systematic error, see page 9. This is useful in detecting trends and systematic changes to the patient's set-up over the treatment course.[39] The NAL protocol does not act on gross errors. Such errors should be corrected before a further fraction is given.

- The SAL[40] uses an action level that reduces according to the number of fractions imaged. The running mean error over all acquired images is compared with the current action level and treatment set-up adjusted by this amount if the discrepancy exceeds the action level. The final action level is determined by the initial action level and number of images considered appropriate for the particular technique. The SAL avoids a set-up being corrected prematurely, where discrepancies observed at the start of treatment may have arisen through random rather than systematic error. A disadvantage of the SAL is that following any correction, the process is restarted and information obtained prior to the restart is lost.[20]

A direct comparison of the SAL and the NAL protocol using an average of ten imaged fractions per patient found the NAL protocol to be more efficient in terms of number of images per reduction in systematic error.[38]

Figure 5 (page 25) illustrates the difference between tolerance and action level using a NAL protocol.

Summary. Tolerances, action levels and corrective strategies
- Gross errors should be acted upon immediately.
- Each radiotherapy department will need to evaluate their own tolerances and action levels.
- All imaging protocols must include correction strategies for all treatment sites.
- A no action level strategy will correct the systematic component of the set-up error after at least three fractions.
- A shrinking action level strategy uses an action level which decreases according to the number of fractions imaged, in order to remove the systematic component of the set-up error. Workload may increase as a consequence.
- All corrections applied to the treatment set-up must be verified.
- Weekly imaging is recommended in addition to the correction policy.

3.6 Dose considerations – concomitant exposure

Concomitant exposures are defined as 'all exposures within the course of radiotherapy other than treatment exposures'.[37] Examples are:

- Exposures for 're-simulation' or repeated CT scans during the radiotherapy course
- All non-treatment fields
  — Large, open segments for double exposures
  — Orthogonal, open fields used purely for imaging
- Exposures from novel image-guided techniques (planar views)
  — Orthogonal radiographs (in-room kV, in-room CT [scout view], kV CBCT [planar imaging], tomotherapy [scout view])
- Exposures from novel image-guided techniques (volume imaging)
  — In-room CT IGRT
  — MV CBCT IGRT
  — kV CBCT IGRT
  — Tomotherapy MV IGRT.

The Ionising Radiation (Medical Exposure) Regulations (IR(ME)R)[34] requires that 'all medical exposures should be justified'. The practitioner must ensure that 'exposures of target volumes are individually planned, taking into account that doses to

Figure 5. Changes in set-up depicted during a fractionated course of radiotherapy to illustrate the concepts of gross error, tolerance and action levels using a NAL protocol (read left to right, top to bottom).

A - Fraction 1

Online verification image taken with the first few MU of the field on day 1 (first fraction), and analysed prior to delivering rest of exposure. – Gross error found; action taken immediately

B - Fraction 1

Error identified and set-up adjusted – repeat image taken; Ok to continue with rest of exposure

C - Fractions 2-5

Four more images taken (on fractions 2–5) for NAL protocol to calculate systematic component of the set-up error for this particular patient. Off-line verification protocol. AL_{NAL} (or AL_{-NAL}) Action Level for the NAL Protocol

D - Fraction 6

Systematic component of the set-up error calculated and reference moves adjusted for the patient. Image taken on fraction 6 (week 2). Within tolerance

E - Fractions 11 and 16

Weekly imaging (fractions 11 and 16, weeks 3 and 4). Both within tolerance

F - Fraction 21

Weekly imaging (fraction 21, week 4) is out of tolerance (beyond the weekly imaging action level). Action taken – check set-up instructions and annotations and repeat the verification image at the next fraction

G - Fraction 22

Repeat imaging (Online protocol) (fraction 22, week 4) is still out of tolerance. Action taken – re-check set-up instructions and annotations. Error in set-up moves identified – corrected

H - Fraction 22

Further image taken – OK. Continue with the rest of fraction

I - Fractions 26 and 31

Weekly imaging (fractions 26 and 31, weeks 5 and 6). Both within tolerance

KEY

T – Tolerance

AL_G (or AL_{-G}) – **Action level for gross errors**

non-target volumes and tissues shall be as low as reasonably practicable and consistent with the intended radiotherapeutic purpose of the exposure'. Most imaging protocols for treatment verification are sufficiently detailed to include methods of image acquisition, recommended machine units (MUs) for acceptable image quality, standard frequency of imaging (for the ideal set-up) and compensation for target dose delivery from verification exposures but may fail to link sufficiently these exposures with concomitant dose to non-target tissues.

For practical purposes, the medical and dental guidance notes[41] advise that 'the IR(ME)R practitioner responsible for treatment can justify the concomitant exposures at the outset or during the radiotherapy course, and in doing so must be aware of the likely exposures and the resulting dose so that the benefit and detriment can be assessed. This can be achieved by including likely concomitant exposures within site-specific protocols with an effective dose agreed'. Estimates of the magnitude of concomitant exposure to non-target tissues, especially organs at risk should therefore be included in a verification imaging protocol under ideal and non-ideal conditions.[42–50]

It is important to emphasise the benefit from imaging which will permit accurate, geometric verification of the irradiated volume which can then permit reduction of treatment margins and reduced normal tissue exposure, hence achieving increased compliance with the IR(ME)R requirements.[12]

All practitioners and operators should be aware of the doses involved in relevant radiotherapy procedures in order to justify exposures based on the benefit over risk.[34,42,44,49,51,52] Steps should be taken to reduce the concomitant exposure dose wherever possible; this may be as simple as using tailored, asymmetric fields for double or single open field exposures (so that only desired anatomy is visible). For more complex techniques and in particular emerging technologies, it may require more detailed assessments of true verification doses.[42,45,46,48,50,53–56]

All sources of non-therapeutic and concomitant exposure should be properly understood throughout the radiotherapy process. These will include doses from:

- CT scanning (planning scans etc)
- Pretreatment verification procedures
- Portal imaging (especially non-target tissue doses)
- Transmission through the MLC during treatment delivery
- Leakage and scatter from the linac during treatment delivery
- Complex therapeutic procedures (such as dynamic IMRT)
- Novel image-guided practices.

The role of verification techniques which do not require radiation exposure should also be considered, such as ultrasound-based techniques, video-based surface tracking and most recently wireless detection of implanted transponders (see Section 6). Some imaging techniques will still use ionising radiation, and the concomitant dose will also depend upon the treatment technique itself. For example, for treatments which use implanted soft-tissue markers, fields used for imaging do not need to be enlarged to 'see' sufficient anatomy; the field sizes need only be equivalent to the treatment fields themselves.

The risks in terms of secondary cancer induction and increased toxicity for organs at risk in the vicinity of the PTV need to be carefully weighed against the overall benefits. This is especially so for modern techniques which increasingly use technological advances like CT simulation, IMRT and IGRT.[42,43,45–47]

Concomitant exposure may need further consideration for organs at risk, particularly those near to the PTV which are already close to acceptable tolerance from the planned dose distribution.[49,57] Where critical structure doses are potentially important, imaging frequency and acquisition method limitations may be imposed at the time of planning, based upon the overall TP and calculated dose-volume-histograms (DVHs).

For secondary cancer induction, doses estimated from ideal and non-ideal imaging protocols (including scatter and leakage from the linac itself) may be used to calculate effective doses delivered and therefore the subsequent probabilities.[42,44,45,57–61] Estimates of typical non-target doses may be made from simple calculations[42,49] or through planning computer models and measurements.[48,50] An example of a simple approach is shown in Box 1, page 27.[49] It is dependent upon the type of imaging protocol being used, which in turn is anatomical site-dependent. Different imaging

technologies will require different concomitant exposures for adequate imaging purposes.[46,55,56] The example shown is for illustration of a method which may be used to discuss and quantify the doses and their possible clinical effects. It uses representative effective doses and probabilities for fatal cancer induction;[50] the associated caveats for those figures should be carefully noted by the reader. A similar table may be formalised for, say, cone-beam and other IGRT procedures, derived from the appropriate dose assessments for those imaging methods[46,55,56] and their expected imaging frequencies throughout the treatment course.

Limits can be applied to frequency and number of repeat exposures in imaging protocols by estimating the second cancer risk from calculated doses to non-target critical structures derived from the recording and monitoring of effective doses from all concomitant exposures. An 'action level' may then be set of 100 mSv, for example, for the chance of second cancer induction to be 0.5%, compared with the natural lifetime risk of approx 25%.[50]

Any consideration of the impact of concomitant exposures must also be set in the context of the clinical situation; the actual risk of second malignancy is clearly greater in a young woman having treatment for Hodgkin's lymphoma or breast cancer with a survival and risk period of several decades than an elderly man having treatment for advanced lung cancer having a prognosis of a few months.

Summary. Dose considerations

- Concomitant exposures should be considered with every verification procedure and kept to a minimum consistent with acquiring the necessary information to deliver accurate treatment.
- It is better to image appropriately to ensure adequate and accurate coverage of the PTV than to avoid imaging for fear of a minimal risk associated with the additional exposure.

Box 1. Hypothetical protocol for radical pelvis imaging		
Basic assumptions	• Six-week radical course of treatment • AP and lateral images used throughout (constituting an imaging session) • Images are approximately 16 x 16 cm, 6 MV, single open-field exposures • Isocentric depth approximately 10 cm	
Imaging frequencies	• *Routine:* AP and lateral images acquired once a week • *Difficult set-up case:* Assume three imaging sessions needed in first week; weekly thereafter[39] • *No action level (NAL) protocol:* Assume five imaging sessions in first week; no imaging thereafter[38]	
Imaging technologies **Amorphous Silicon (*aSi*)**	• *aSi EPIDs:* 4 MUs per image, 8 MUs per imaging session • *Film or older EPID:* 8 MUs per image, 16 MUs per imaging session	
Concomitant doses	*EPID*	*Film/older EPID*
Isocentre dose per session	0.07 Gy	0.14 Gy
Routine imaging	0.42 Gy per course	0.84 Gy per course
Difficult set-up case	0.56 Gy per course	1.12 Gy per course
NAL protocol	0.35 Gy per course	0.70 Gy per course
Effective doses (adult male):		
Routine imaging	16 mSv per course	32 mSv per course
Difficult set-up case	21 mSv per course	42 mSv per course
NAL protocol	13 mSv per course	26 mSv per course
Chance of second cancer induction:		
Routine imaging	0.08%	0.16%
Difficult set-up case	0.11%	0.22%
NAL protocol	0.07%	0.14%

3.7 Audit

Audit is an essential process. It is used to assess both the success of the implementation of the verification processes and measure the standards of the ongoing service provided. Regular audit of practice assesses the continuing effectiveness and appropriateness of the verification processes and gives the opportunity to update protocols in line with current evidence. Guidance in creating audit programmes is given by the National Institute for Health and Clinical Evidence (NICE)[62] and the NHS Clinical Governance Support Team.[63]

Clinical audit evaluates services against a standard that has already been set by examining:

- Whether what ought to be happening is happening
- Whether current practice meets required standards
- Whether current practice follows published guidelines
- Whether clinical practice is applying the knowledge gained from current evidence.

Useful assessment criteria for the verification process would include identification of, adherence to and effectiveness of:

- The management process – whether there was a designated verification team and whether there was a single team for the department or it was tumour-specific and the components of that team in terms of specifying the disciplines involved
- Quality assurance programmes for maintaining the safety and accuracy of verification equipment
- Protocols for image acquisition and analysis for each tumour site
- Action levels and correction strategies and responsibilities within these protocols
- Protocols for incorporating the set-up accuracies measured in margin calculations for common treatment sites where verification is particularly relevant to the application of highly technical radiotherapy; for example, prostate cancer and head and neck cancer
- Training and competencies programmes, preferably benchmarked to standards set out elsewhere
- Inclusion of peer review standards into any audit once these have been revised
- Adherence to IR(ME)R regulations.

3.7.1 Use of audit to evaluate imaging protocols

The recommendations made within this document should be evaluated for their applicability to local practice. It is suggested that each anatomical site should be selected for detailed review of imaging protocols. Specifically the procedures for image acquisition, the quality of images and their subsequent use for treatment modification should be audited.

3.7.2 Use of audit to evaluate techniques and immobilisation systems

Under the site-specific sections of this document, patient immobilisation is included in the suggested protocols for breast, brain, head and neck, prostate, thorax and paediatrics. If these suggestions are followed, it is recommended that a local audit should be carried out to assess their applicability. Initially, this might be confined to the major sites of breast, prostate and thorax for which there is the most supporting evidence, giving greater strength to the recommendations.

Regular audit of the set-up data provides a method for assessing treatment techniques and the effectiveness of immobilisation systems. Set-up accuracies can be monitored over time, to identify trends or changes in standards. Comparisons can be made between different immobilisation systems or techniques to assess the benefit of one method over another.

3.7.3 Identification of systematic errors in the departmental processes

Auditing population data for each treatment site can identify problems in the treatment process; systematic errors detected in all patients for a particular treatment technique can indicate a problem with that technique.

> **Summary. Audit**
> - Regular audit is necessary, assessing process, management, training, protocols, equipment and techniques.

4 Derivation of systematic and random set-up errors and relationship to the CTV-PTV margin

This section describes:

- How the random and systematic set-up errors for a group of patients may be derived from portal images. An example is presented to demonstrate the method
- The interrelationship between CTV-PTV margin and treatment verification.

4.1 Set-up error

The set-up error (Δ) is defined as the deviation between actual and expected position, normally calculated as a shift in the isocentric position when an image is compared against its corresponding reference. For ease of analysis, and more importantly subsequent set-up correction, the set-up error should be resolved into orthogonal directions (for example, A–P and S–I from a lateral image and R–L and S–I from an anterior image). Conversion of these measurements into the required co-ordinate axes may be made if the acquired images are not orthogonal.[29] It is crucial that vector quantities are calculated so the correct direction information is maintained. For example, if shifts in the anterior direction are given a negative sign then those in the posterior direction are always positive. Necessary de-magnifications must be applied to all measurements at this stage.

