

IAEA-TECDOC-1588

***Transition from 2-D Radiotherapy to
3-D Conformal and Intensity
Modulated Radiotherapy***



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TRANSITION FROM 2-D RADIOTHERAPY TO 3-D CONFORMAL AND
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FOREWORD

Cancer is one of the leading causes of death globally and radiotherapy is currently an essential component in the management of cancer patients, either alone or in combination with surgery or chemotherapy, both for cure or palliation. It is now recognized that safe and effective radiotherapy service needs not only substantial capital investment in radiotherapy equipment and specially designed facilities but also continuous investment in maintenance and upgrading of the equipment to comply with the technical progress, but also in training the staff. The recent IAEA-TECDOC publication "Setting up a Radiotherapy Programme: Clinical, Medical Physics, Radiation Protection and Safety Aspects" provides general guidelines for designing and implementing radiotherapy services in Member States.

Advances in computer technology have enabled the possibility of transitioning from basic 2-dimensional treatment planning and delivery (2-D radiotherapy) to a more sophisticated approach with 3-dimensional conformal radiotherapy (3-D CRT). Whereas 2-D radiotherapy can be applied with simple equipment, infrastructure and training, transfer to 3-D conformal treatments requires more resources in technology, equipment, staff and training. A novel radiation treatment approach using Intensity Modulated Radiation Therapy (IMRT) that optimizes the delivery of radiation to irregularly shaped tumour volumes demands even more sophisticated equipment and seamless teamwork, and consequentially more resources, advanced training and more time for treatment planning and verification of dose delivery than 3-D CRT.

Whereas 3-D CRT can be considered as a standard, IMRT is still evolving. Due to the increased interest of Member States to the modern application of radiotherapy the IAEA has received a number of requests for guidance coming from radiotherapy departments that wish to upgrade their facilities to 3-D CRT and IMRT through Technical Cooperation programme. These requests are expected to increase in number in the near future. Since these treatment techniques are perceived as the cutting-edge of development in the field, there is a concern that centres and countries need orientation as to the preparatory conditions and resources involved. In addition the current status of the evidence supporting the use of IMRT in terms of patient outcomes has to be kept in mind when planning to invest in these technologies.

To respond to the needs of Member States to establish the guidelines for the transition from 2-D radiotherapy through 3-D CRT to IMRT several consultants and advisory group meetings were convened to discuss the necessary steps and the milestones for the transfer from 2-D to 3-D conformal radiotherapy and to IMRT. As a result, the present report serves as complementary recommendations to an IAEA recent publication on setting-up a basic radiotherapy programme. Both reports provide a comprehensive overview of the required radiotherapy infrastructure and processes for a broad spectrum of radiotherapy services.

The current publication is addressed to those professionals and administrators involved in the development, implementation and management of radiation oncology programmes who seek to improve the conventional approach with the aim of achieving higher precision by transition from simpler radiation treatment approaches to advanced radiotherapy. This report provides the guidelines and highlights the milestones to be achieved by radiotherapy centres in the transition from 2-D to 3-D treatment planning and delivery and further, in transitioning to IMRT. These guidelines and milestones facilitate the process and represent continuation of the work at the IAEA for providing access to safer and better quality treatment for the steadily increasing number of cancer patients in Member States.

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GENERAL INTRODUCTION

This publication is divided into two Chapters. In Chapter 1 the requirements for 3-D conformal radiotherapy (3-D CRT) are given, together with details of the clinical processes involved in its introduction. In Chapter 2 issues relating to Intensity Modulated Radiotherapy (IMRT) are discussed. This latter Chapter provides only general guidance as the details of the implementation of IMRT are beyond the scope of the current publication. Appendix A provides a self-evaluation questionnaire to be used to determine the state of readiness of a centre to proceed to 3-D CRT, together with some additional questions relating to the subsequent step to IMRT. Appendix B gives an example of the detailed steps in the chain for practical delivery of 3D-CRT. This example is presented in the context of the treatment of head and neck cancer. Appendix C provides indicative costs of the equipment required. A list of the abbreviations used in the text together with explanation of the meaning of these and other terms associated with radiotherapy is given at the end of the publication. Note that reference lists are provided at the end of each Chapter so that the two Chapters can be read independently of each other.

It must be emphasised that the development of radiotherapy facilities should be regarded as a stepwise process. This report assumes that the basic radiotherapy facilities as described in the IAEA publication “Design and implementation of a radiotherapy programme: Clinical, medical physics, radiation protection and safety aspects” [1.1] and its latest reissue [1.2] are already in place. Once a department has gained experience in 3-D CRT, consideration may be given to IMRT, but there is no implication that this is a necessary onward step.

1. CONFORMAL RADIOTHERAPY

1.1. INTRODUCTION TO CHAPTER 1

This part of the publication describes the patient benefits of conformal radiotherapy and the technological, logistical and personnel requirements to enable the safe and accurate delivery of conformal radiotherapy, including guidelines on the establishment of treatment facilities. The report is written as an extension to the IAEA publication “Setting up a radiotherapy programme: Clinical, medical physics, radiation protection and safety aspects” [1.2]. This IAEA publication should be consulted in conjunction with the current report, particularly its Appendix F, which describes the requirements for establishing a radiotherapy programme.

3-D conformal radiotherapy (3-D CRT) is the term used to describe the design and delivery of radiotherapy treatment plans based on 3-D image data with treatment fields individually shaped to treat only the target tissue. The European Dynarad consortium has proposed that the complexity of radiotherapy planning and treatment methodologies can be captured in four levels [1.3]. Level 0 represents basic radiotherapy where no attempt is made to shape the treatment fields and as such cannot be described as conformal. This level will not be considered further in the current publication. Levels 1 to 3 are illustrated in [Table 1](#), in which the original table of Kolitsi et al. [1.3] has been considerably adapted for the purposes of this publication. Individually shaped fields can be designed from planar radiographs or with limited computer tomography (CT) data. This level of conformal radiotherapy (referred to as Level 1 in [Table 1](#)) can be carried out in any radiotherapy department with the minimal facilities described in [1.2] and is a useful way to begin the move towards full 3-D CRT. Level 2 conformal radiotherapy requires a full 3-D data set, usually of CT images, on which the tumour volume is defined following the concepts of ICRU 50 and 62 [1.4], [1.5], [1.6]. This level may include the use of non-coplanar beams. Level 3 represents the most complex radiotherapy treatments, including IMRT, many of which are still at the research stage in University Hospitals. [Table 1](#) is intended to give a flavour of the progression of techniques that may be available at each level and should not be regarded as a prescriptive indication that every treatment should use all the techniques listed.

TABLE 1. CLASSIFICATION OF CONFORMAL THERAPY ACCORDING TO THE METHODOLOGY AND TOOLS ASSOCIATED WITH EACH STEP OF THE PROCEDURE