Definitions and causes of random and systematic errors are given in Section 2.3. The equations used to calculate these are given below and split into two basic forms, those calculating a mean and those a standard deviation (SD). The SD is a measure of how widely values are dispersed from the mean value and in this context defines the size of the error.

The term 'treatment population' is used to represent all patients treated with a specific technique (treatment site and immobilisation method). The set-up errors for this population are estimated by calculating the errors for a group of patients whose results are assumed to accurately represent those of the population from which they are drawn.

4.1.1 Systematic set-up errors

4.1.1.1 Individual mean set-up error

The systematic error ($m_{individual}$) is the mean set-up error for an individual patient. It is calculated by summing the measured set-up error for each imaged fraction ($\Delta_1 + \Delta_2 + \Delta_3 \ldots$) then dividing by the number of imaged fractions (n). This can be expressed by the formula:

$$m_{individual} = \frac{\Delta_1 + \Delta_2 + \Delta_3 + \ldots + \Delta_n}{n}$$

(E1)

4.1.1.2 Overall population mean set-up error

The overall mean set-up error (M_{pop}) is the overall mean for the analysed patient group and should ideally be zero. Significant departures from zero indicate an underlying error common to this patient group and requires investigation. This parameter is a strong indicator of the efficacy of any given treatment technique and is often omitted. The equation is essentially the same as equation 1 with the means for each individual patient (m_1, m_2, $m_3 \ldots$) now being summed and the total divided through by the number of patients in the analysed group (P).

$$M_{pop} = \frac{m_1 + m_2 + m_3 + \ldots + m_p}{P}$$

(E2)

4.1.1.3 Population systematic error

The systematic error for the population ($\sum_{set-up}$) is defined as the SD (spread) of the individual mean set-up errors about the overall population mean (M_{pop}). It is calculated by summing the squares of the differences between the overall population mean derived from equation 2, and each individual patient mean derived from equation 1, in turn.

Note that the resultant sum is divided by the number of patients minus one and the square root of the resultant value is required to give $\sum_{set-up}$.

$$\sum\nolimits^{2}_{set-up} = \frac{(m_1 - M_{pop})^2 + (m_2 - M_{pop})^2 + (m_3 - M_{pop})^2 + ... + (m_n - M_{pop})^2}{(P - 1)}$$

(E3)

4.1.2 Random set-up errors

4.1.2.1 Individual random error

For each individual, the interfractional random (daily) set-up error ($\sigma_{individual}$) is the SD of the set-up errors around the corresponding mean individual value (m) derived from equation 1. It is calculated by summing the squares of the differences between the mean and set-up error from each image in turn. Note that the resultant sum is divided by the number of images minus one and that the square root of the resultant value is required to give $\sigma_{individual}$.

$$\sigma^{2}_{individual} = \frac{(\Delta_1 - m)^2 + (\Delta_2 - m)^2 + (\Delta_3 - m)^2 + ... + (\Delta_n - m)^2}{(n - 1)}$$

(E4)

4.1.2.2 Population random error

The population random error (σ_{set-up}) is the mean of all the individual random errors (σ_1, σ_2, σ_3....). This equation assumes that the number of images acquired per patient is identical or that the likely differences will have minimal effect on the final result.

$$\sigma_{set-up} = \frac{\sigma_1 + \sigma_2 + \sigma_3 + ... + \sigma_p}{P}$$

(E5)

4.1.2.3 Worked example

Using equations 1 to 5 inclusive, a worked example is presented in Tables 1 to 4, pages 31 and 32.
All measurements are in millimetres.

Table 1. Individual set-up errors (Δ) acquired from three patients. The data presented do not incorporate any corrections made during the course of treatment.

Patient	Image fraction	Anterior field		Lateral field	
		R–L	S–I	S–I	A–P
1	1	2.1	−1.6	−1.1	1.6
1	3	−3.2	1.0	1.6	1.1
1	4	−2.6	1.0	1.1	−2.1
1	5	−4.0	1.5	0.7	−4.0
1	6	−2.0	0.3	ND	ND
1	7	1.3	3.0	2.0	0.8
1	13	0.2	1.2	0.9	−3.5
1	15	ND	ND	1.1	2.1
1	16	0.3	0.3	1.3	−1.0
2	1	4.5	0.7	−1.0	−0.2
2	2	3.9	−0.8	−3.5	−2.2
2	3	1.9	1.6	−0.4	0.6
2	4	5.3	2.2	1.1	1.7
2	5	3.0	3.3	2.8	3.1
2	6	2.4	2.1	−1.1	0.5
2	7	1.3	−0.2	−3.2	−1.7
2	8	2.8	0.7	0.2	0.4
2	9	2.2	2.2	0.4	1.3
2	10	3.0	3.8	2.2	3.0
2	12	−1.3	2.9	−2.8	0.0
2	13	4.5	0.7	−1.0	−0.2
2	16	3.9	−0.8	−3.5	−2.2
2	22	1.9	1.6	−0.4	0.6
2	26	5.3	2.2	1.1	1.7
2	31	2.5	−0.9	−3.2	−2.0
2	36	3.0	3.3	2.8	3.1
3	1	0.8	6.6	5.7	−1.7
3	1	0.3	0.3	0.8	−1.0
3	2	−3.0	0.3	0.0	0.0
3	3	0.0	1.8	0.3	−5.3
3	3	0.0	ND	0.0	−2.5
3	7	−1.8	0.3	0.8	3.8
3	8	0.3	0.3	1.4	0.6
3	13	−0.8	2.7	1.0	0.5

ND = No data measured.

Table 2. Individual mean and random set-up errors for Patients 1, 2 & 3 derived from the data in Table 1 using equations 1 and 4

Patient	Mean error	Orthogonal directions			
		R–L	S–I (Ant)	S–I (Lat)	A–P
1	m_1	−1.0	0.8	1.0	−0.6
2	m_2	2.9	1.4	−0.6	0.4
3	m_3	−0.5	1.8	1.3	−0.7
Patient	Random error	R–L	S–I (Ant)	S–I (Lat)	A–P
1	σ_1	2.2	1.3	0.9	2.4
2	σ_2	1.6	1.5	2.2	1.8
3	σ_3	1.3	2.3	1.9	2.7

Table 3. The mean set-up errors for a ten-patient group, including Patients 1–3 from above, are given below along with the calculated overall population means (equation 2) and the resultant population systematic set-up errors in each orthogonal direction (equation 3)

Patient	Mean error	Orthogonal directions			
		R–L	S–I (Ant)	S–I (Lat)	A–P
1	m_1	−1.0	0.8	1.0	−0.6
2	m_2	2.9	1.4	−0.6	0.4
3	m_3	−0.5	1.8	1.3	−0.7
4	m_4	−0.4	−0.5	0.1	0.8
5	m_5	−0.5	−1.6	−0.5	−0.8
6	m_6	0.2	1.4	0.1	−2.1
7	m_7	−0.6	2.0	2.8	−0.4
8	m_8	0.4	1.8	0.0	−1.6
9	m_9	2.0	0.6	0.3	1.3
10	m_{10}	−0.5	1.8	1.0	1.7
Overall mean	M_{pop}	0.2	1.0	0.6	−0.2
Population systematic set-up errors	$\Sigma_{set\text{-}up}$	1.3	1.2	1.0	1.2

Table 4. Individual random errors for the ten-patient group, including Patients 1–3, are given below along with the calculated population random set-up errors in each orthogonal direction (equation 5)

Patient	Random errors	Orthogonal directions			
		R–L	S–I (Ant)	S–I (Lat)	A–P
1	σ_1	2.2	1.3	0.9	2.4
2	σ_2	1.6	1.5	2.2	1.8
3	σ_3	1.3	2.3	1.9	2.7
4	σ_4	3.0	2.1	2.0	3.2
5	σ_5	1.9	2.1	1.7	3.3
6	σ_6	1.8	2.5	2.3	3.1
7	σ_7	1.8	2.4	1.9	4.2
8	σ_8	1.8	2.2	2.4	2.6
9	σ_9	2.0	2.3	2.2	2.7
10	σ_{10}	1.7	1.9	2.2	2.9
Population random set-up error	$\sigma_{set\text{-}up}$	1.9	2.1	2.0	2.9

4.1.2.4 Comments on the example

- Although some reported studies have analysed images from as few as ten patients, it has been shown[37] that small patient studies of this size can result in a large uncertainty in the population systematic set-up error. The random set-up error is likely to be more accurate even for small patient numbers as long as sufficient images are acquired per patient and inter-patient variability is not excessive. It is recommended therefore that at least 20 patients are included in a study with at least five images per patient.

- The equations above apply equal weight from each patient to the overall results rather than the number of images acquired per patient. This is the generally accepted method.[64-67]

Summary. Why perform a portal imaging study?

- To determine the overall mean set-up error. This is a strong indicator of any unwanted systematic component acting on all patients within the analysed group.
- To aid in the design of a portal imaging correction strategy using evidence-based action levels.
- For comparison with similar immobilisation and treatment techniques in the literature.
- To provide local input data into CTV-PTV margin calculations or used as evidence to support currently applied margins.

## 4.2 Relationship between the CTV-PTV treatment margin and treatment verification

4.2.1 Effect of correction protocols on margins

This section describes the interrelationship between treatment margins and treatment verification. A generic CTV-PTV margin calculation recipe is described and the input data required for this calculation are discussed. The systematic and random set-up errors derived from a portal imaging study may be fed into this margin recipe but these are not the only contributing components. The use of a treatment verification protocol to control set-up errors may be used as a basis to reduce or justify currently applied margins. The levels of margin reduction achievable are based on the type of imaging protocol undertaken (see Section 2.3). This is summarised in Figure 6 opposite and explained in more detail in the examples below.

Three cases are presented in Figure 6 opposite to illustrate this.

- **Case A**. No correction to measured set-up errors. The calculated margin must include all contributing sources.

- **Case B**. An off-line protocol imaging bony anatomy is used to correct set-up errors. This enables correction for the phantom transfer and systematic patient set-up components of the treatment preparation error (see Section 4.2.3.1) and may be used to justify a reduction in the corresponding margin. By definition, an off-line protocol applies any correction at the next fraction and so cannot account for the random patient set-up variations occurring from one fraction to the next. The contribution to the treatment margin from the treatment execution errors therefore must remain unchanged between Case A and B.

- **Case C**. An online protocol imaging the target is used to correct set-up errors. This requires imaging, analysis and set-up correction before each fraction and compared to Case B will additionally detect the random patient set-up error as well as both errors associated with variations in target position and shape. This may be used as a basis to further reduce the random (treatment execution) and systematic components of the margin.
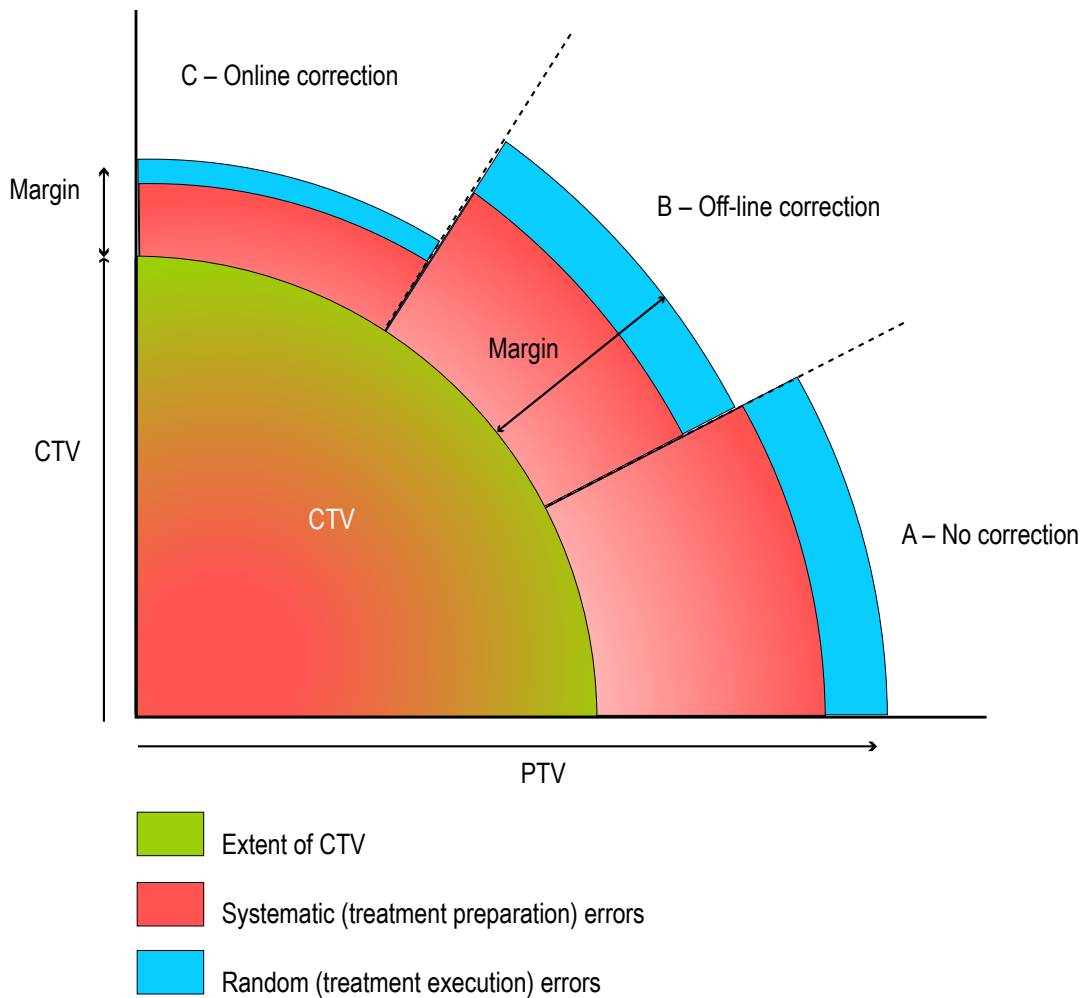
Figure 6. The CTV to PTV margin is governed by the combined systematic (treatment preparation) and random (treatment execution) errors occurring from all possible sources (see Section 2.3 for definitions). The application of treatment verification with imaging protocols designed to quantify and reduce some of these contributing sources can provide justification to reduce the applied margin

4.2.2 *Margin derivation*

It is beyond the scope of this document to discuss the derivation and calculation of CTV-PTV margin calculations in detail. Several population-based margin calculation recipes have been proposed.[17,18,68] These address the differences between treatment execution and treatment preparation errors and how these are to be combined to produce an appropriate margin. All of these margin calculation recipes can be expressed as follows:

$$CTV\text{-}PTV margin = a\sum + b\sigma + c$$

(E6)

where $\sum$ and σ are the combined sum of the SDs of <u>all</u> contributing systematic and random errors respectively (Section 2.3) and **a**, **b** and **c** are constants. The constant **c** is included to account for parameters that affect the margin in a linear manner, such as breathing.[69] The two constants **a** and **b** characterise the relative contributions of the systematic and random components and these depend on factors such as the beam arrangement and chosen coverage probability.[17,68] Typically '**a**' is 3–4 times greater than '**b**' and $\sum$ is generally much larger than σ indicating that the key contributor to the margin is the combined systematic error.[70] Figure 3, (page 15) in Section 2.3 demonstrates the relative effects systematic and random errors have on the cumulative dose to the CTV.

The combined systematic error includes all possible sources of error as described in detail in Section 2.3. The SDs of these four contributing sources ($\sum_{delineation}$ = target delineation, $\sum_{motion}$ = target position and shape, $\sum_{transfer}$ = phantom

transfer and $\sum_{patient\ set-up}$ = patient set-up error) are assumed to be normally distributed and independent of each other, and may be combined in quadrature (equation 7) to produce the combined systematic error $\sum$. Recent work[71] suggests that $\sum_{delineation}$ may require handling in a different way than the other components and needs an alternate theoretical approach. For the purposes of the analysis below, it is assumed to be normally distributed.

$$\sum{}^2 = \sum{}^2_{delineation} + \sum{}^2_{motion} + \sum{}^2_{transfer} + \sum{}^2_{patient\_set-up}$$

(E7)

The components contributing to the combined random error are $\sigma_{patient\ set-up}$ and σ_{motion} where $\sigma_{patient\ set-up}$ is the random patient set-up error and σ_{motion} the random variation in organ position and shape (except breathing). These two components can also be combined in quadrature in a similar manner to equation 7 to give the combined treatment execution error σ.

It can be seen that a portal imaging study will provide important input data to the margin calculation for both the random and systematic components.

4.2.3 Margin control

A portal imaging protocol designed to reduce set-up errors may be used either as a basis to reduce margins or to justify currently used margins. The question is, what components relevant to the CTV-PTV margin will be controlled and what is the likely effect on the overall margin?

4.2.3.1 Example 1. Control of systematic components

For a given treatment population, it is decided to implement a protocol designed to correct mean set-up errors greater than 2 mm. For an uncorrected patient group, a portal imaging study for this population reveals a systematic set-up error ($\sum_{set-up}$) of 3 mm. Application of an off-line correction strategy has the effect of reducing the accumulated contributions of both the patient set-up and the phantom transfer error (see Section 2.3). It has been shown that correcting the mean set-up over the course of treatment to within $\pm$ X of the expected position gives a theoretical approximation to this combined SD of $X/\sqrt{3}$.[72] This corresponds to 1.2 mm for the example of X=2 mm. Table 5 gives representative values for the contributing systematic components for a prostate treatment[73] and shows the combined systematic error for the uncorrected and corrected cases.

Table 5. The effect of an off-line correction strategy on the systematic components of the CTV-PTV margin

Systematic errors (mm)	No correction	Correction
$\sum_{delineation}$	2	2
$\sum_{motion}$	3	3
$\sum_{transfer}$	3	Combined error = 2/√3 = 1.2
$\sum_{patient\ set-up}$	3	
$\sum$ (sum in quadrature, see Equation 7)	**5.6**	**3.8**

There is, therefore, a reduction from 5.6 to 3.8 mm in the combined systematic set-up error as a result of employing a correction protocol. For a typical margin recipe,[17,18] the constant '**a**' has a value of 2.5 leading to a theoretical margin reduction of 2.5 x 1.8 = 4.5 mm for this example.

Following full implementation of the correction protocol, a portal imaging study repeated on the corrected patient group data should give a theoretical value closer to $\sum_{set-up}$ = 1.2 mm. This example demonstrates how a correction strategy designed to limit the mean set-up error constrains the combined effects of $\sum_{patient\ set-up}$ and $\sum_{transfer}$ and can lead to a reduction in the calculated CTV-PTV margin.

4.2.3.2 Example 2. Control of random components

Measured random patient set-up error can be controlled on an individual basis using online imaging. This assumes that the daily set-up variation can be assessed and corrected before any further intrafractional movement occurs. Direct or indirect imaging of the target could also enable correction for target position and

shape, σ_{motion}. It should be noted that the systematic patient set-up and phantom transfer errors will also be corrected with an online strategy, just as they are with an off-line approach.

On a population basis, random errors can be reduced by improved immobilisation, adherence to set-up protocols and training.

This document is concerned with treatment verification and implicit within this is the control of set-up errors. Figure 6 and the two examples above demonstrate the relationship between this process and the CTV-PTV geometric margin (Equation 6). Any such approach used to justify margin reduction should be applied with caution and not used to override clinical judgement.

Summary. Verification and treatment margins

- The magnitude of the CTV-PTV margin is largely governed by the combined systematic (treatment preparation) errors.
- An off-line portal imaging correction strategy can be used to constrain the patient set-up and phantom transfer components of the preparation error.
- An online correction strategy can also control random patient set-up errors.
- An online correction strategy capable of detecting target position can additionally control both the systematic and random errors associated with organ motion.

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5 Training and competency assessment

5.1   Training and competency assessment

Training and maintaining competency is an integral part of the electronic portal imaging (EPI) process.[74] A training programme will ensure that each individual is trained to a consistent level which can reduce inter-observer variability.[75]

The content of a training and competency manual could include the following.

5.1.1   Training manual covering the following subjects

- Ability to acquire images.
- Understanding the use of different acquisition modes.
- Ability to create anatomical templates from a reference image.
- Knowledge of appropriate anatomy to use for each site.
- Ability to perform a matching technique resulting in a record of isocentre displacement.
- Ability to analyse images with awareness of in-plane rotations.
- Ability to apply current isocentre correction methods under protocol.
- Knowledge of systematic and random errors.
- Knowledge of quality assurance necessary on the EPI systems.
- Knowledge of data movement/archiving/deleting and retrieving files.

5.1.2   Competency assessment methods

The aims of the competency assessment should be to:

- Identify current levels of knowledge and skill.
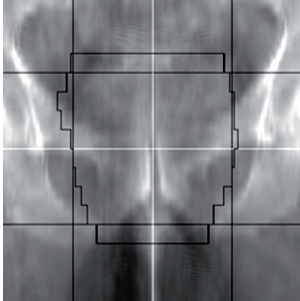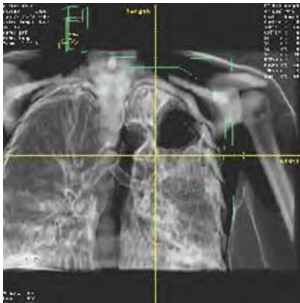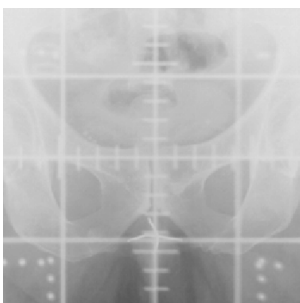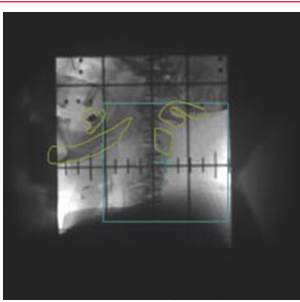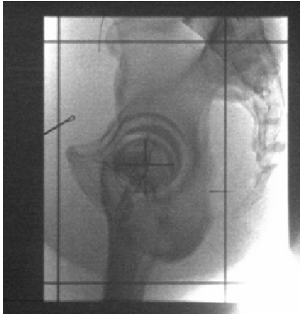
5.1.3   Clinical competency knowledge and skills

- As covered in training manual above.

5.1.4   Further competency assessment for advanced practice
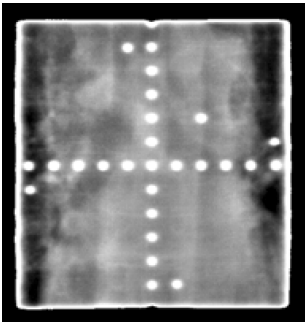
- Ability to train other members of staff.
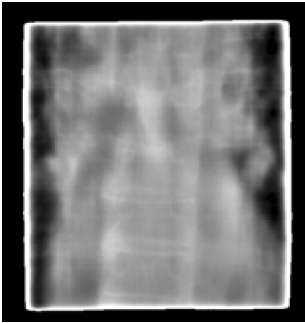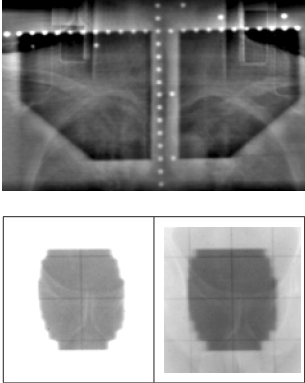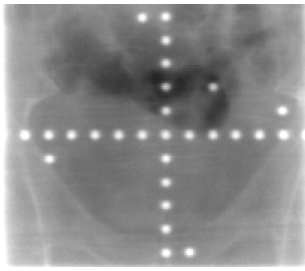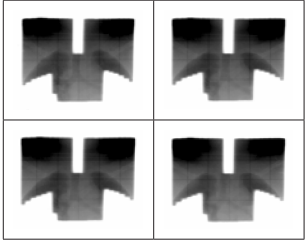- Knowledge of different isocentre correction methods.
- Ability to identify times when and what type of protocol should be used for an individual patient, such as online imaging for a patient demonstrating large random errors.
- Knowledge of dosimetric considerations; such as, identify if replanning is required.
- Ability to identify causative factors relating to displacements; for example, immobilisation causes or patient-specific causes.
- Awareness of limitations of EPI.
- Management of quality assurance programmes.
- Understanding of risk/benefit of ionising radiation.
- Document relevant experience and reflection on decision-making
    a)   Outline objectives to achieve the required level of competence
    b)   Record of clinical competencies and related reflections on practice.

6 Equipment used for geometric verification

6.1 Reference images

Image type	Example
DRRs – digitally reconstructed radiographs	
DCRs – digitally composited radiographs[76]	
Simulator images – film (digitised)	
Simulator images – digital image intensifier	
Simulator images – flat panel	

6.2 Image acquisition modes

Acquisition Mode	Comment	Example
Single exposure – short	Simplest image – taken at the start of the treatment field. Fine if sufficient anatomy within field to assess set-up errors. Good for 'interventional' (online) portal imaging, where judgements can be made before delivering the rest of the treatment field. Energy may be chosen different to that of the treatment field. Minimises blurring due to respiration and internal organ motion Image may be of reduced quality (since short exposure). Full online correction is time-consuming	
Single exposure – long	Usually taken throughout the treatment field delivery. Improved image quality for static anatomy. Reduced image quality for fields involving moving anatomy (blurring)	
Double exposure	Often used for instances where there is insufficient anatomy within the treatment field to accurately assess any set-up error. Collimator jaws are opened to an appropriate size (open field segment) to 'see' the desired anatomy for a short exposure (usually 1–5 MU). Collimators are then returned to the treatment field size/shape and a second exposure taken. The two images are added digitally to produce a double exposure Some commercial companies simply display the treatment field edge overlaid onto the open field segment Delivers extra (concomitant) dose to the patient outside the target volume	
Single exposure – open field	Identical in purpose to the double exposure, but makes use of the open field segment only For systems which digitally add both segments together in a double exposure, the contrast is often improved for the open field segment For this and the double exposure, collimator settings are chosen to maximise useful anatomical information, but minimise concomitant exposure	
Movie loops	Multiple images acquired throughout all or part of the treatment field Ideal for showing anatomical movement for clinical sites (such as lung, breast) where it may significantly affect the coincidence of the target and irradiated volumes	

6.3 Traditional equipment and techniques

Equipment	Comment
Simulator	Reference (kV) planar images in the planned treatment position
	Images may be radiographic film, digital fluoroscopy or digital flat panel
	If acquired for pretreatment verification, should be compared (registered) with planned treatment source data (usually CT)
CT simulator and Virtual Simulation software	Multislice CT scanner with software for performing virtual simulation
	Images for geometric verification are usually DRRs (or more recently DCRs)
	For novel technologies, reference data may be the full 3D CT dataset with appropriate isocentre reference
TPS	Imports CT/MR/PET data for treatment planning
	Images for geometric verification are as for CT simulator
EPID	Electronic detector for acquiring images (portal) during treatment delivery, using the MV treatment beam[77–79]
Film	Traditional radiographic medium for acquiring images (portal) during treatment delivery, using the MV treatment beam. As with diagnostic radiography, film is placed in an imaging cassette on the beam exit side of the patient[30,78,79]
Computed radiography (CR)	A replacement for radiographic film for acquiring simulator (kV) or portal (MV) images. A special plate replaces film inside a traditional cassette. However, the plate is insensitive to ambient light (no darkroom is necessary) and is reusable. The plate is examined in a special reader and the image is produced in a digital format straight away[30,78,80]
Implanted markers	Fiducial markers (usually small gold seeds or wire coils) implanted in soft tissue within the target volume. Markers are large enough and dense enough to be seen on portal images taken with film and EPIDs. Are particularly clear when using aSi-type EPIDs[81–84]
In-room ultrasound	Ultrasound used in the treatment room for visualising soft tissue targets (for example, the prostate). Position of the transducer is linked (either mechanically or optically) to a detection system that relates its position to the isocentre of the treatment machine. Target position is determined with patient on the treatment couch immediately prior to treatment delivery; isocentre position is often moved at this point using an online protocol[85–88]