	Level 1 Basic CRT	Level 2 3-D CRT	Level 3 Advanced 3-D CRT
1. Patient data acquisition			
Immobilization	Desirable	Customized to the patient	Customized to the patient
Imaging system	Localization films, few CT slices optional	Thin adjacent CT slices, MR optional	Co-registered CT with MR or PET
Anatomical data			
Reference marks for setup	Height above table and skin marks	External markers or frame	Implanted markers or frame
Critical organs	Contour individual slices	3-D segmentation	3-D segmentation
Inhomogeneities	Optional	Contouring every slice or voxel based correction	Voxel based correction
Gross tumour volume (GTV)	May not be formally defined	Contouring every slice	3-D segmentation
Clinical target volume (CTV)	May not be formally defined	Grown from GTV using auto-margin growing	Margin growing from GTV + functional imaging
Internal target volume (ITV)	May not be formally defined	Based on standard decision rules	4-D CT data to define ITV customized to patient
2. Beam definition			
Accounting for beam setting uncertainty	Margins are not customized	3-D margins based on audit of setup errors	Image guidance
Type of radiation and beam modifiers	Photons or electrons \pm wedge filters	Photons, wedges, field in field, compensators	Photons + IMRT
Beam incidence	Coplanar beams	Several (including non-coplanar) beams	Multiple non-coplanar beams or arcs
Isocentre	SSD or SAD technique	SAD technique (auto centred on target)	SAD technique (auto centred on target)
Beam limiting device	Non-customized shielding blocks	Customized blocks or MLC	MLC or mini MLC
PTV – CTV margin	Shape drawn on simulation films	Protocol margins based on audit	Individual margin based on e.g. 4-D CT
3. Dose calculation and optimization			
Calculation model	1-D or 2-D (slice) \pm inhomogeneity	2-D or 3-D with inhomogeneity	3-D or 4-D with inhomogeneity
Evaluation of treatment plans	Isodoses on central slice or several slices	Isodoses viewed in 3-D on computer + DVH	3-D isodose surface + DVH, TCP, NTCP
Treatment plan optimization	Successive trials + visual appreciation	Successive trials + simple optimisation	Inverse planning
4. Treatment verification and execution			
Verification simulation	Normal practice	Useful	Replaced by IGRT on treatment machine
Immobilization (see above)	Desirable	Customized to the patient	Individual cast or stereotactic frame
Aids for positioning	Lasers + light field	Isocentre lasers	Lasers or frameless stereotaxy
Patient positioning	Height above couch + skin marks	Move from anatomical reference or stereotaxy	Daily image guidance
Verification reference image	Simulation film	DRR	CT data compared to cone beam CT
Record and verify system	Desirable	Essential but network is optional	Essential including network transfer
In vivo measurements	Desirable	TLD or diodes recommended	TLD or diodes or EPID transit dosimetry

This Table is based on the paper by Kolitsi et al. [1.3].

Level 1 represents the basic entry level for conformal radiotherapy that can be performed with minimal facilities. Level 2 is the 3-DCRT that is the subject of this report. Level 3 represents the highest level of accuracy using IMRT or stereotactic radiosurgery, which is the subject of Chapter 2 of this publication. Note that simple IMRT can also be carried out on a cobalt-60 unit, or a linac without an MLC, using compensators.

Conformal radiotherapy permits the delivery of a radical dose of radiotherapy while limiting the dose to normal tissue structures, thus minimising the adverse effects of treatment. Its principle benefit therefore is to patients who are to be given potentially curative radiotherapy. Where radiotherapy is being given with palliative intent the prescribed total doses are usually lower and the adverse effects of palliative radiotherapy are therefore likely to be less. For this reason conformal radiotherapy is not often used when delivering palliative treatment, although it is always desirable to minimise the volume of non target tissue that is irradiated.

Conformal radiotherapy can be regarded as a step towards intensity modulated radiotherapy (IMRT). However, the delivery of IMRT, where fields are made up of multiple beamlets, is considerably more costly than conformal radiotherapy and requires an even higher level of expertise. There is considerable evidence for the benefits of 3-D CRT (see Section 1.2), but the benefits of IMRT are less well established (see Chapter 2 Section 2.2). The incremental benefits in the transition from conventional radiotherapy to 3-D CRT are therefore substantially greater than those achieved in the transition from 3-D CRT to IMRT. It is therefore recommended that the implementation of 3-D CRT should be given priority over the implementation of IMRT. The transition from 3-D CRT to IMRT is considered in Chapter II.

The design and delivery of a 3-D CRT treatment requires a chain of procedures all of which must be in place if the treatment is to be safe and accurate. A chain is as strong as its weakest link. If any of the links of a chain are weaker than the others the chain will break at that point, which illustrates the need for all the components of the conformal therapy programme to be in place. It is therefore essential that all the links have been established before embarking on patient treatment. The links in this chain are:

- the precise immobilization of patients throughout the whole process;
- the use of high quality 3-D medical imaging to determine the gross tumour volume (GTV), clinical target volume (CTV), planning target volume (PTV) and planning organ at risk volume (PRV);
- the use of 3-D planning systems to choose beam orientations and to display beam's-eye-views (BEVs);
- the planning of beams;
- the computation of 3-D dose to the PTV and PRV;
- the evaluation of the dose plan and the biological effect using dose volume histograms (DVH), tumour control probability (TCP), normal tissue complication probability (NTCP);
- the transfer of these planning data to the delivery machine;
- the verification of patient position, beam placement and dosimetry;
- the measurement of outcome.
- To this end Section 1.3. provides a list of milestones that should be achieved in the project plan in order to set up a 3-D CRT programme.

1.2. CLINICAL EVIDENCE FOR 3-D CONFORMAL RADIOTHERAPY

The ideas of three-dimensionality, beam shaping, and irradiation of tumours through multiple fields from different beam angles to reduce the dose to normal tissues have always been present in radiotherapy practice. When the appropriate technology to deliver 3-D CRT, such as CT simulators, radiation treatment planning systems (RTPS) capable of performing three dimensional dose calculations, producing digitally reconstructed radiographs (DRRs) and DVHs, and beam shaping devices such as multi-leaf collimators (MLCs) became available, this way of planning and delivering radiotherapy soon gained popularity. This has now become standard practice in the developed world when treating many types of tumours with curative intent.

The aims of 3-D CRT are to achieve conformity of the high dose region to the target volume and consequently to reduce the dose to the surrounding normal tissues. This should reduce both acute and late morbidity [1.7], [1.8], [1.9], [1.10], [1.11]. If the adverse effects of treatment can be reduced in this way, the dose to the target volume can be increased with the expectation of improved cure of the tumour.

The largest body of available evidence in support of 3-D CRT is in the treatment of prostate and lung cancers. By conforming the dose to the target volume, a reduction in the treated volume of about 30% to 50% can be achieved using 3-D CRT [1.12], [1.13], and this reduction includes only normal tissues. Local control can therefore be improved by increasing the dose delivered to the tumour, without unacceptable toxicity. Evidence exists of a dose-response relationship in many tumours [1.7]. This possibility of escalating doses, thus increasing local control and potentially improving survival, can help to change the treatment approach in many tumours from palliative to potentially curative.

3-D CRT with dose escalation has been used to study the possible improvement in tumour control in a number of Phase II [1.14], [1.15] and randomised studies [1.16] in prostate cancer. Hanks et al. [1.17] demonstrated that doses over 74 Gy improve local control in prostate cancer and Zietman et al. [1.18] reached the same conclusion in a randomized trial. In a randomised study of 3-D CRT against conventional radiotherapy, Dearnaley et al. [1.19] demonstrated a significantly lower risk of developing late radiation-induced proctitis in the patients treated in the 3-D CRT arm. Their subsequent RT01 randomised trial showed improved biochemical prostate specific antigen (PSA) control with dose escalation of 74 Gy versus 64 Gy, using 3-D CRT [1.20]. A systematic review of 3-D CRT for prostate cancer was carried out by American Society of Therapeutic Radiology and Oncology (ASTRO) and the paper by Morris et al. [1.21] summarised the results. Seventy two published articles were included. It was found that gastrointestinal and genitourinary toxicities were lower in patients treated with 3-D CRT than with earlier techniques. Nilsson et al. [1.22] published another systematic review of radiotherapy in prostate cancer, including randomized trials, prospective trials, and 210 retrospective studies, with a total of 152 614 patients. The conclusions were that dose escalation could be safely performed with 3-D CRT, and that its use resulted in reduced late rectal toxicity and acute anal toxicity compared with radiotherapy administered with non-conformal treatment volumes. A third systematic review on prostate cancer, published by Brundage et al. [1.23] showed that the use of 3-D CRT reduces the rates of both early and late bowel and bladder toxicity, and that escalation of the dose results in increased biochemical response and control rates.

A number of Phase I studies have demonstrated the tolerability and feasibility of dose escalation with 3-D CRT in lung cancer [1.24], [1.25], [1.26]. Bradley [1.27] reviewed the dose escalation RTOG lung trials and reported that doses can be escalated using 3-D CRT from 60 Gy (RTOG 9410) to 83.8 Gy (RTOG 9311). When 3-D CRT is combined with chemotherapy, the maximum tolerable dose is in the range of 70 Gy to 74 Gy.