6.4 Novel equipment and techniques

Equipment	Comment
In-room kV imaging	Linac *(standard)*: Floor and ceiling mounted diagnostic X-ray tubes and image intensifiers to give orthogonal views of the patient on the treatment couch. Static or dynamic (fluoroscopy) images may be used to evaluate patient set-up both before and during field delivery. In dynamic mode, it may be used to influence the beam on timing of the linac[89–91] Linac *(robotic)*: Imaging component for a robotic linac. Identical to the standard linac (above), except that it can also influence the position and beam on timing of the linac[92–94]
In-room CT imaging	Often described as 'CT-on rails'; uses a standard CT scanner at one end of the treatment couch. However, instead of the couch moving through the CT gantry, the CT scanner itself moves linearly over the couch. Full CT volume data is acquired (precisely the same as planning CT scans) prior to treatment. Patient and couch must rotate by 180 (or 90) degrees between imaging and treatment. Direct geometric relationship between the CT scan co-ordinates and the isocentre of the treatment machine[53,95,96]
kV CBCT	Diagnostic X-ray tube and associated imaging panel are attached orthogonally to, or diametrically opposite, the treatment machine gantry arm and EPID. Full-volume cone beam CT scan may be acquired in one single rotation of the linac gantry prior to treatment. Patient is in the treatment position. Static diagnostic X-rays and dynamic fluoroscopic images may also be acquired. Direct geometric relationship between the imaging and treatment isocentres[46,54,56,97–99]
MV CBCT	No extra 'arms' need be attached to the treatment machine gantry for MV CBCT. An MV X-ray beam and EPID are used to acquire a full volume cone beam CT scan in one revolution of the linac gantry prior to treatment. Static and dynamic images are possible, identical in operation to the standard EPID. Imaging isocentre IS the treatment isocentre[55]
Cone-beam simulator	Uses a flat panel imaging system in place of the image intensifier on the simulator. Thus can be identical to the treatment machine (ie, with no need for movement of the X-ray tube head). Can use cone beam technology and software for acquiring full volume cone beam CT data as the reference for treatment verification
Tomotherapy	A modality of X-ray radiation therapy which combines the use of a computer-controlled linear accelerator, multileaf collimator (MLC) and CT detector subsystem, all mounted on a rotating gantry. Intensity-modulated therapy is delivered in a helical fashion as the patient is moved on the couch through the rotating gantry[100,101]
Surface and marker tracking	Uses the principle of photogrammetry to measure optically the position of markers placed on the patient's skin, or the entire skin surface itself, relative to a reference point (such as the machine isocentre in the treatment room). Light of optical or infrared wavelengths may be used. As a set-up or geometric verification device, it can register pretreatment and treatment images to determine associated patient set-up errors. This may be performed continuously throughout the patient set-up and treatment delivery process, and has no associated concomitant radiation exposures[102,103]
Implanted transponders	Beacon (wireless) transponders which may be implanted in the tissue volume whose position is to be verified, in the same way as gold fiducial markers for prostate localisation. The location of the markers relative to the treatment isocentre is determined post-planning, and verified in the treatment room using a magnetic source and receiver coil. The detector array itself is tracked in real-time (with respect to the machine isocentre) using an infrared optical tracking system[104]
MR linac/MR cobalt source	A concept to utilise the very high-quality soft tissue imaging capability of MR imaging for image guidance during treatment delivery. Designs use a combination of diagnostic MR imaging equipment with an added linac mounted on a ring structure (similar to tomotherapy) in the midtransverse plane of the MR magnet. An alternative is, instead of the linac, to mount three cobalt sources (with MLC) on the rotating structure[16,105]
Gating	A method of addressing respiratory motion during the delivery of radiotherapy. Uses optical (visible light or infrared) or mechanical (pressure transducers) methods to correlate movement of the chest or diaphragm (external surrogates) with internal movement of the target volume, during initial CT scanning. During treatment delivery, the movement of the external surrogates is used to indicate when the target volume is centred on the treatment isocentre and is correlated with the beam-on timing of the treatment machine[106]

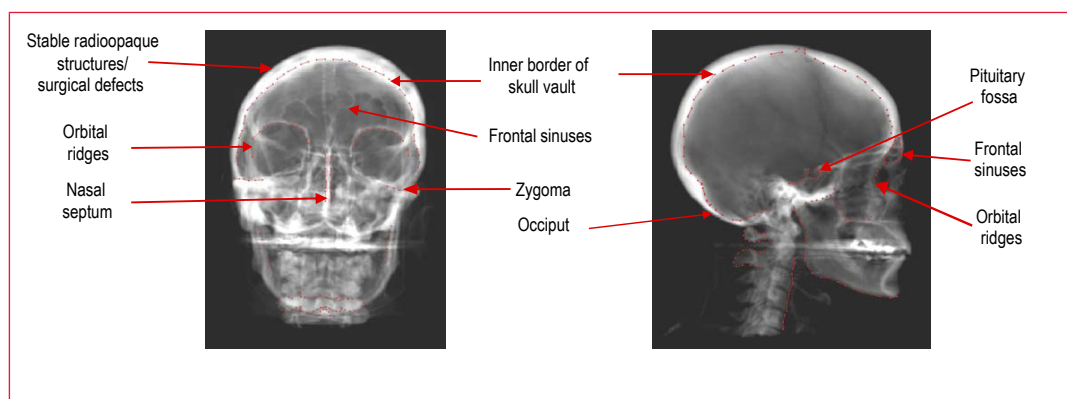# 7 Site-specific protocols for geometric verification

7.1 Brain

7.1.1 Suggested protocol for brain verification

Fraction 1 (images acquired & actioned before treatment delivery)	• Acquire orthogonal image set, minimising dose to critical structures (where possible) • If field edge verification is needed, where possible acquire images of all treatment fields • Assess for and correct gross errors immediately
Fractions 2 & 3	• Acquire orthogonal image set • Assess each image against tolerance levels set and correct gross errors for each fraction where necessary
Action before Fraction 4	• Calculate the overall systematic error (average of the isocentric set-up error) in each orthogonal direction • If set-up error is greater than the action level, apply the systematic set-up error correction (NAL recommended)
Fractions 4 & 5	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions) • If practical, calculate the new overall systematic set-up error and correct values greater than action levels
Weekly & first day of each phase of treatment plan	• Acquire orthogonal image set each week • Assess each image and correct gross errors for each fraction where necessary • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Apply any systematic set-up error correction
• Daily verification may be required for treating tumours planned with very small margins such as those treated stereotactically	
• Intrafractional verification is unnecessary	
• Special consideration should be given for reducing concomitant exposure when treating benign tumours such as pituitary adenomas	
• Tolerances and action levels to use will vary, particularly with the immobilisation used and compliance of the patient and should be chosen accordingly	

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

On target: ensuring geometric accuracy in radiotherapy

7.1.2 Evidence for brain verification guidelines

A particular issue with intracranial radiotherapy is the proximity of structures that are particularly sensitive to radiation and where damage with functional loss can have major consequences. Some treatments require radiotherapy to be planned with steep dose gradients to avoid these critical structures. Effective immobilisation and accurate radiation delivery methods are therefore crucial to provide the higher degree of set-up accuracy required.

Immobilisation and patient positioning

Achievable accuracy of treatment delivery varies with:

- Immobilisation used – the material type, fixation method, area of material in contact with the patient and supporting technique all affect the achievable reproducibility

- Compliance of the patient – accuracy may be compromised by the inability of the patient to remain still for the treatment duration. This can be due to problems such as neurological deficit, where the patient is physically unable to keep still, nausea from raised intracranial pressure or anxiety. Immobilisation for brain treatments may often require whole face shells or masks to be used; this can be problematic in patients with claustrophobia. These patients should be identified pretreatment and the problem resolved or the appropriate margins planned, and an individual tolerance set rather than conforming to the standard for the technique

- The uncertainty resulting from the multiple imaging modalities used in planning with image registration. This arises from each imaging stage carrying its own level of uncertainty, as well as the many opportunities for transfer errors to occur.

Set-up reproducibility

Reproducibility will vary with immobilisation used. Studies using stereotactic frames have reported set-up errors in the region of 1.3[107] and 2 mm.[108,105] The set-up error using immobilisation masks has been measured as ranging from approximately 3 mm using high melting point thermoplastic (acrylic) systems[110] to 4–5.5 mm using low melting point thermoplastic systems[111] and 3.27 mm using thermoplastics in combination with bite block.[112]

Internal organ motion

The brain can move very little inside the cranium and the contribution to set-up accuracy from internal organ motion is very small in this group of patients. Thus intrafractional analysis is not required.

Imaging and radiotherapy fields to image

The timing and frequency of imaging for verification of radiotherapy to the brain is currently undefined. The structure of the head is such that effective immobilisation may result in less patient positional variation than in other anatomical sites and the anatomy of the brain is not subject to large internal motions. If immobilisation has been previously evaluated and the department is confident with the process, first-day only images may be sufficient to identify gross and systematic data preparation errors. However, there are other factors that may introduce large systematic and random uncertainties and daily images for a minimum of the first three days would be required to identify these.[113] Imaging for a minimum of the first three days is therefore recommended. Additional uncertainties may occur if the fit of the immobilisation device changes over time; for example, with steroid use. Weekly imaging is therefore recommended.[39]

The proximity of critical structures in the brain means that for all radical treatments, images should be taken of all treatment fields wherever possible, so that the field edges can be reviewed as well as the isocentre. Where insufficient anatomy is seen in the image, double exposures should be used, taking care to use asymmetrical fields to avoid exposing critical structures. It may not be possible to image some planned beams such as vertex fields. If the margins are critical, visual verification of the linac light field compared to anatomy may be made. The structure of stereotactic immobilisation devices and the non-coplanar arrangement of treatment fields may result in the inability to gain clear images, therefore measurements of fiducial surrogates can give good information.[108]

Special consideration should be given for reducing concomitant exposure when treating benign tumours such as pituitary adenomas. For other tumours, where double exposures are required, consideration should be given to where the anatomical information can be gained without imaging through critical structures.
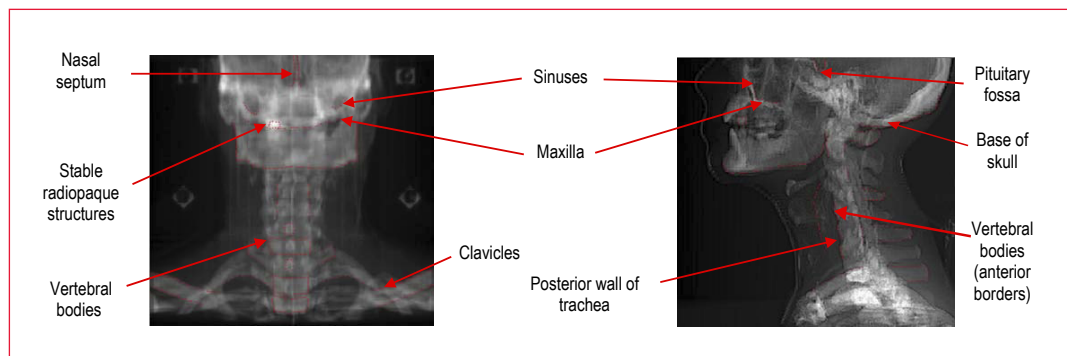
7.2 Head and neck

7.2.1 Suggested protocol for head and neck verification

Fraction 1 (images acquired & actioned before treatment delivery)	• Acquire orthogonal image set, minimising dose to critical structures (where possible) • If field edge verification is needed, where possible acquire images of all treatment fields • Assess for and correct gross errors immediately
Fractions 2 & 3	• Acquire orthogonal image set • Assess each image against tolerance levels set and correct gross errors for each fraction where necessary
Action before Fraction 4	• Calculate the overall systematic error (average of the isocentric set-up error) in each orthogonal direction • If set-up error is greater than the action level, apply the systematic set-up error correction (NAL recommended)
Fractions 4 & 5	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions) • If practical, calculate the new overall systematic set-up error and correct values greater than action levels
Weekly & first day of each phase of treatment plan	• Acquire orthogonal image set each week • Assess each image and correct gross errors for each fraction where necessary • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Apply any systematic set-up error correction

- Daily verification may be required for treating tumours planned with very small margins or hypofractionated techniques
- Immobilisation is mandatory
- Effect of organ movement of larynx and tongue should be considered
- Intrafractional verification may be necessary
- Oblique images are difficult to interpret and it is recommended that the isocentre is verified using anterior/posterior and lateral views
- The images acquired must be of sufficient size to ensure bony anatomy is visible
- Tolerances and action levels to use will vary, particularly with the immobilisation and treatment technique used as well as compliance of the patient and should be chosen accordingly

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

7.2.2 Evidence for head and neck verification guidelines

Immobilisation and patient positioning

Immobilisation devices are routinely used in head and neck cancer and should now be considered mandatory for other tumour types involving this region, such as lymphoma. There are three main types of device:

- Low melting point thermoplastic masks

- High melting point thermoplastic masks, such as Perspex or acrylic

- Bite block using dental casts.

The bite block immobilisation offers a small improvement in positional accuracy but is not suitable for all patients (since many are edentulous) and it has to be used with skin marks or other means of identifying the isocentre.

Change in shape of anatomy is potentially important in head and neck cancer and may lead to ill-fitting immobilisation masks and subsequent patient movement. This is due to both tumour shrinkage and weight loss. Where there are large nodal masses at the start of treatment, gross tumour volume (GTV) has been shown to decrease by a median of 1.8% per day.[114] Selected patients with bulky disease should be considered for re-masking and re-planning in the third or fourth week of treatment.

Set-up reproducibility

Overall, the literature shows good concordance with all of the immobilisation methods stated above. Reported set-up errors vary between 1.6 and 4.6 mm.[36] Material type, fixation method and headrest used also affect the achievable reproducibility; the more rigid the material, the greater the number of fixation points and the more the shape of the headrest matches the anatomy of the patient, the more effective the immobilisation. Thermoplastic masks should not be used immediately after being made since there may be shrinkage of up to 2 mm in the first 24 hours.

Set-up error is most marked in the shoulder region. This can be minimised by ensuring there are additional fixation points on each shoulder as well as the standard points over the head.[115] This is particularly important where the field covers the lower neck and supraclavicular fossae.

Internal organ motion

The tongue and larynx may show some movement on swallowing which is of particular relevance when selecting sites suitable for anatomical matching.

Imaging and radiotherapy fields to image

Imaging should be on Days 1–3 of treatment, and similarly at the beginning of each new phase of treatment. It should be weekly thereafter using site-specific tolerances determined locally but which is likely to be in the order of 2–3 mm.[37–39]

Multiple fields are routinely used in head and neck cancer. Oblique images are difficult to interpret and it is difficult to determine couch corrections from this, therefore it is recommended that the isocentre is verified using anterior/posterior and lateral views with a NAL protocol. The images must be of sufficient size to ensure bony anatomy is visible. This is of particular importance where small fields are used such as in glottic cancer or boost volumes. Dose-sensitive structures such as the eyes are to be avoided when imaging.
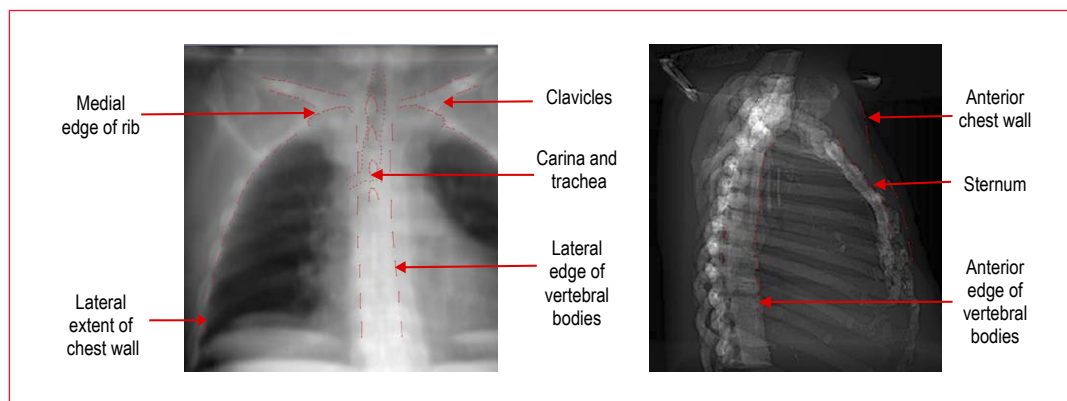
7.3 Thorax and mediastinum

7.3.1 Suggested protocol for thoracic and mediastinum verification

Fraction 1 (images acquired & actioned before treatment delivery)	• Acquire orthogonal image set, minimising dose to critical structures (where possible) • If field edge verification is needed, where possible image all treatment fields where field shaping is used (manual shielding or MLCs) • Assess for and correct gross errors immediately
Fractions 2 & 3	• Acquire orthogonal image set • Assess each image against tolerance levels set and correct gross errors for each fraction where necessary • If available, acquire a movie loop to assess intrafractional movement
Action before Fraction 4	• Calculate the overall systematic error (average of the isocentric set-up error) in each orthogonal direction • If set-up error is greater than the action level, apply the systematic set-up error correction (NAL recommended)
Fractions 4 & 5	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions) • If practical, calculate the new overall systematic set-up error and correct values greater than action levels
Weekly & first day of each phase of treatment plan	• Acquire orthogonal image set each week • Assess each image and correct gross errors for each fraction where necessary • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Apply any systematic set-up error correction
	• Daily verification may be required for treating tumours planned with very small margins or hypofractionated techniques
	• Patient immobilisation devices to help maintain treatment position is essential
	• Compensation for organ movement due to respiration and cardiac contractions should be considered
	• Oblique images are difficult to interpret and it is recommended that the isocentre is verified using anterior/posterior and lateral views
	• Tolerances and action levels to use will vary, particularly with the immobilisation and treatment technique used as well as compliance of the patient and should be chosen accordingly

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

7.3.2   Evidence for thoracic and mediastinum verification guidelines

Immobilisation and patient positioning

Most radical treatments will have the patient supine with their arms raised, unless a superior tumour is being treated. Immobilisation with a T bar or similar is necessary. Patient set-up errors can be more important than internal organ motion.[113] Simple devices to improve patient comfort for this position therefore may have a significant effect on reproducibility. Complex extra cranial stereotactic devices are currently being evaluated for this site.

Set-up reproducibility

For radical lung treatments, set-up errors have been reported between 1 to 5 mm.[36] For lymphoma treatments, greater systematic errors are reported with large 'mantle type' fields ranging from 3 to 10 mm.

Internal organ motion

The thorax and mediastinum presents a particular problem because of internal organ movement during respiration and the cardiac cycle. Greatest movement is seen with lower lobe tumours which have no attachment to adjacent structures when average cranio-caudal movement has been measured at 12 mm.[117] Other studies have reported a range of movement due to respiration of up to 22 mm.[118] Movement of tumours close to the heart due to cardiac function may be 1–4 mm. These movements due to respiration, or the cardiac cycle, must be addressed for radical radiotherapy by one of the following approaches.

- Screening or preferably video imaging or 'slow CT' to measure the extent of movement and an appropriate increase in the PTV expansion made. This is the least satisfactory since although it will ensure coverage of the PTV it will increase the volume of normal tissue irradiated, but is the simplest and most readily adopted in departments which do not have the additional equipment or expertise for more complex approaches. Typical expansions will be of 15 mm in the cranio caudal direction and 10 mm laterally.[119]

- Breathing control during radiation exposure. This may use either voluntary breath[120] or active breathing control (ABC) in which temporary breath holding at a chosen point in the respiratory cycle is used.[121] However, the breath-hold level and patient training can affect reproducibility and the interfraction and intrafraction reproducibility of the breath holds should be established.[122,123]

- Gated radiation exposure using one of the systems which pulse linear accelerator output with a specific phase in the respiratory cycle, usually inspiration determined by implanted markers or external markers as a surrogate for lung position.[124] Implanted markers are an extremely invasive procedure. However, for external markers to be effective, the relationship between the external marker and tumour position must be constant. Erratic breathing patterns affect the reproducibility,[125,126] although audio breathing instructions have been found to make breathing more regular.[127,128]

Imaging and radiotherapy fields to image

It may be possible to visualise some lung tumours on EPI, but for the majority of patients it will only be possible to verify the patient position using bony anatomy.

The frequency of the imaging will depend on the treatment technique used. Techniques to compensate for breathing motion may require additional imaging to verify the reproducibility of the technique.

Radical treatments will require three or four field plans; oblique views of the thorax are difficult to interpret; the recommendation therefore is for antero-posterior and lateral views to locate the isocentre with adoption of the no action level protocol as described earlier.

Lymphoma treatments are usually parallel opposed fields but also often incorporate complex shielding. Verification fields should include all shielded areas together with reference anatomy to enable effective validation of the shielding accuracy as well as the field set-up. To ensure all the information is acquired, two EPIs or port films may be required.
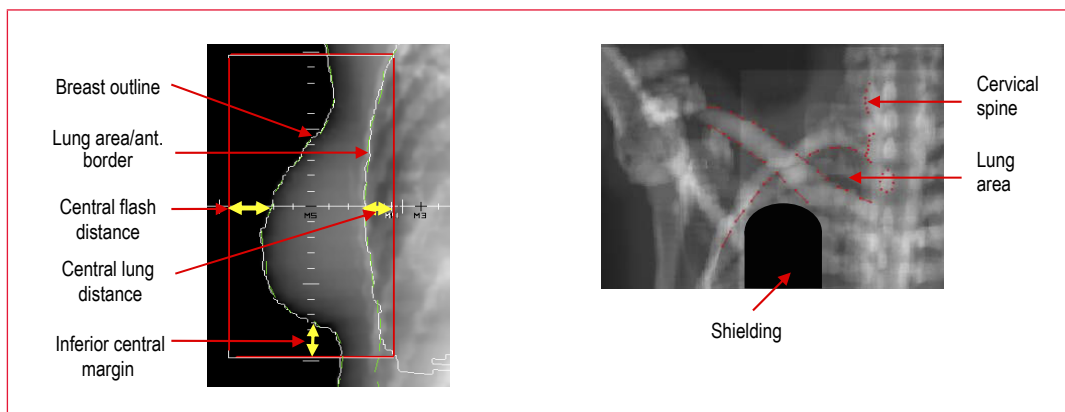
7.4 Breast

7.4.1 Suggested protocol for breast verification

Fraction 1 (images acquired and actioned before treatment delivery)	• For standard whole-breast radiotherapy, acquire images of either or both treatment fields and all nodal fields, avoiding dose critical structures (where possible) • Double exposures not necessary • Set-up error should be determined as a measure of central lung distance and skin coverage rather than isocentre displacement (critical aspects of whole-breast RT) • For partial field irradiation or dynamic IMRT deliveries, use other pretreatment checks to verify the MLC pattern and use open field images to verify anatomy • Opposed fields cannot resolve set-up errors into all three orthogonal directions. Based on the planar image, correction is made by either: — Estimating changes to isocentre and re-imaging to check correction — Determining isocentre shift using simulation equipment
Fractions 2 & 3	• **Further images only applicable where isocentre displacements are calculable and actionable** • A more accurate evaluation of the systematic component of the set-up error in each planar image will be obtained by repeat imaging over a number of fractions • Calculation of corrective couch shifts is difficult with tangential images. Accurate correction of a systematic set-up error will generally require re-simulation • Any systematic set-up correction should be applied before Fraction 4 and imaging repeated (typically 2 or more fractions). Any corrections applied to the treatment set-up must be verified.
Weekly	• Acquire images of tangential fields each week to assess shape change or trends • Assess each image and correct gross errors for each fraction where necessary if set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions)

- A more accurate evaluation of the intrafractional variability of set-up will be obtained by using multiple intrafractional imaging such as cine acquisition or movie loops. Intrafractional verification to be considered where possible to inform planning margins
- Daily verification may be required for tumours planned for IMRT or partial organ irradiation
- Patient immobilisation devices to help maintain treatment position are essential
- Control of systematic and random set-up errors is more effectively achieved on a treatment population basis by improved immobilisation, adherence to protocols and training
- Tolerances and action levels to use will vary, particularly with the immobilisation and treatment technique used as well as compliance of the patient and should be chosen accordingly

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

7.4.2 Evidence for breast verification guidelines

Immobilisation and patient positioning

Verification is an important component of breast radiotherapy. Uncorrected gross and large systematic set-up errors may result in reduced treatment efficacy and increased complications.[129,130] Daily variations arise from two main sources, the reproducibility of the patient positioning and the internal movement of the breast tissue and nodes caused by respiratory and cardiac motion. Patient positioning can be improved by using effective immobilisation; breast position and shape are altered by the arm position and angulation of the immobilisation device. Footrests, knee and bottom supports may minimise patient slippage.

Set-up reproducibility

The immobilisation used will affect the set-up reproducibility. Set-up errors of 2.1 mm and 6.5 mm have been reported, varying between immobilisations such as arm poles and tilted boards and alpha cradle.[66,131]

From a comprehensive survey of set-up errors reported in the literature,[70] median values for the 'standard' immobilisation method of angled board, arm support and various combinations of foot, knee and buttock supports were derived and are reproduced below.

Anatomical parameter	$\Sigma_{\text{set-up (mm)}}$	$\sigma_{\text{set-up (mm)}}$
Central lung distance (CLD)	3.0	2.4
Central flash distance (CFD)	2.8	3.1
Inferior central margin (ICM)	3.8	3.2
Mean	**3.2**	**2.9**

Therefore 3 mm may be used as suitable starting value for both $\Sigma_{\text{set-up}}$ and $\sigma_{\text{set-up}}$ and action levels should be set appropriately. A shrinking action level or fixed action level is therefore most appropriate.[40] For example, a fixed action level of twice the random set-up error, σ (typically around 6 mm) could be employed. Where possible, local values of σ should be ascertained from a portal imaging study. Breast swelling during radiotherapy may affect the relative accuracy of the measurements used for assessment.

Internal organ motion

Breathing and cardiac motion are challenging and verification protocols should explore the use of 4D detection and correction strategies.[69] The contribution to set-up accuracy from respiration can be measured by taking multiple images through the treatment fraction.[132]

Imaging and radiotherapy fields to image

Where the planned treatment field covers the whole breast, sufficient anatomical information should be available with which to make a decision and double exposures will not be necessary. For non-IMRT techniques, central lung distance is the most reliable landmark for anatomy matching.[131] Both tangential fields should be imaged where there is a need to verify non-rectangular field shaping, or where the variation in lung volume treated throughout the entire fraction needs to be assessed.[132]

Correction of systematic errors is difficult for breast radiotherapy as orthogonal images are not usually acquired. Tangential opposed fields alone cannot resolve set-up errors into all three orthogonal directions. Accurate correction of a systematic set-up error will generally require re-simulation. Control of systematic and random set-up error is more effectively achieved on a treatment population basis by improved immobilisation, adherence to protocols and training.