The initial cost of implementing 3-D CRT is greater when compared with the implementation of a conventional 2-D programme. On the other hand, the replacement of custom blocks by an MLC can save between 5% and 20% of treatment time [1.28], [1.29], [1.30], [1.31]. Some cost analyses have demonstrated that the initial bigger implementation cost is counterbalanced by the improvement in treatment outcome, resulting in lower overall costs of care [1.32], [1.33].

1.3. MILESTONES FOR 3-D CONFORMAL RADIOTHERAPY

A conformal radiotherapy programme should be built on a firm foundation of expertise in conventional radiotherapy, and should not be embarked on until certain basic milestones have been met. The questionnaire given in Appendix A provides a checklist of steps in the process. The following is a summary of the milestones for the project of setting up a 3-D CRT programme. Numbers in brackets refer to the questions in the Appendix A.

Milestones that must be achieved before resources are committed to the establishment of 3-D CRT:

- Facilities are in place for the provision of conventional radiotherapy;
- Adequate diagnostic imaging facilities are in place for diagnosis and staging;
- Adequate imaging facilities are in place for planning CT scans;
- There is an intention to deliver curative radiotherapy;
- Demonstration by audit that satisfactory setup accuracy can be achieved.

Milestones in the process once the project has started:

- Appointment of sufficient staff that the existing programme of conventional therapy will not be compromised (1, 6, 14);
- Academic training of staff (radiation oncologist and medical physicist) (2, 4, 7, 11);
- Specification and purchase of necessary additional equipment (16 – 22);
- Practical training of radiation oncologist and medical physicist (3, 5, 8 – 10, 13);
- Commissioning of RTPS etc for 3-D CRT (23 - 36);
- Practical training of other staff (treatment planners and radiation therapy technologists (RTTs)) (12, 15);
- Extension of quality assurance (QA) programme to cover 3-D CRT;
- Establishment of clinical treatment protocols (37 – 49).

1.4. APPROACHES TO CONFORMAL RADIOTHERAPY

Starting a conformal radiotherapy program requires considerable planning. There are significant differences between conventional 2-D radiation treatment planning and delivery and 3-D conformal radiation therapy. To establish 3-D CRT in an institution the following steps should be taken:

- define the scope of the programme,
- develop staffing needs for the programme,
- identify necessary space and equipment,
- develop a programme budget,
- prepare space and purchase equipment,
- hire new staff,
- train all personnel to be involved with the programme,
- acceptance test new equipment,
- commission new equipment,
- develop necessary policies and procedures,
- develop and implement a comprehensive QA programme.

It is important to allow sufficient time for physics staff training prior to the arrival of the equipment so that trained staff are in place to carry out acceptance testing and commissioning. A complete understanding of all these steps is necessary before one can successfully begin a new programme in 3-D CRT. The resources required to establish such a programme are outlined in this section, while detailed consideration of each step in the process of 3-D CRT is provided in Section 1.5. Appendix C provides indicative costs of the equipment required.

1.4.1. Imaging equipment

All radiation therapy centres require diagnostic imaging equipment for optimum imaging of each tumour site. Ideally, each cancer centre will have a CT simulator housed in the radiation therapy department. If this is not possible, radiotherapy departments must have access to a CT scanner for planning conformal radiotherapy. Other imaging modalities that are useful (but not essential) in the delineation of target volume are magnetic resonance imaging (MRI), ultrasound (US), and various functional imaging modalities such as positron emission tomography (PET), single photon emission

computer tomography (SPECT), functional MRI, MR spectroscopic imaging, and molecular imaging. The rationale for use of 3-D image information is to improve the accuracy with which both the target to be irradiated, and the organs at risk to be spared, may be defined. The incorporation of information from multiple imaging modalities has proven useful in this regard, but again is not an essential prerequisite. For this purpose it is useful to be able to co-register the data from other imaging modalities with the planning CT data (see Section 1.5.3.2). In the case of PET images this can be difficult because of the need to identify common structures and the relatively poor resolution of PET images. For this reason PET scanners are often combined with CT scanners (PET/CT) so that the frames of reference of the PET and CT scans are identical and the images are automatically in registration with each other.

1.4.2. Immobilization

Because of the nature of conformal radiation therapy treatment, reproducible immobilization techniques are essential to safely use this treatment technique. Examples include thermoplastic masks with bite block fixation, alpha cradle etc. However, it is not necessary that such positioning systems are used for every treatment. Techniques to reduce or follow internal organ motion, such as by using ultrasound localization of the prostate or respiratory gating, may be desirable in some applications. All these procedures will impose their own costs with respect to procedure design, training, and validation. If not already known, it will be necessary to study the reproducibility that can be achieved with the immobilization system in order to establish realistic margins for treatment planning.

1.4.3. 3-D radiation treatment planning systems

All centres should have a 3-D RTPS that must have a number of particular features for satisfactory planning of conformal radiotherapy. These will include features pertaining to data acquisition, dose calculation and information display. Guidance on the particular aspects of treatment planning involved in conformal radiotherapy will be given in Section 1.5. More details are given in IAEA TRS-430 [1.34].

1.4.4. Treatment machine

A linear accelerator fitted with a MLC is ideal for the delivery of planned conformal radiation therapy. Ideally, the accelerator will also be fitted with an electronic portal imaging device (EPID) that can be used for the verification of patient setup and geometric verification of beam portals. If an accelerator is not fitted with an EPID, conventional port films can be used for the verification of patient setup and beam portals. Additionally, if MLCs are not available, conformal radiation therapy can be delivered by making use of low-melting-point-alloy blocks. Successful 3-D CRT can also be achieved with a cobalt-60 unit using low-melting-point-alloy blocks (and it is also possible to do IMRT using solid compensators).

1.4.5. Record and verification system and networking

When a MLC is used, a record and verification (R&V) system is needed to ensure, as a minimum, that the planned conformal radiation therapy is delivered as per prescription. Care must be taken to ensure that errors do not occur during transfer of data between treatment planning systems, simulator and treatment machine. An electronic network system for data transfer from imaging facilities to the RTPS and then to the delivery systems is desirable and this should comply with DICOM (**D**igital **I**maging and **C**ommunications in **M**edicine) DICOM-RT protocols. If networking capabilities are not available, then an alternative means of data transfer, such as the use of CD-ROM, should be developed to ensure accurate transfer of digital data from scanning facilities to RTPS and from the RTPS to the delivery systems.

1.4.6. Staffing and training

Dose planning in conformal radiation therapy is accomplished in a very intuitive manner by optimizing the weights of strategically placed radiation portals that conform to the target volume. However, for many disease sites planning solutions can be developed that are easily adapted from one patient to another. Treatment of patients using 3-D CRT is a significant departure from treating patients with conventional 2-D radiotherapy. Therefore, there is a significant potential of treating a patient with a sub-optimal treatment plan if members of the treatment team lack the necessary training in the 3-D CRT process. Thus, it is essential that the treatment team, consisting of radiation oncologists, medical physicists, dosimetrists and radiation therapy technologists, are well-trained in image guided treatment planning and delivery and that they have a good understanding of the uncertainties involved in these techniques.

1.5. CLINICAL IMPLEMENTATION OF 3-D CONFORMAL RADIOTHERAPY

This section describes the clinical implementation of a 3-D CRT programme. There are many steps that are required to implement this in the clinic. These are summarised in Section 1.4 and a self assessment questionnaire is provided in Appendix A. The treatment team should work through the questionnaire before treating their first patient using 3-D CRT. This Appendix is designed to help the treatment team decide on their readiness for treating their first patient using 3-D conformal radiotherapy and may be used as a guide throughout the development of the programme.