It has been demonstrated that breast volume changes occur between the 5–8 fractions,[133] which may have dosimetric consequences.[134] Weekly imaging is recommended for detecting surface outline changes and systematic trends.[39] For standard whole-breast radiotherapy, there is only small benefit in using daily imaging protocols over weekly after the initial assessment of the first few fractions.[132,135]

A national study aims to assess the imaging protocols needed for partial breast irradiation and IMRT (IMPORT).[136] For partial field irradiation or dynamic IMRT deliveries, other pretreatment checks can be used to verify the MLC position or pattern and an open field image used to verify anatomy position.[137]
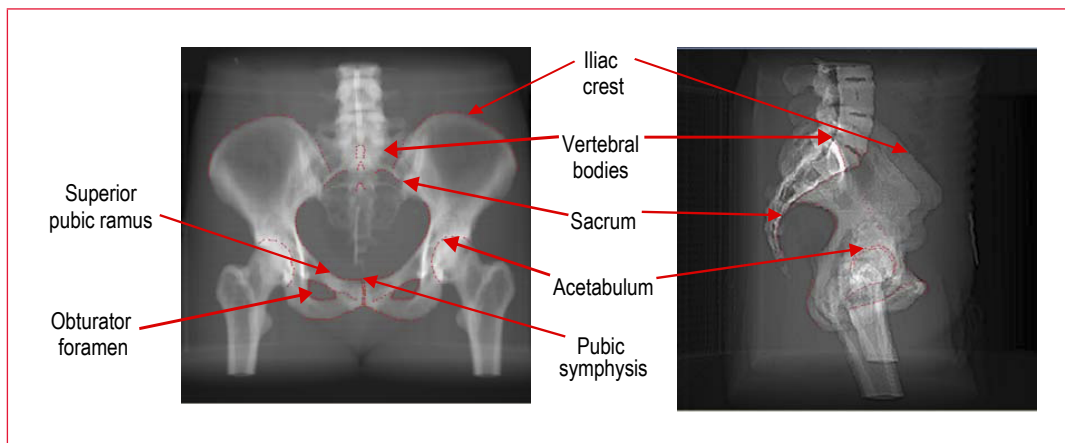
7.5 Pelvis (prostate, bladder, gynaecological and colorectal cancers)

7.5.1 Suggested protocol for pelvis verification

Fraction 1 (images acquired & actioned before treatment delivery)	• Image all treatment fields where possible • Use open fields or double exposures, where necessary, to ensure sufficient stable anatomy can be seen in the images • Avoid exposing dose critical structures by reducing imaging borders where possible • Assess for and correct gross errors immediately
Fractions 2 & 3	• Image orthogonal set • Assess each image against tolerance levels set and correct gross errors for each fraction
Action before Fraction 4	• Calculate the overall average of the isocentric set-up error in each orthogonal direction • If set-up error is greater than the action level value, apply correction to isocentre
Fractions 4 & 5	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions), calculate the new overall average set-up error and correct values greater than action levels
Weekly & first day of each phase of treatment plan	• Image orthogonal set each week • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Assess and correct set-up based on new average set-up errors
• Daily online verification may be required for treating tumours planned with very small margins or those likely to have large internal movements	
• Intrafractional verification may be necessary when using imaging to calculate the impact of internal movement for population planning margins	

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

7.5.2 Evidence for pelvis verification guidelines

Using bony anatomy with EPI for verification of the patient's position provides no information regarding the soft tissue organs; the effect of internal organ movement on the position of the target is therefore not gained. Where verification using bony anatomy alone is used, the lack of information should be taken into consideration in planning treatment margins. Methods exist to overcome this, some can image soft tissue and some use a radio-opaque surrogate that is implanted in the soft tissue target and moves with it.

1. *Implanted markers*

   It is possible to use implanted gold markers[81,83,138] to enable soft tissue imaging using EPI when treating prostate patients and is under investigation for other sites.[82] This is an invasive procedure and the possibility of marker migration has to be eliminated before clinical use.

2. *Ultrasound*

   The accuracy of using ultrasound techniques is currently under debate. One study shows the B-mode acquisition and targeting (BAT) system is equivalent to within 3 mm when compared with daily CT scans for prostate localisation.[85] However, other studies have shown larger systematic errors when compared to CT or implanted marker verification methods.[88,139] Additionally, there may be significant inter-user variation of the contour alignment process either as a result of misidentification of the target structures on the ultrasound image, or due to prostate movement at the time of BAT acquisition.[140,141]

3. *Cone beam CT*

   X-ray volumetric imaging allows a 3D image to be taken prior to treatment with the patient remaining in the treatment position.[54,99,142] Initial studies have focused on prostate and bladder cancer patients but this technology has potential to be useful for all the sites mentioned above.

4. *Tomotherapy*

   Helical tomotherapy is another method of achieving volume imaging in pelvic patients. This is under investigation at present and there are a few publications describing early experience.[143,144]

General pelvic tolerances

The tolerances used depend on the site treated, the motion observed and the margin used, as discussed previously. Hurkmans *et al*[36] have summarised motion for these sites. This information can be used as a guideline to help set tolerances but it is essential that the tolerance is investigated in each individual department. Tolerances for pelvic treatments tend to be between 3 mm and 5 mm depending on site and size of treatment field.

The mean displacement using bony anatomy in the pelvis and no correction can be expected to be in the range of 2–5 mm. This can be reduced to <2.5 mm by the use of correction protocols in all directions. To achieve the same reduction in prone patients requires more corrections and/or online imaging.

7.5.3 Evidence for prostate verification guidelines

Immobilisation and patient positioning

- Patients treated supine have been associated with less internal prostate movement and patient movement than patients treated prone.[89,145] However the prone position has been related to a reduction of the dose to the rectum and bowel.[19,146]

- Leg movement and pelvic tensing can affect the position of the prostate when in the supine position.[147,148] Foot and/or ankle supports can be used which maintain the angle between the ankles and so a stable position. Also avoiding over-full bladders and ensuring the patient is in a relaxed state.

- Setting the isocentre height from the couch top is a more accurate method of setting the isocentre than using skin marks since it is not influenced by changes in patient separation.[146]

Set-up reproducibility

The tolerance used for EPI depends on the site treated, the motion observed and the margin used, as discussed above. Hurkmans et al[36] have summarised motion for these sites. This information can be used as a guideline to help set tolerances but it is essential that the tolerance is investigated in each individual department. Tolerances for pelvic treatments tend to be between 3 mm and 5 mm depending on site and size of treatment field.

The mean displacement using bony anatomy in the pelvis and no correction can be expected to be in the range of 2–5 mm. This can be reduced to <2.5 mm by the use of correction protocols in all directions. To achieve the same reduction in prone patients requires more corrections and/or online imaging.

Internal organ motion

- Changes in rectal size and shape are the main factors which affect prostate movement, independent of bony anatomy,[147,150–152] which can be 10–11 mm in the anterior–posterior direction and up to 13.1 mm (mean 0.8 mm; SD 2.3 mm) superiorly. [147,153–155]

- Methods to reduce the variation in rectal distension include the use of enemas or rectal balloons.[155,156] The use of a rectal balloon has the added advantage of significantly decreasing the dose to the rectal wall by distending the rectum so that more of it is outside the high-dose radiation target volume.[157] The use of enemas in reducing rectal distension is being investigated as are changes in diet, but at the time of writing, evidence of their efficacy does not exist.

- It is a matter of debate whether bladder filling has an impact on prostate movement,[150,151] although it will affect the dose volume histograms.

Imaging

The frequency of imaging will vary according to the size of the volume being treated and the internal movement of the prostate. If the prostate itself can be imaged and the volume to be treated or margins planned are relatively small, daily online verification may be needed.

Radiotherapy fields to image

Sufficient stable anatomy needs to be visible in the verification images to ensure accurate matching can be made. For small treatment beams or beams covering soft tissue targets only, open fields or double exposures are necessary. The verification images should be taken avoiding exposing dose critical structures where possible, by reducing the imaging borders.

The pelvic rim is routinely used on the anterior image to verify the position in the superior–inferior direction. However, this must be used with the knowledge that pelvic rotation may occur around the lateral axis and so affect the readings.

In lateral fields the femora, although visible, should not be used as the position varies too easily. The acetabulum and symphysis or sacrum are more stable and better visualised.

7.5.4 Evidence for bladder verification guidelines

Immobilisation and patient positioning

- Bladder patients tend to be treated supine which is stable in terms of patient position but internal organ movement must be considered.
- Setting the isocentre height from the couch top is a more accurate method of setting the isocentre than using skin marks.[149]

Set-up reproducibility

The tolerance used for EPI depends on site treated, the motion observed and the margin used, as discussed above. Hurkmans *et al*[36] have summarised motion for these sites. This information can be used as a guideline to help set tolerances but it is essential that the tolerance is investigated in each individual department. Tolerances for pelvic treatments tend to be between 3 mm and 5 mm depending on site and size of treatment field.

The mean displacement using bony anatomy in the pelvis and no correction can be expected to be in the range of 2–5 mm. This can be reduced to <2.5 mm by the use of correction protocols in all directions. To achieve the same reduction in prone patients requires more corrections and/or online imaging.

Internal organ motion

Conventionally patients treated for bladder cancer are treated with an empty bladder.

- Despite advising patients to empty their bladder immediately prior to treatment, the bladder volumes during a treatment schedule can vary.
- The most evident motion is in the superior inferior direction and the anterior–posterior direction.[142,158]
- This trend is reflected when treating patients with a full bladder.[156] Treating patients for bladder cancer can require margins of up to 23 mm posteriorly and superiorly.

Imaging

The frequency of imaging will vary according to the size of the volume being treated and the internal movement of the bladder. If the bladder itself can be imaged and the volume to be treated or margins planned are relatively small, daily online verification may be needed.

Radiotherapy fields to image

Sufficient stable anatomy needs to be visible in the verification images to ensure accurate matching can be made. For small treatment beams or beams covering soft tissue targets only, open fields or double exposures are necessary. The verification images should be taken avoiding exposing dose critical structures where possible, by reducing the imaging borders.

The pelvic rim is routinely used on the anterior image to verify the position in the superior inferior direction. However, this must be used with the knowledge that pelvic rotation may occur around the lateral axis and so affect the readings.

In lateral fields the femora, although visible, should not be used as the position too easily varies. The acetabulum and symphysis or sacrum are more stable and better visualised.

7.5.5   Evidence for colorectal verification guidelines

Immobilisation and patient positioning

- Rectal volumes are treated prone which as mentioned previously, can be unstable depending on the immobilisation used.

- There is potential for the pelvic muscle tension to affect anal verge displacements and affect the anterior posterior and superior inferior position of the field.[160]

- A colorectal immobilisation device in which the patient lies prone, called a belly board, is often used to reduce the amount of small bowel in the PTV. Care must be taken to standardise the position of the patient within a belly board.[161,162]

- Using no immobilisation in seven patients, interfraction movement was most evident in the anterior–posterior direction (23% movements were >10 mm) compared to the right–left and superior–inferior (3% and 16% respectively). The frequency of interfraction displacements >5 mm was more similar for each direction.[102]

Set-up reproducibility

The tolerance used for EPI depends on site treated, the motion observed and the margin used, as discussed above. Hurkmans et al[36] have summarised motion for these sites. This information can be used as a guideline to help set tolerances but it is essential that the tolerance is investigated in each individual department. Tolerances for pelvic treatments tend to be between 3 mm and 5 mm depending on site and size of treatment field.

The mean displacement using bony anatomy in the pelvis and no correction can be expected to be in the range of 2–5 mm. This can be reduced to <2.5 mm by the use of correction protocols in all directions. To achieve the same reduction in prone patients requires more corrections and/or online imaging.

Internal organ motion

There is also a possibility of internal organ motion occurring in these patients. Although there are no data available for colorectal patients, there is extensive data on rectal movement in prostate patients mentioned previously.

Imaging

The frequency of imaging will vary according to the size of the volume being treated and the internal movement of the target. If the target itself can be imaged and the volume to be treated or margins planned are relatively small, daily online verification may be needed.

Radiotherapy fields to image

Sufficient stable anatomy needs to be visible in the verification images to ensure accurate matching can be made. For small treatment beams or beams covering soft tissue targets only, open fields or double exposures are necessary. The verification images should be taken avoiding exposing dose critical structures where possible, by reducing the imaging borders.

The pelvic rim is routinely used on the anterior image to verify the position in the superior inferior direction. However, this must be used with the knowledge that pelvic rotation may occur around the lateral axis and so affect the readings.

In lateral fields the femora, although visible, should not be used as the position too easily varies. The acetabulum and symphysis or sacrum are more stable and better visualised.

7.5.6 Evidence for gynaecological verification guidelines

Immobilisation and patient positioning

The data available on the treatment set-up and movement of gynaecological patients are much more limited than that available for prostate and bladder cancer patients.

- Belly boards with the patient prone have also been used to reduce the amount of small bowel in the treatment field.[163]

Set-up reproducibility

The tolerance used for EPI depends on site treated, the motion observed and the margin used, as discussed above. Hurkmans *et al*[36] have summarised motion for these sites. This information can be used as a guideline to help set tolerances but it is essential that the tolerance is investigated in each individual department. Tolerances for pelvic treatments tend to be between 3 mm and 5 mm depending on site and size of treatment field.

The mean displacement using bony anatomy in the pelvis and no correction can be expected to be in the range of 2–5 mm. This can be reduced to <2.5 mm by the use of correction protocols in all directions. To achieve the same reduction in prone patients requires more corrections and/or online imaging.

Internal organ motion

Internal motion is also an important factor in gynaecological patients though less well documented.

- Movement of the cervix and uterus has significant impact on margins.[163]
- The uterus has been found to move with respect to bladder filling and the largest effect was in the SI direction.[164] The median movement for the corpus uteri was 7 mm and (95% CI 3–15 mm) and the cervix 4 mm (1–6 mm).

Imaging

The frequency of imaging will vary according to the size of the volume being treated and the internal movement of the target. If the target itself can be imaged and the volume to be treated or margins planned are relatively small, daily online verification may be needed.

Radiotherapy fields to image

Sufficient stable anatomy needs to be visible in the verification images to ensure accurate matching can be made. For small treatment beams or beams covering soft tissue targets only, open fields or double exposures are necessary. The verification images should be taken avoiding exposing dose critical structures where possible, by reducing the imaging borders.