Figure 1.1 shows a flow chart of a typical 3-D CRT process. Details of this process may vary from one institution to another. However, this figure serves as an illustration to understand and discuss the various steps in the clinical implementation of 3-D CRT in a typical clinic. Appendix B gives an example of the detailed steps in the chain for practical delivery of 3D-CRT. This example is presented in the context of the treatment of head and neck cancer.

1.5.1. Patient assessment and decision to treat with radiation

The first step in the process is patient assessment and deciding how the patient should be treated. During assessment various diagnostic and investigative procedures are undertaken to define the state of the disease. This involves imaging, biochemical testing and review of pathologic information to identify the type, stage and grade of the cancer. The decision to treat the patient with radiation should be made by a team of clinicians.

1.5.2. Immobilization and patient positioning

Before starting to develop the treatment plan the team needs to decide on the position required for the patient treatment and on any immobilization aids that are to be used.

The use of 3-D CRT is usually associated with a reduction in the margins around the CTV, but this is only safe if random and systematic errors (see Section 1.8.4.1) can be reduced. Effective immobilization can significantly reduce setup errors [1.35], [1.36]. Therefore design of a given immobilization system for accuracy, comfort and ease of use is an important factor affecting the precision of patient set up on the treatment machine during the entire course of treatment delivery. Each centre should evaluate the immobilization system used for a given site for accuracy of reproducibility of patient positioning.

An accurately set up laser alignment system is an essential requirement for accurate radiotherapy. This should consist of at least three lasers to provide two lateral crosses and a sagittal line which can be used in conjunction with appropriately placed tattoos to ensure the patient is not rotated. Special immobilization systems are available for immobilizing different parts of the body. For example, knee supports and ankle stocks are used for pelvic and abdominal immobilization, adjustable breast boards are used for breast and vacuum immobilization bags or alpha cradles are used for chest, thermoplastic masks are used for head and neck treatment, and relocatable stereotactic frames are used for brain tumours. The key to satisfactory positioning of the patient is to ensure that they are as comfortable and relaxed as possible. It is often more practical and accurate to have minimal immobilization aids accurately placed by a skilled team of RTTs, than an over-complex system [1.37].

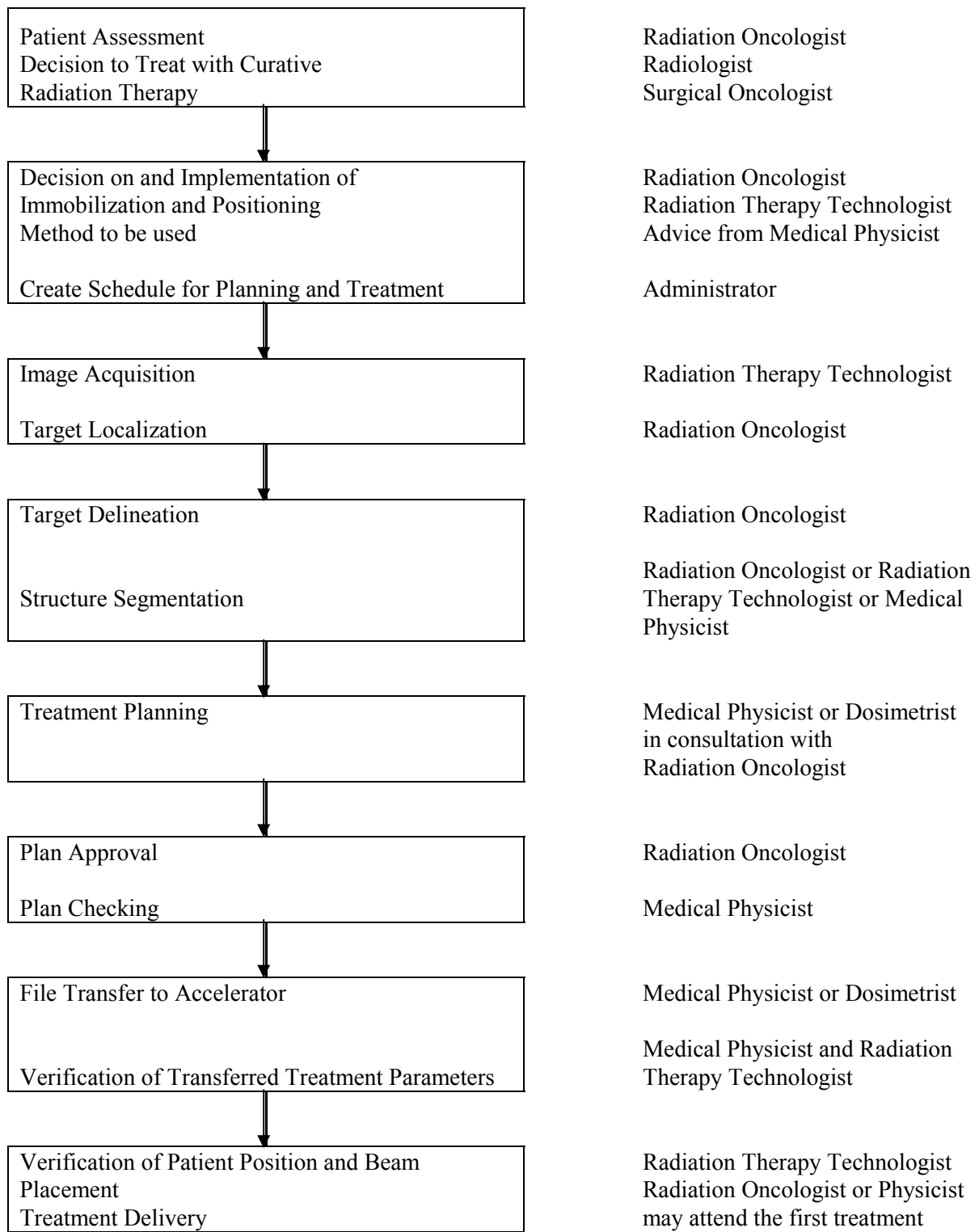


Figure 1.1 A typical 3-D CRT Process. The right column shows the staff involved in each step.

However, a rigid couch top surface is essential at each stage. Immobilization systems, where used, should ideally attach to the couch top in a unique position. This will avoid daily variation in couch sag (see Section 1.8.4.1) due to patient weight distribution and allow Record and Verification (R&V) systems to give a reliable indication of set-up accuracy during the course of treatment. For increased accuracy in head and neck radiotherapy it is preferable to have five fixation points. For instance, a superior attachment to the couch will reduce cranio-caudal rotation.

It should be stressed that if no immobilization is used, an appropriate margin should be established to account for patient motion in the design of the PTV. While immobilization is important for any radiotherapy, when performing 3-D CRT or advanced level 3-D CRT it is essential to use some form of immobilization to ensure that the patient setup at the time of imaging is accurately reproduced on the treatment machine, even if it is as minimal as the use of knee rests and ankle stocks in pelvic radiotherapy. In such situations, the uncertainty of setup reproducibility should be included in the design of the PTV.

1.5.3. Image acquisition and target Localization

Every radiotherapy department should develop protocols for image acquisition for various body sites. These protocols will define the requirements for the most common treatment sites. Where a protocol is not available, or in cases where it needs to be modified, a discussion with regard to the goals of the treatment should take place between the treating radiation oncologist, medical physicist, dosimetrist and CT technologist. This is necessary so that a clear understanding of the planning needs is well established prior to image acquisition.

1.5.3.1 CT imaging

For many tumour sites CT scanning provides the optimal method of tumour localization. All CT planning must be carried out under conditions as nearly identical as possible to those in the treatment room, including the patient support system (couch top), laser positioning lights and any patient positioning aids. For conformal therapy a slice separation and thickness of between 3 mm and 5 mm is recommended for CT scanning. For head and neck and Central Nervous System (CNS) planning this may be reduced to between 2 mm and 3 mm. In order to define anatomy adequately and generate DRRs of high quality, it may be beneficial to acquire CT slices in the anatomic regions of interest at closer spacing than for the rest of the volume, provided that the RTPS can cope with different slice spacing. Using radio-opaque markers lateral and anterior reference points should be established on the patient or the immobilization device.

In CT based tumour localization the scout or pilot image provides information on patient alignment. These images do not include divergence along the scanning axis. Therefore, one needs to generate orthogonal DRRs using a virtual simulation software package which can then be used for comparison with corresponding films obtained from simulators or electronic portal images obtained on treatment machines to establish correct isocenter localization.

Where the imaging facilities are located within the diagnostic imaging department it is essential that the radiotherapy department has an input to the technical specification of imaging equipment and networking facilities that will be required to interface with radiotherapy planning. There are differences in the objectives of the acquisition of diagnostic and radiotherapy planning CT scans and it is important that, if diagnostic staff are responsible for scanning, appropriate radiotherapy personnel are present to aid in the acquisition of the CT scans for radiotherapy planning.

The CT scanner couch top must be flat, securely fitted and compatible with the therapy machine couch. Transverse and longitudinal lasers with additional laser positioning lights are needed in the CT room identical to those in the treatment room to ensure exact positioning of the patient. A CT scanning laser should be at the same tolerance (1 mm) as the simulator laser lights. These are the keys to a system of coordinating the positioning of external radiotherapy treatment beams with internal CT-delineated tumour and normal organs for daily treatment. Radiotherapy dose calculation algorithms take account of electron density values for different tissues. These are derived from CT Hounsfield numbers and so it is essential that the QA programme of CT scanner includes checks for variation in Hounsfield number calibration.

The requirements for quality control of the CT scanner are dealt with in Section 1.8.1.

1.5.3.2 MR and other imaging modalities

- In radiation therapy, the main application of MRI involves mapping of anatomical data across to a planning CT study (by, for example, co-registration of the MR image set to the CT image set and the use of a linked cursor to transfer contours to the CT data). This process retains the benefits of the CT study for dose calculation and treatment verification [1.38], while benefiting from the improved tumour visualisation of MR images, particularly in the CNS and prostate.

Improved image registration software packages are now available although their use still adds significantly to the length of the treatment-planning process. There are often differences in the apparent target volumes as defined by CT and MRI and further studies are required to validate the target volumes so defined and to demonstrate how these should be used to optimize the outcome of treatment [1.39], [1.40]. There are a number of tumour sites where MRI is a valuable aid in localising the disease [1.41], [1.42]. However, the direct use of MRI for radiotherapy planning purposes suffers from the following disadvantages:

- geometric distortion of the image;
- absence of tissue density information;
- poor definition of bone;
- DRRs cannot be created;
- disease visualization is strongly dependent upon the scan settings.

In recent years, significant advances have taken place in PET and SPECT imaging. Information from these imaging modalities can be used for diagnosis, staging and radiotherapy treatment planning and monitoring response to the treatment although they are not essential for 3-D CRT and caution must be exercised in the interpretation of data from these modalities. CT planning provides the oncologist with detailed tumour information for many tumour sites as well as the essential anatomical and body contour data and electron density information necessary for treatment planning. In order to use the optimum imaging information for modalities such as CT, MR, PET and SPECT, these images need to be registered at a single workstation to ensure that the state-of-the-art diagnostic imaging information is used to provide an accurate GTV on a CT-based treatment planning system (TPS) [1.43], [1.44].

1.5.4. Segmentation of structures

3D-CRT treatment planning is based on an image based simulation approach for accurately delineating tumour and organs at risk volumes for an individual patient. These volumes are drawn on a slice-by-slice basis on a CT data set. Target volumes are contoured manually although modern treatment planning systems provide capabilities to segment various structures automatically. It is incumbent upon the radiation oncologist to ensure that target volumes drawn by him/her or via the automatic segmentation process are accurate. This places a premium demand on the radiation oncologist to specify targets with greater precision and on the medical physicist to develop procedures for accurate imaging, patient setup reproducibility and organ motion assessment and treatment delivery verification. The following provides guidelines for delineation of target volumes and organs at risk volumes.

1.5.4.1 Target volume delineation

Volume definition is a prerequisite for meaningful 3-D treatment planning and for accurate dose reporting. ICRU Reports No. 50 and 62 [1.4], [1.5] define and describe several target and critical structure volumes that aid in the treatment planning process and provide a basis for comparison of treatment outcomes. Figure 1.2 shows the definition of these volumes. It is strongly recommended that these ICRU definitions for volumes are adhered to when delineating tumour and critical structures for the purpose of 3-D CRT.

1.5.4.2 Gross tumour volume

“The gross tumour volume (GTV) is the gross palpable or visible/demonstrable extent of location of malignant growth” [1.4].

The GTV is usually based on information obtained from physical examination by the oncologist and the results from imaging modalities (such as CT, MR, PET etc.) and other diagnostic modalities (such as pathologic and histopathologic reports).

1.5.4.3 Clinical target volume

“The clinical target volume (CTV) is the tissue volume that contains a demonstrable GTV and/or sub-clinical microscopic malignant disease, which has to be eliminated. This volume thus has to be treated adequately in order to achieve the aim of therapy, cure or palliation” [1.4].

In order to define the CTV, a margin has to be created for sub-clinical microscopic spread and other areas considered being at risk and requiring treatment (i.e. positive lymph nodes). Data for this are derived from histopathological specimens removed at operation or studies of local failure patterns for individual tumours. Postoperatively the CTV is often the whole organ, e.g. breast, following the excision of the primary tumour (GTV). When specified, the CTV is usually obtained from a somewhat empirical fixed or variable margin added to the GTV (e.g. $CTV = GTV + 1 \text{ cm margin}$), but in some cases the CTV may be the same as the GTV.

There can be several non-contiguous CTVs, which may require different total doses to achieve the treatment goals.

1.5.4.4 Internal target volume

The internal target volume (ITV) is a new concept introduced in ICRU Report 62 [1.5]. To compensate for variations in size, shape and location of the CTV relative to the patient's reference frame (i.e. bony landmarks), an internal margin is added to the CTV to create an internal ITV. The variations in size, location and shape of the organ may be small (e.g. brain) or large (e.g. physiological movements such as respiration, bladder and rectal filling, etc.). When defining the ITV it is important to account for the asymmetric nature of the organ motion. For example, it is now well established that the side-to-side motion of the prostate is different from the anterior-posterior motion. These internal variations are physiological ones and cannot be easily controlled, although studies are addressing these issues using devices such as respiratory gating, active breathing control, rectal stenting, etc. As can be seen from Figure 1.2, ICRU recognises that it may not be appropriate to add all the margins together directly as the volume may become so large that the maximum safe dose may not be sufficient, and they recommend that some statistical reduction in the margin size can therefore be introduced. Methods of dealing with respiratory motion are covered in AAPM Report 91 [1.45].