The pelvic rim is routinely used on the anterior image to verify the position in the superior–inferior direction. However, this must be used with the knowledge that pelvic rotation may occur around the lateral axis and so affect the readings. This has been shown to be true in cervix patients. The position of the lumbar vertebrae may be more accurate for the longitudinal direction in large pelvic fields.
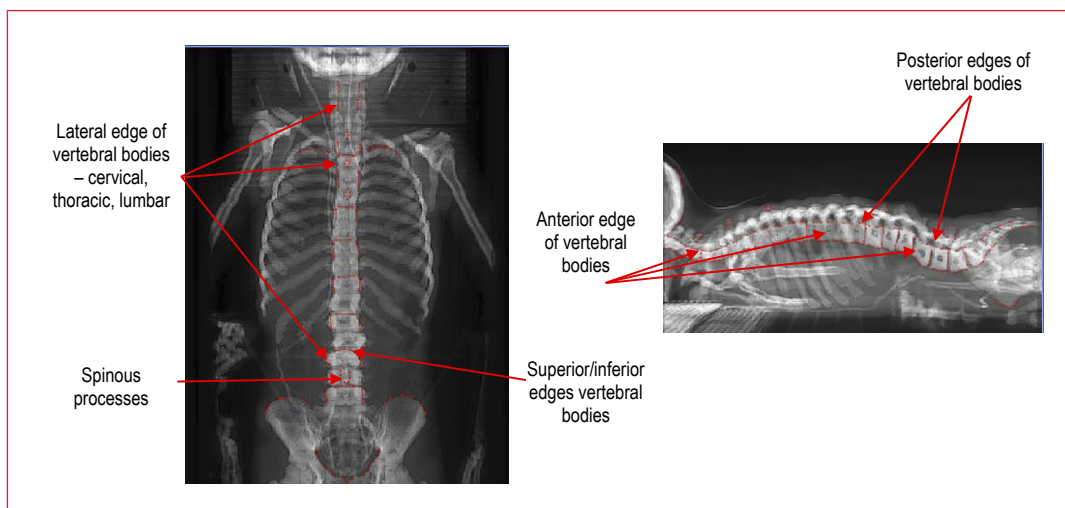
7.6 Spine

7.6.1 Suggested protocol for spinal verification

Fractions 1–3 (images acquired & actioned before treatment delivery)	• Image all treatment fields where possible, avoid exposing dose-critical structures • Assess each image against tolerance levels set and correct gross errors for each fraction
Action before Fraction 4	• Calculate the overall systematic error (average of the isocentric set-up error) in each orthogonal direction • If set-up error is greater than the action level, apply the systematic set-up error correction (NAL recommended)
Fractions 4 & 5	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions) • If practical, calculate the new overall systematic set-up error and correct values greater than action levels
Weekly & first day of each phase of treatment plan	• Image all treatment fields weekly • Assess each image and correct gross errors for each fraction where necessary • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Apply any systematic set-up error correction
•	Daily verification may be required for treating tumours planned with very small margins or to identify length changes from the variability of daily spinal compression
•	Concomitant exposures should be especially considered in children and adolescents
•	Imaging field width should be increased to provide sufficient additional anatomy to enable spine identification, where necessary
•	Particular attention should be paid to field junctions
•	Length of some spinal fields may cause problems with image acquisition and may need to be acquired in sections
•	Tolerances and action levels to use will vary, particularly with the immobilisation used and compliance of the patient and should be chosen accordingly

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

7.6.2 Evidence for spinal verification guidelines

Immobilisation and patient positioning

Achievable accuracy of treatment delivery varies with:

- Immobilisation used – the patient's body may be immobilised by using restraining accessories such as vacuum bags, alpha cradles and stereotactic body frames. The patient may be immobilised in a supine or prone position.

- Some patients may not be immobilised but variations in their position may be minimised by palpating vertebral anatomy and correcting accordingly.

- Compliance of the patient – accuracy may be compromised by the inability of the patient to remain still for the treatment duration, due to neurological deficit or pain. The reproducibility of fit can also be affected if the patient is unable to feel their position inside the immobilisation. These patients should be identified pretreatment and the problem solved or the appropriate margins planned, and an individual tolerance set rather than conforming to the standard for the technique.[166]

Set-up reproducibility

Very few studies have measured set-up reproducibility for spinal treatments. The use of alpha cradles has been shown to give $\Sigma_{set\text{-}up}$ of –0.5 mm and $\sigma_{set\text{-}up}$ of 5.39 mm.[165] Set-up reproducibility with vacuum bags has been measured to be in the region of 4 mm[167] and sterotactic frames a mean value of 3.6 mm.[168]

Internal organ motion

Spinal treatments have the same disadvantages as other extracranial sites and are therefore subject to positional and internal movement variations. The relative position of the individual vertebrae may change due to compression or rotation.

Imaging and radiotherapy fields to image

Imaging frequency and distribution are as for the general guidelines; first 3–5 fractions then weekly.[39]

The entire spinal length that is treated should be imaged, paying particular attention to field junctions. Where stepping or feathering of matched field edges occur, each step should be verified.

The identification of vertebral level is often difficult on small field spinal images. Where it is deemed that level identification is not possible (assess using the reference images), imaging field width should be increased to provide sufficient additional anatomical information. The length of some spinal fields may cause problems with image acquisition on some simulators and electronic portal imagers – the superior and inferior aspects of the field may need to be imaged by separate port films.

Many of the patients treated for spinal tumours will be children and the impact of a small increase in overall integral dose from imaging and the associated risks of secondary malignancies are unknown. Long-term follow-up is needed to answer this question.
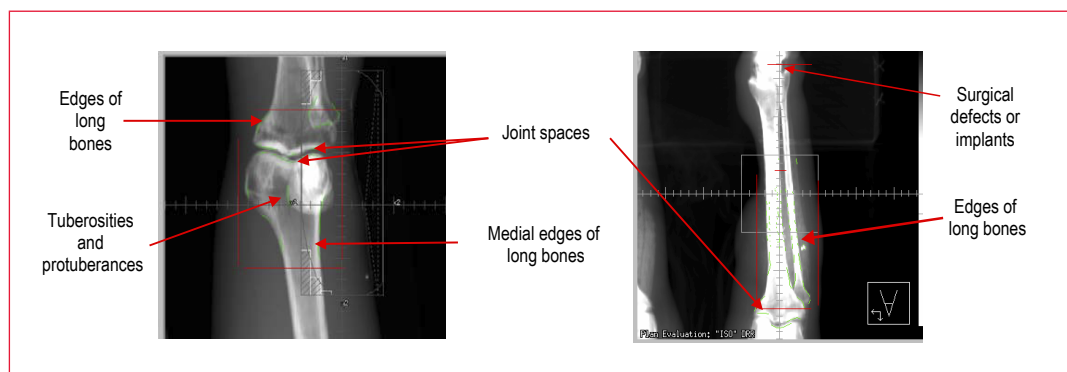
7.7 Limb

7.7.1 Suggested protocol for limb verification

Fraction 1 (images acquired & actioned before treatment delivery)	• Image treatment fields (usually anterior or direct lateral fields) • Take care to avoid exposing dose-critical structures where possible (testes) • For small fields, use open imaging fields or double exposures, where necessary, to ensure sufficient stable anatomy can be seen in the images • Assess for and correct gross errors immediately
Fractions 2 & 3 (not necessary for all patients)	• Image treatment fields • Assess each image against tolerance levels set and correct gross errors for each fraction where necessary
Fraction 4 (not necessary for all patients)	• Calculate the overall systematic error (average of the isocentric set-up error) in each orthogonal direction • If set-up error is greater than the action level, apply the systematic set-up error correction (NAL recommended)
Before Fraction 5 (not necessary for all patients)	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions) • If practical, calculate the new overall systematic set-up error and correct values greater than action levels
Weekly & first day of each phase of treatment plan	• Image treatment fields each week • Assess each image and correct gross errors for each fraction where necessary • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Apply any systematic set-up error correction

- Daily verification may be required for treating tumours planned with very small margins, prosthesis boosts or IMRT
- Immobilisation and positioning is critical
- Daily visual check of radiation light field required
- Particular attention should be paid to field junctions
- Length of some limb fields may cause problems with image acquisition and may need to be acquired in sections
- Concomitant exposures should be especially considered in children and adolescents

Anatomical match structures

It is recommended that at least three structures visible within the field be outlined. The anatomies identified below indicate the most stable features. It is recommended that these structures should be used for comparison, wherever they fall within the field arrangement chosen.

7.7.2   Evidence for limb verification guidelines

Immobilisation and patient positioning

Soft tissue sarcomas will be the principal disease where limbs are treated with radical radiotherapy.

Good immobilisation and positioning is essential to facilitate irradiation of the planned volume while sparing a corridor of normal skin and subcutaneous tissues. The use of immobilisation shells and masks is recommended. A good fit is essential to reduce/prevent rotation within the mask.

Visually checking the position of the radiation light field at each treatment in order to ensure the corridor of normal skin is spared is as important as imaging checks in this site.

Set-up reproducibility

There are currently no published data regarding accuracy and reproducibility for radical limb treatments. The quality of the immobilisation and stability of patient's position will be the most important factor in reproducibility.

The tolerance used should be related to the field margins. Recommended margins are between 3–5 cm proximally and distally and 2 cm laterally.

Internal organ motion

There is no internal organ motion.

Imaging and radiotherapy fields to image

Orthogonal imaging fields to assess isocentre position are not necessary; the field borders are important here. Open field sizes or the use of double exposure to include stable bony anatomy may be necessary when treating small field sizes, so that sufficient anatomy can be seen with which to assess position. Care should be taken, however, to avoid imaging radiosensitive structures such as the testes.

There is a variety of imaging protocols currently in use in the UK; some image for the first 3–5 days to determine systematic set-up errors, while others image on the first day and then weekly. This depends on the immobilisation used, the size of the planning margins and the ease of visualising the treatment field on the patient. Weekly imaging detects trends and systematic changes in set-up.[39]

When deciding on which fields to image, care should be taken to avoid exposing the radiation sensitive electronics of the portal imager. If the field is too long to image, without causing damage, the field may be portal imaged in two separate parts (not recommended if the patient has to be moved between imaging), may be imaged at a reduced imager distance (to reduce field size on imager) or port film can be used. The use of port film or CR cassettes, however, removes the ability for rapid gross error assessment.

7.8 Paediatric

7.8.1 Suggested protocol for paediatric verification

Fraction 1 (images acquired & actioned before treatment delivery)	• Acquire orthogonal image set, minimising dose to critical structures (where possible) • If field edge verification is needed, where possible image all treatment fields • Assess for and correct gross errors immediately
Fractions 2 & 3	• Image orthogonal set • Assess each image and correct gross errors for each fraction where necessary
Action before Fraction 4	• Calculate the overall systematic error (average of the isocentric set-up error) in each orthogonal direction • Apply the systematic set-up error correction
Fractions 4 & 5	• If the set-up has been corrected, confirm by repeat imaging (typically two or more fractions) • If practical, calculate the new overall systematic set-up error and correct
Weekly & first day of each phase of treatment plan	• Image orthogonal set each week • Assess each image and correct gross errors for each fraction where necessary • If set-up error is greater than the tolerance value, check by repeat imaging (typically two or more fractions) • Apply any systematic set-up error correction
• Daily verification may be required for treating tumours planned with very small margins or hypofractionated techniques	
• Patient immobilisation devices to help maintain treatment position is essential	
• Anaesthesia may be necessary for adequate immobilisation	
• Concomitant exposures should be especially considered in children and adolescents	
• Tolerances and action levels to use will vary, particularly with the immobilisation and treatment technique used as well as compliance of the patient and should be chosen accordingly	

Anatomical match structures

As per site-specific protocol guidelines.

7.8.2 Evidence for paediatric verification guidelines

The therapeutic irradiation of children should only be undertaken in recognised centres which comply with the requirements of the NICE guidance on cancer services *Improving Outcomes in Children and Young People with Cancer.*[169] These departments will have a full range of staff trained and experienced in the management of patients in the paediatric and adolescent age group.

The art of target volume definition and dose prescribing in paediatric radiotherapy is to achieve a balance between maximising the curative potential and minimising morbidity. It should be the norm for children to receive treatment in the context of international clinical trials, and the trial protocol should be checked to ensure that any quality assurance recommendations are complied with.

Immobilisation and patient positioning

One of the key parts of the clinical assessment, usually undertaken by the clinical oncologist in conjunction with a hospital play specialist and/or specialist paediatric radiographer, is to decide whether, with appropriate preparation, the child can manage to co-operate with the requirements of radiotherapy, or will require general anaesthesia for planning and treatment. Usually, children over three to four years of age can be successfully prepared for radiotherapy without anaesthesia. This varies not just on the age and mental state of the child, but also on the treatment position or the need for an immobilisation shell. For example, a three-year-old might cope easily with lying supine without an immobilisation device for the treatment of an abdominal tumour, but would require a general anaesthesia for immobilisation in a prone shell or whole CNS treatment. In a given child, the need for general anaesthesia is not always absolute. Often, planning and treatment need to be started with the help of anaesthesia, but play preparation for treatment without it can continue through the initial weeks of a course of radiotherapy, with transition at the time when the child has demonstrated an ability to co-operate.

Children and adolescents require immobilisation devices for radical radiotherapy planning and treatment appropriate to the anatomical part as described in the preceding sections.

Set-up reproducibility

As per site-specific guidelines.

Internal organ motion

As per site-specific guidelines.

Imaging and radiotherapy fields to image

During radical courses of treatment, geometric verification images should be acquired daily for the first three to five fractions, thereafter weekly, assuming that there is no indication for more frequent imaging.[39]

Careful attention to the impact of concomitant exposures as described in Section 3.6 is particularly crucial in paediatric radiotherapy.

7.9 Palliative

7.9.1 Suggested protocol for palliative verification

Fraction 1 (action all gross errors immediately)	• Image treatment fields • If parallel opposed field arrangement is used and no field shaping is used (manual shielding or MLCs), image one side only • Assess for and correct gross errors immediately
Daily (where appropriate)*	• Image treatment fields • If parallel opposed field arrangement is used and no field shaping is used (manual shielding or MLCs), image one side only • Assess for and correct gross errors immediately
• Verification should be no less rigorous for palliative treatments than for radical treatments	
• Single fractions should be verified at the beginning of treatment delivery to identify gross error	
• The images acquired must be of sufficient size to ensure bony anatomy is visible	

* Where there is a risk of gross error because of poor patient compliance

Anatomical match structures

As per site-specific protocol guidelines.