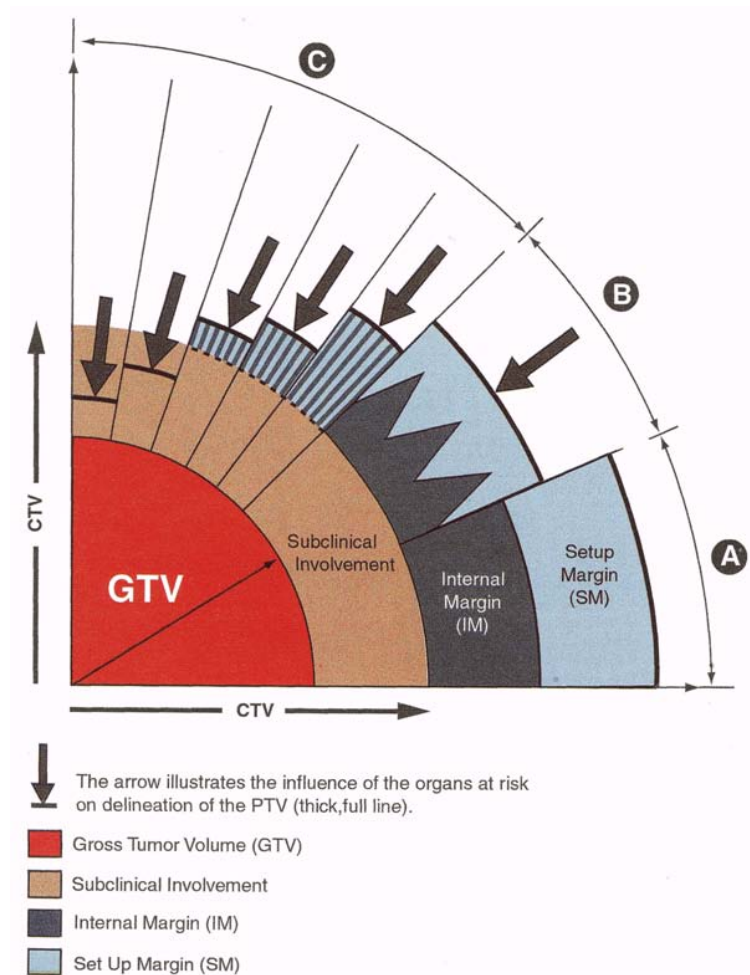


Figure 1.2 Schematic representation of different possibilities to combine uncertainties to define the PTV from the GTV: (A)=linear addition of margins (B)=probabilistic addition of IM and SM (C)=definition of a “global” safety margin based on an empirical compromise between adequate coverage of GTV and unacceptable irradiation of organs at risk (OARs) (from ICRU 1999,[1.5] with permission).

1.5.4.5 Planning target volume

“The planning target volume (PTV) is a geometrical concept, and it is defined to select appropriate beam arrangement, taking into consideration the net effect of all possible geometrical variation, in order to ensure that the prescribed dose is actually absorbed in the CTV” [1.4].

In order to achieve the prescribed dose to the CTV throughout the course of irradiation, margins need to be added to the ITV to account for uncertainties in patient positioning and alignment of treatment beams throughout a fractionated course of radiotherapy (set-up margin). Set up errors are the result of both random and systemic uncertainties in patient set-up, which occur with daily repositioning of the patient over a fractionated course of treatment. To compensate for all these variations, a margin is added around the ITV to create the PTV. Careful and accurate patient immobilization and verification studies are needed in each department to quantify these geometric uncertainties in the position of the ITV for each treatment technique. These local data can be compared with that available in the literature to aid in derivation of protocols for margin generation for each particular tumour site.

1.5.4.6 Organ at risk volumes

ICRU Report 62 [1.5] recognises that normal tissue structures are subject to the same movement uncertainties as the target volumes. They have therefore introduced the concept of the Planning Risk Volume (PRV) which is the volume of an organ at risk with an appropriate margin for

the uncertainty in its position. As shown in Figure 1.2 these margins may need to be varied depending on the proximity to the target volume and a balance needs to be drawn with the requirement to give an adequate dose to the tumour tissue.

1.5.4.7 Contouring (image segmentation)

Contouring the GTV, CTV, PTV, PRV and the body contour (except with certain planning systems where it is not needed) are essential steps in the conformal 3-D radiotherapy treatment planning process. When the GTV is delineated, it is important to use the appropriate CT window and level settings to determine the boundaries of what is considered to be potential gross disease. Defining the CTV is even more difficult than defining the GTV or any normal organs at risk because CTV includes areas of sub-clinical microscopic spread of disease and other areas considered to be at risk and the current imaging technologies are not capable of detecting this spread directly. The GTV and CTV must therefore be defined by the radiation oncologist based on clinical experience and availability of all imaging and histopathologic information. It is mandatory that the radiation oncologist receives training in cross-sectional anatomy and develops significant experience in segmenting the target and critical structure volumes before starting a 3-D CRT programme. Failure to do so may result in geometrical miss of the tumour and/or overdosing the critical structures resulting in significant harm to the patient.

Inter-clinician variability of target volume description is a weak link in the planning process and may compromise the benefits of dose escalation. Close collaboration with a radiologist and specific training in interpretation of CT and MR images is essential for clinicians to delineate the GTV accurately. However, it should be pointed out that the tumour volume defined by a radiologist is not necessarily the appropriate CTV for radiotherapy [1.46]. It is important to have in place a programme to enable those staff performing image segmentation to audit their performance against that of their peers. 3-D volume segmentation is time consuming and may be an area where the skills mix of other staff groups such as dosimetrists or radiotherapy physicists could occur with rigorous training, well-defined protocols and audit, leading to multidisciplinary role development. Institutions that have introduced contouring by non-medical personnel have usually started with normal tissue contouring, in some cases they have progressed to the target volume in some sites. However, the radiation oncologist is responsible for contouring the GTV, CTV, PTV and PRV and the overall planning process and should review the volumes created by other staff.

It is particularly helpful to examine a 3-D view of the target and sensitive structures. By rotating the viewpoint it is possible to determine potential beam directions to produce an optimum treatment plan.

For conformal radiotherapy it is essential that the final 3-D PTV and PRV are agreed between the radiation oncologist and treatment planner and a well-defined treatment plan outlined. This should include the likely number of beams and their orientation, dose constraints to the target and critical structures and possible compromise solutions.

1.5.5. Treatment planning for 3-D conformal radiotherapy

1.5.5.1 The treatment planning process

Once the target volume, organs at risk, and the required doses have been defined, the treatment plan will be produced by a person trained in 3-D planning. The aim of the treatment planning process is to achieve the dose objectives to the target and critical structures and to produce a dose distribution that is “optimal”. The radiation treatment planning systems have the capability to display a three dimensional view of the virtual patient on the computer monitor with contoured structures and target volumes utilizing various renderings, colours and degrees of transparency. The beam angles can be chosen using standard templates such as a six field prostate plan or by using a beam’s-eye-view display to maximize PTV coverage and to minimize irradiation of critical structures. When a beam aperture is defined, an additional margin of about 7 to 8 mm needs to be added beyond the PTV in all directions in the transverse plane to obtain the desired dose coverage to the PTV. In the

superior inferior directions one needs to add about 12 to 15 mm margin because of beam divergence effects. These margins are needed to cover the PTV with a minimum isodoses line or surface. A number of iterations are often required and, unless the radiation oncologist is actually doing the plan, there may need to be discussions between the radiation oncologist and the planners when dose objectives conflict. For conformal radiotherapy it is recommended that the radiation dose should be reported according to ICRU Reports 50 and 62 [1.4, 1.5], for the purpose of correlating dose with clinical outcome. In most cases, the dose prescription will specify the dose using the same ICRU criteria as those for reporting, i.e. the dose is specified at the ICRU reference point at or near the centre of the PTV, stating the maximum and minimum doses over the 3-D target volume as well as the mean dose. Specification of doses used for both prescription and reporting of IMRT is difficult where non-uniform dose distributions present new problems. Modal doses (i.e. the most frequently occurring dose value) within target volumes may in some cases be lower than for current treatment techniques and this may influence the choice of prescription doses. It is likely that entire DVHs for each volume (PTV, CTV and PRV) will need to be reported to allow correlation with clinical outcome.

In its most basic implementation conformal radiotherapy may consist of coplanar static beams in a standard geometric configuration with MLCs or conformal blocks used to achieve the required conformal shape. Non-coplanar planning increases complexity and raises questions not encountered in traditional coplanar planning, e.g. beams may enter and exit through different anatomical structures. This may affect acute or late responses and non-coplanar beam arrangements should be used with caution. However, for brain treatments a shaped non-coplanar beam may be very useful to create a concave volume normally only achievable by IMRT. Sufficient information must be provided to ensure precise treatment prescription, set up and delivery. For non-standard configurations of beams, DVHs may aid in the selection of the best plan, but it is important to note that DVHs contain no geometric information, i.e. they do not indicate which part of the organ is receiving a high or low dose. Clinical plan comparison should therefore involve inspecting DVHs and physical dose distributions (slice by slice or using volume rendered images) at the treatment planning terminal. Additionally, biological modelling with computation of tumour control probability (TCP) and normal tissue complication probability (NTCP) may be valuable, but such modelling is complex and can be very sensitive to the choice of values for various parameters. Where complex computer calculations are to be used (e.g. non-coplanar beams, asymmetric beams or 3-D-algorithms), it is particularly important to have expert input from an experienced radiotherapy physicist. For non-coplanar planning, documentation should follow the recommendations given in [1.4] and [1.5]. This should typically include specification of beam set-up parameters, isodose plots on one or more sections, DVHs, and BEVs with or without DRRs.