7.9.2 Evidence for palliative verification guidelines

Verification should be no less rigorous for palliative treatments than for radical treatments, indeed where only a small number of fractions are to be given it is critical to identify gross error before the first treatment exposure. Best practice would demand that reference images for all palliative treatments should be obtained as described in *Towards Safer Radiotherapy*.[8]

Immobilisation and patient positioning

It is important that the immobilisation used is comfortable, so that the patient is in a position that they are able to maintain for the length of the treatment fraction. This is of particular importance for longer single-fraction treatments. Often, patients being treated with palliative intent will not be able to be positioned with the same immobilisation as used for patients treated with radical intent. Soft immobilisations are available using foam-based accessories and rapid manufacture thermoplastic materials.

Set-up reproducibility

The set-up reproducibility is likely to be affected by more random variables. The immobilisation is likely to be less rigid and the patient's ability to maintain the position during the fraction, less. The planned margins are usually therefore greater and the imaging tolerances used may reflect this. The set-up reproducibility is likely to vary for each individual patient.

Internal organ motion

The impact of internal organ motion should be taken into account when planning treatment margins, as intrafractional verification is not practical here, as treatment times may be extended beyond the patient's comfort limit.

Imaging and radiotherapy fields to image

Images should be taken of each field where field shaping is used (manual shielding or MLCs), to assess the shielding position. Where no shielding is used and a parallel opposed pair field arrangement is used, only one image is required.

For single fraction treatments such as bone metastases and non-small cell lung cancer, the only opportunity to obtain a verification image is at the beginning of the treatment. Gross error should ideally be identified at this stage and it is possible to take a megavoltage image and analyse this before delivering the full dose. The patient should be carefully monitored throughout treatment delivery to ensure the patient remains in this validated position. If the patient moves or the treatment is interrupted, another image may be taken to ensure accurate repositioning of the patient.

For short treatment courses delivering three to ten fractions, the NAL protocol is not feasible and correction of each fraction which is imaged is recommended, where possible and feasible.

8 Glossary

6D couch movement (for example, hexapod): The patient couch (or support system) which is capable of movement which has six degrees of freedom. Three traditional linear movements (lateral, longitudinal and height movement) and three rotational movements around each of the axes of linear movement.

Action level: An action level for a measurement or parameter may be defined as the point at which further action is necessary.

Central beam axis: The imaginary axis or line which passes through both the X-ray source and the isocentre of the machine.

Clinical target volume (CTV): A clinically defined target volume that contains the demonstrable tumour (gross tumour volume or GTV) unless it has been surgically excised and microscopic invisible tumour. This volume contains cancer cells and must be treated with the prescribed radiation dose adequately to achieve a cure.

Computed radiography: A method of radiographic imaging which uses reusable plates as the detection media. The plates are used in place of film and the readout process produces a direct digital image.

Concomitant exposure: Any exposure within the course of the radiotherapy process which is not a treatment exposure.

Conformal radiotherapy (CFRT): A treatment technique which aims to shape the 3D high-dose volume to the planning target volume while minimising dose to healthy tissue.

Corrective strategy: The process by which information gathered during the verification procedure is used to minimise set-up errors throughout the course of treatment delivery.

Critical structures: Normal tissues or organs near the tumour whose tolerance dose for serious late radiation damage limits the amount of radiation that can be administered.

CT simulator: A specially designed CT scanner with a flat-top couch and a laser field positioning system. It can provide 3D CT images for tumour volume localisation and can also reconstruct an equivalent simulator radiograph, thus providing virtual simulation.

Digitally composited radiograph (DCR): Similar (geometrically) in construction to the digitally reconstructed radiograph (DRR), but uses selective suppression or enhancement of various ranges of CT numbers that relate to certain tissue types.

Digitally reconstructed radiograph (DRR): a planar radiograph made by computer-projected rays through 3D CT density information.

Displacement (or deviation): The difference in a measured parameter from its reference value. It may be positive or negative.

Dosimetric verification: The process of assessing the correctness of the delivered dose to the patient with respect to the desired reference, defined by the treatment plan. The procedure is termed *in vivo* dosimetry when it is performed on the patient during a treatment fraction.

Dynamic multileaf collimator (DMLC) technique: One of the IMRT delivery methods in which the MLC leaves move continuously during beam delivery with a variable speed and window size.

Electronic portal imaging device (EPID): An electronic system for acquiring verification images of the geometry of treatment during radiotherapy delivery.

Exposure: Each time the radiation beam is turned on to treat the patient from a new direction. A fraction may be made up of one or more exposures.

Fractionation: The practice of dividing a determined dose of radiation into fractions, usually administered once or twice daily.

Gating: Gating or respiratory gating is a treatment delivery technique which allows the treatment of tumours at certain defined points in the respiratory cycle.

Geometric imaging error: A systematic error introduced during the imaging process. Either due to imaging hardware, for example, misaligned CT lasers or due to inherent geometrical inaccuracy of the imaging modality, for example, MRI. Contributes to the phantom transfer error.

Geometric (treatment) verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan.

Gross errors: Geometric displacements in patient set-up (localisation) with respect to the desired reference defined by the treatment plan, which are deemed to be of such a magnitude that the set-up MUST be changed, either during the current fraction or in the following fraction. Any particular treatment technique will have a normal distribution of random set-up errors for the patient population. A set-up error may be considered to be gross if its magnitude is greater than 1 cm or 3 x SD of the population data; whichever is the smaller.

IGRT (image-guided radiotherapy): Uses additional imaging equipment within the treatment room or mounted on the linac's gantry, to acquire images prior or during treatment to evaluate and correct set-up errors before treatment delivery.

Image acquisition: The process of acquiring image data. In the context of geometric verification, it may be a 2D (planar) or a 3D (volume) set of data, and may be obtained with either ionising or non-ionising radiation.

Image matching: Methods of aligning two 2D image sets; for example, DRR, PI, PF etc. Image sets may be overlaid or structures may be mapped between the sets.

Image registration: Methods of aligning two 3D image sets; for example, CT, MRI, PET etc. Image sets may be overlaid or structures may be mapped between the sets.

Imaging fractions (or sessions): The treatment fraction during which imaging is scheduled to occur for the purpose of geometric (treatment) verification.

Imaging protocols: A set of procedures, instructions and processes put in place to acquire, analyse and store images for the purpose of (in this context) geometric treatment verification.

Immobilisation: A set of instructions, processes and/or equipment used in conjunction with the patient to ensure accurate and reproducible geometric set-up both during a single fraction, and from one fraction to the next. The same immobilisation should be used at all points in the radiotherapy process.

In-plane rotation: Rotation occurring within the viewing plane. For a field showing X and Y axes, rotation about the Z axes can be seen. For a field showing Y and Z axes, rotation around the X axis can be seen.

Interfractional verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan, from one fraction to the next.

Intrafractional motion: Patient movement which may be physical or internal organ motion which may be present during a single treatment fraction. The movement may occur during delivery of a single exposure or at any time throughout the period from the end of patient set-up through to the end of delivery of the final exposure for that fraction.

Intrafractional verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan, during a single treatment fraction. It may be assessed during delivery of a single field, and/or throughout the time period from the end of patient set-up through to the end of delivery of the final exposure for that fraction.

Inverse planning: A novel treatment planning process which begins with the specification of optimum dose distribution in the patient and allows the treatment planning computer to generate a plan of beam directions and intensities that best satisfies the required dose distribution.

Isocentre: A single point within the treatment room (in space) towards which the radiation beam always points. The central beam axis passes through this point and, on a Linac, the three principal rotational movements of gantry, collimator and floor are all around axes which intersect at this point. For a tomotherapy machine, it is a point of intersection between the centre of the scan plane and the axis of rotation of the scan circle.

Linac geometry error: A systematic error due to inaccuracy in the position of the radiation treatment beam from a chain of uncertainty in the linear accelerator. Examples are errors in the field-edge position, the FSD indication or the isocentre location. It contributes to the phantom transfer error.

Linear accelerator (Linac): A treatment machine generating megavoltage X-rays or electrons.

Multileaf collimator (MLC): A collimation system on a linear accelerator which uses a number of 'leaves' to create an irregular-shaped radiation beam. It is used to shape the beam to the target volume geometrically (CFRT) and is also used to modulate intensity of the beam (IMRT).

Off-line treatment verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan, after the delivery of a treatment field and/or whole fraction. Desired geometric changes in patient set-up as a consequence of this process are conducted retrospectively in the following fraction(s).

Online treatment verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan, immediately prior to the delivery of a treatment field and/or whole fraction. Desired geometric changes in patient set-up as a consequence of this process are conducted prospectively during the fraction.

Orthogonal image pair: A pair of 2D images (planar) acquired at 90 degrees gantry rotation to one another.

Out-of-plane rotations: All possible rotations of the patient around axes which are not orthogonal to the imaging plane.

Patient set-up error: Any geometric displacement in patient set-up (localisation) with respect to the desired reference defined by the treatment plan, which is due to the patient themselves (for example, organ motion, respiratory motion, involuntary movement etc).

Phantom transfer error: This is the geometric displacement accumulated throughout the radiotherapy process (from pretreatment imaging through to treatment delivery). Comprises the geometric imaging error, the treatment planning system error and the linac geometry error.

Planning organs at risk volume (PRV): As is the case with the PTV, the organs at risk during treatment may also move and an integrated margin must be added to the organs at risk volume to compensate for these variations and uncertainties using the same principles as for the PTV.

Planning target volume (PTV): The geometrical 3D volume within the patient used for treatment planning and specification of dose. It includes a margin around the clinical target volume (CTV) to allow for variations (both intra- and interfraction) due to patient position and set-up, physiological changes such as respiration, and variations in machine and human factors.

Portal imaging (PI): Imaging of the part of the body being irradiated to check the accuracy of geometry of treatment delivery and sometimes also to check dosimetry.

Pretreatment verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan before the commencement of a course of radiotherapy.

Quality assurance (QA): All procedures that ensure consistency of the medical prescription and safe delivery of that prescription as regards to dose to the target volume, together with minimal dose to normal tissue, minimal exposure to personnel and adequate patient monitoring aimed at determining the end result of treatment (WHO 1988).

Random errors: Geometric displacements in patient set-up (localisation) with respect to the desired reference defined by the treatment plan, which vary in both magnitude and direction for each treatment fraction. These are primarily due to variations of daily positioning and/or organ motion.

Real-time treatment verification: The process of assessing the correctness of patient set-up (localisation) with respect to the desired reference defined by the treatment plan in real-time, during the delivery of a treatment field and/or whole fraction.

Record and verify system: Hardware and software designed to record and verify treatment parameters during a patient's treatment simulation and delivery. The system may contain software that can provide an electronic patient record and general database functions as well.

Reference data (images): A 2D planar image or 3D volume image dataset which represents the desired reference positioning of the patients anatomy (the treatment plan) with respect to a datum. The datum may be an indication of the beam central axis or field edges (2D) or the isocentre (3D) of the treatment machine.

Registration (and registration algorithms): A means of comparing geometrically the anatomical position within one image with the same anatomical features within another, with respect to a datum. For the case of treatment verification, one image will be termed a reference derived from the correct desired isocentre position in the treatment plan and one will be an image acquired during the course of treatment. The images may be 2D planar images or 3D volume datasets. The datum may be an indication of the beam central axis or field edges (2D) or the isocentre (3D) of the treatment machine. The registration algorithm is the mathematical method used to perform the comparison.

Residual error: Displacement from planned position remaining after initial correction has been made.

Set-up errors (field placement errors): Any geometric displacement in patient set-up (localisation) with respect to the desired reference defined by the treatment plan, which is present at the time of patient set-up during treatment delivery.

Simulation: The use of X-rays to plan treatment through locating and marking the area to be treated.

Simulator: A diagnostic energy X-ray machine (kilovoltage X-ray tube) with geometric movements similar to those of the linear accelerator for viewing a simulated treatment. It is used for localisation of treatment areas and for verification of treatment plans prior to starting treatment.

Systematic errors: Geometric displacements in patient set-up (localisation) with respect to the desired reference defined by the treatment plan, which are similar in both magnitude and direction for each treatment fraction. These are primarily due to systematic differences in equipment or protocol throughout the radiotherapy process (that is, from pretreatment imaging to treatment planning to pretreatment verification etc).

Target delineation error: The systematic error introduced and 'frozen' into the treatment preparation process at the time of target delineation. It represents the difference between the defined and 'ideal' CTV. Because this 'ideal' or standard CTV is not known, assessment of this error must be undertaken on a population basis using different methods. One approach to define a standard CTV may be the consensus CTV outline from a group of doctors working to the same protocol (inter-clinician). Another may be the mean CTV outline of a given target drawn repeatedly over time by the same doctor (intra-clinician). Once the standard or 'ideal' CTV is determined and the discrepancy evaluated, the target delineation error may be defined as the standard deviation for this discrepancy. It is impractical to calculate this error on an individual patient basis and as it cannot be quantified and corrected using imaging the consequences of the target delineation error must be incorporated into the CTV-PTV margin.[5]

Target volume: The area meant to receive the radiation; usually areas containing verified or suspected tumours.

Tolerances: The permitted observed variation in a parameter or measurement from its desired value.

Tomotherapy: A modality of radiotherapy which combines a linear accelerator, binary MLC and megavoltage CT scanner on a rotating gantry. IMRT is delivered in a continuous, helical (360 degree) fashion as the patient is moved through the rotating gantry on the couch.

Treatment planning system (TPS): The hardware and software used for simulating the irradiation geometry to be used for patient treatment and for calculating the distribution of dose within the patient. Software tools use 3D patient data from CT and other imaging modalities to visualise volumes of interest. The main function is to design the optimum dose distribution with the patient in three dimensions. It can network with the linear accelerator and CT scanner and with facilities for designing shielding blocks and compensators.

Treatment planning system error: The systematic error resulting from either the treatment planning software or the interaction of that software with the rest of the treatment planning process. Contributes to the phantom transfer error.

Verification (geometric) protocols: A set of procedures, instructions and processes put in place to ensure the geometric correctness of the positioning of all patients set-up (localisation) with respect to the desired reference defined by the treatment plan.

X-ray volume imaging: The process of acquiring a 3D dataset (volume) of the patient's anatomy using X-rays.

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