1.5.5.2 Radiation treatment planning system requirements

The treatment planning system must have a number of features for planning of conformal radiotherapy. These can be divided into geometric and dose computational features. A list of the general requirements for a treatment planning system is given in [1.2], but IAEA TRS-430 [1.34] should be consulted for a full discussion of treatment planning. In the next two sections the particular features relevant to 3-D CRT are discussed.

1.5.5.2.1 Geometric features

The planning system must be able to handle a large data volume set which may include as many as 120 CT slices. A narrow slice spacing (≈ 3 mm) is necessary to produce satisfactory DRRs but this may make dose calculation rather slow. It is therefore advisable, if it is possible, to select a subset of slices for contouring and the dose calculation. Systems for 3-D visualisation of anatomy, of the outlined structures and of the dose overlay are essential. Co-registration of images from different modalities is a useful feature that becomes essential for some sites. Systems for design of treatment aids (e.g. shielding blocks, compensators, etc.) and visualising the position of the radiation beam in 3-D are also useful.

1.5.5.2 Dose computation models

The combination of beams from many directions, especially if these are non-coplanar, means that purely geometrical considerations are no longer adequate to determine the position of MLC leaves. It is therefore important that the computer has a fully 3-D dose computation model that will permit accurate calculation of the dose both at the centre of the volume and at the position of isodose lines close to the edges of the beams. When multiple beams are in use, the calculation of the doses at points that are geometrically shielded by the collimation system may become significant. Accurate modelling of all the components of the linear accelerator collimation system is important, especially in terms of the attenuation of the leaves and leaf ends of the MLC and the combination of the leaves with the jaws.

1.5.5.3 Number of planning workstations

While the number of workstations required depends on the organisation of the department, it is essential that there are a sufficient number of workstations so that staff are not having to carry out 3-D treatment plans under time pressure. With increasing use of CT data associated with 3-D CRT, the requirement for workstations is likely to increase. A minimum number is one workstation per megavoltage treatment machine, but two per treatment machine is recommended.

1.5.6. Data transfer for treatment delivery

Once the treatment plan has been designed and approved by the radiation oncologist the details need to be transferred to the treatment unit. If possible, a R&V system should be used to control the treatment unit and with data transfer carried out electronically, preferably over a radiotherapy network. Several studies [1.47], [1.48] have shown that treatment errors are reduced by electronic data transfer. If custom blocks are being used it may be acceptable to use manual systems, but when a MLC is being used to shape the fields, there is so much data to transfer that electronic data handling is mandatory. Although electronic data management reduces errors, vigilance must nevertheless be exercised because the transfer of data may involve several data translations between different proprietary formats even though the transfer itself follows the DICOM RT standard. A printout of the field shape is a useful method to allow comparison of the treatment planning system output with the field shape on the treatment machine. Safeguards must be put in place to prevent data corruption due to infection by computer viruses, etc. If there are connections to other computer network systems, e.g. hospital information technology (IT) networks, the risk of data corruption due to viruses may be increased because ensuring the integrity of “firewalls” may be more difficult.

1.5.7. Position verification and treatment delivery

Conformal radiotherapy by its nature requires good geometrical accuracy in order for it to be successful. It is normally the intention of conformal therapy to reduce the volume of normal tissue included within the treated volume. However, if there are problems of setup accuracy with a particular patient, it is in principle possible to keep the treated volume the same and to use a wider conformal margin around the target volume. If the border of the treated volume is tightly conformed to the target volume and the patient is not set up accurately the impact of this setup error will be greater than for a non-conformal field.

It is therefore an essential requirement of 3-D CRT that careful attention is paid to position verification. It is important for the staff to be fully aware of issues relating to systematic and random errors. In many situations the two types of error can be of similar magnitude and in such circumstances there is a danger that making a positional correction based on just one position measurement may lead to greater inaccuracies. The primary aim of position verification is to reduce the systematic errors. If, for example, there is a systematic positional error of 2 mm for a particular patient, but at the time of simulation there is an additional 3 mm random error in the same direction, the field placement error measured will be 5 mm. If this 5 mm correction is applied throughout treatment, the patient setup will be worse than if no verification is carried out. It is for this reason that many centres have moved away from the traditional approach of verification using a simulator (where

there is the added complication of possible differences between the simulator and the treatment machine geometry) in favour of verification on the treatment machine. However, some would argue that verification in the simulator prior to treatment can prevent gross setup errors.

A number of publications (e.g. [1.49], [1.50]) recommend systems for position verification based on an understanding that multiple measurements are required in order to be able to make corrections for the systematic errors while minimising the impact of the random errors. Before embarking on 3-D CRT it is important to establish the reproducibility of patient positioning that is being achieved by carrying out an audit of setup accuracy, and if necessary to take steps to improve it. This study of reproducibility should also provide information on the margins to be applied between the CTV and the PTV to allow for setup errors. A formula for this is given by Van Herk [1.51].

Attention must also be paid to ensuring that patient setup is consistent throughout treatment. It is sometimes the case that patients relax systematically more and more throughout the course of treatment, and if tight margins are being applied it is therefore necessary to repeat the portal imaging part way through the treatment. Depending on the anatomy site being treated, consideration also needs to be given to achieving reproducibility of the target position relative to the external anatomy used to set the patient up. For example, in treating prostate cancer, it is important to achieve consistency of rectal and bladder filling and in treating lung cancer, consideration needs to be given to the movement of the tumour with respiration (e.g. using gating, breathing control or by applying pressure on the diaphragm to reduce diaphragmatic breathing).

Because the complexity of the treatment is greater there is potentially also an increased possibility of error. In addition, the prescribed dose is likely to be closer to tolerance and therefore the effect of a dose error will be greater. It is therefore recommended that in-vivo dosimetry should be carried out on the first fraction of each patient's treatment course [1.52].

1.6. EDUCATION AND TRAINING REQUIREMENTS

There are significant differences between conventional 2-D RT and 3-D CRT. Making a transition from one to the other is a substantial undertaking. Experience gained by carrying out conventional 2D RT is essential; however, additional skill sets are necessary to make the transition to 3-D CRT. Section 1.5 gives a description of how to implement 3-D CRT in a given clinic. It is imperative that each member of the team involved in the planning and delivery of 3-D CRT understands his/her role well so that safe and effective use of this technique can be assured. The 3-D CRT training program must include detailed exposure to each of the steps outlined in Sections 1.4. and 1.5. The following gives a description of the minimum training requirements for the 3-D CRT team members (which is summarised in the form of a questionnaire in Appendix A). Items indicated with an asterisk are optional.

1.6.1. Radiation oncologist

(1) Academic knowledge:

- Cross sectional anatomy, surface and radiological anatomy;
- Target volumes and critical structures [1.4], [1.5];
- Dose response data;
- Understanding of beam shaping methodologies – MLC, customized blocks;
- Linacs (where appropriate), basic understanding especially choice of energy, choice of modality;
- Immobilization methods for 3-D CRT.

(2) Practical training in contouring of target volumes and critical structures.

(3) Familiarity with CT scanning procedures — unless there is a diagnostic radiologist available who has sufficient time to devote to the support of radiotherapy.

(4) Practical training in the operation of the RTPS for contouring, image registration*, treatment planning, BEV planning for MLCs (or customized blocks).

(5) Practical training in the evaluation and analysis of dose distribution and dose volume histograms.

1.6.2. Medical physicist

(1) Academic knowledge:

- Basic understanding of cross sectional anatomy, surface and radiological anatomy as it relates to radiotherapy planning and understanding of treatment plans;
- Target volumes and critical structures [1.4], [1.5];
- Dose response data;
- Understanding of beam shaping methodologies – MLC, customized blocks;
- Full understanding of linear accelerator concepts, commissioning and acceptance testing of linacs or knowledge of beam shaping with cobalt-60 units;
- Portal imaging systems;
- Random and systematic errors in radiotherapy treatment;
- In-vivo dosimetry;
- Quality control (QC) for MLCs, portal imaging, and in-vivo dosimetry;
- Commissioning and acceptance of a 3-D RTPS;
- Immobilization methods for 3-D CRT;
- QC of CT (and MR*) scanners especially in relation to geometry and Hounsfield units.

(2) Practical training in contouring of critical structures.

(3) Practical training in the operation of the RTPS for beam data modelling, contouring, image registration*, treatment planning, BEV planning for MLCs (or customized blocks).

(4) Practical training in QC for 3-D CRT.

(5) Practical training in the evaluation and analysis of dose distribution and dose volume histograms

1.6.3. Dosimetrist

(1). Academic knowledge:

- Basic understanding of cross sectional anatomy, surface and radiological anatomy as it relates to radiotherapy planning and understanding of treatment plans;
- Target volumes and critical structures [1.4], [1.5];
- Understanding of beam shaping methodologies – MLC, customized blocks;
- Immobilization methods for 3-D CRT;
- Basic understanding of the physics of treatment planning dose calculation.

(2). Practical training in planning 3-D CRT.

1.6.4. Radiation therapy technologists

(1) Training and experience in the additional requirements for 3-D CRT:

- Basic understanding of cross sectional anatomy, surface and radiological anatomy as it relates to radiotherapy planning and understanding of treatment plans;
- Immobilization techniques;
- Portal imaging and registration techniques;
- Use of customized blocks or MLC operation;

- Daily QC for linacs and MLCs;
- R&V systems;
- CT operation for radiotherapy planning.

1.7. STAFFING REQUIREMENTS

Defining the target volume on multiple CT slices can be a time consuming process that may take several hours, depending on the experience of the operator. This means that sufficient time, and hence staff numbers, must be allowed for delineating target volumes and critical structures. Conducting the treatment plan is also substantially more time consuming when it is necessary to consider the dose distribution on multiple slices and perhaps calculate the TCP and NTCPs for different organs. On the treatment machine some increase in workload is associated with portal image analysis, but if a MLC is used the actual treatment time does not need to be any greater than for conventional treatments. Thus, the staffing implications are related to clinician time and treatment planner time. It is difficult to be precise about the staffing levels required and there are few published recommendations specifically relating to the impact of 3-D CRT, although the Institute of Physics and Engineering in Medicine in the United Kingdom (IPEM) [1.53] recommended that 0.2 physicists and 0.2 dosimetrists are required per 100 patients treated with 3-D CRT per annum. It is also important to remember that an appropriate resource is also needed for diagnostic imaging prior to treatment. The workload of the radiation oncologist should be constrained so that they have sufficient time to devote to the process of delineating target volumes and critical structures.

1.8. QUALITY ASSURANCE AND QUALITY CONTROL IN CONFORMAL RADIOTHERAPY

For the safe practice of 3-D CRT it is essential that there is a QA programme covering the whole process from CT scanning through to treatment delivery. This must include all staff and activities involved in the process. Each member of the team needs to be aware of the impact of their contribution. For example in Section 1.9 the importance of monitoring the clinical outcome as part of the overall QA process is stressed.

The subject of QA in radiotherapy as a whole is covered in detail in [1.2]. Here we concentrate on the aspects of QC that need to be emphasised for 3-D CRT. These include each aspect of the process shown in Figure 1.1.

1.8.1. CT Scanner

Movement of the couch must be assessed regularly, particularly if using helical scanning, to verify the accuracy of slice reconstruction and couch movement accuracy. The amount of couch deflection under load with respect to different anatomical treatment areas must be evaluated during commissioning and taken account of.

Regular QC must be carried out on the CT scanner. This should include couch movements and alignment, tolerance of the laser positioning lights and Hounsfield CT number calibration. Details on the QA of CT scanners and CT simulators can be found in the Report of AAPM Task Group 66 [1.54], and in IPEM Report 81[1.55].

When using MRI for treatment planning particular consideration must be given to the issue of image distortion. Issues related to its use in radiotherapy are considered in IPEM Report 81 [1.55]. Reports on image registration and the use of MR in treatment planning are being prepared by the AAPM.

1.8.2. Radiation treatment planning system

The IAEA TRS-430 [1.34] is the most comprehensive publication covering commissioning and QA of RTPS. Details of acceptance testing and commissioning testing for typical treatment

techniques are given in other IAEA TECDOCs [1.56], [1.57]. For the RTPS it is particularly important to consider the geometric aspects of the calculation and the modelling of the MLC. Some planning systems may treat the MLC as if it were a standard collimator jaw (appropriate for Elekta where the MLC is an integral part of the collimation system) or as a block (appropriate for Varian and other add on MLCs). Ideally it should be specifically modelled including the leaf end shape, the tongue and groove effect, and interleaf leakage (although it is unusual for the latter to be included). It is particularly important that gaps between fully closed leaves are accounted for and, in the case of Elekta, the partial transmission of the backup jaws. Where blocks are used the RTPS must correctly account for the block tray and for the geometric position of the blocks (which determines the penumbra width).

Attention must also be paid to the geometric accuracy of the RTPS which is more demanding in 3-D CRT. It is desirable to create a treatment plan for a phantom which has a known geometry including some internal markers, from CT scanning to treatment on a regular basis. This test will allow verification of the geometry as well as the dose calculation. The frequency of such a test will depend on the other approaches to verification that are in place [1.34]. Consideration should also be given to assessment of the accuracy of the dose volume histogram calculation [1.58]. Consideration must also be given to QA of the network system used to communicate with the linac [1.59].

1.8.3. Treatment machine

1.8.3.1. Treatment machine with MLC

On the treatment machine it is important that the beams are correctly aligned. MLCs require particular QC measures depending on their application. Some recommendations for these are given in IPEM Report 81 [1.55], the report of AAPM Task Group 50 [1.60], and in SFPM Report 20 [1.61]. For simple field shaping the requirements are less demanding than for intensity-modulated radiotherapy where errors in leaf positioning can lead to errors in the delivered dose (see Chapter 2 of the current publication, Section 2.5.6).

When establishing the leaf calibration, there are two stages: setting the mean position of the whole set (or bank) of leaves and then setting the position of individual leaves (sometimes referred to as minor offsets). The relationship between the mean position of the leaves and the position of the backup jaws (if any) must also be established. Several factors must be considered when setting up the MLC leaf calibration. For MLCs with rounded leaf ends (as those of Varian and Elekta) the part of the leaf that defines the field edge varies as the leaf is tracked across the beam and it is therefore necessary to test leaf alignment at different positions relative to the centre of the beam [1.62]. It is not possible to adjust the light field by using light field trimmers. This means that once the optics have been adjusted so that the (virtual) light source is on the central axis of the beam, no further adjustment of the relationship of the optical field to the radiation field is possible.

As discussed in [1.63], when leaves are used to define rectangular fields in conjunction with backup jaws (as in the Elekta design) the position of the 50% isodose line will be different in relation to the leaf position compared to when the leaves define the edge of the field alone. It is a useful test to expose a single film using a series of adjacent strip fields, usually 20 mm wide. Any error in leaf position will show up as a non-uniformity in the resulting film. This is a very sensitive test and a non-uniformity of 5% represents an error of about 0.5 mm. The exact technique for setting up leaf calibration is dependent on the particular MLC. The procedure for Varian MLC's is described in [1.64] and [1.65], for Elekta MLC's it is described in [1.66] and [1.67], and for Siemens MLC's in [1.68] and [1.69].

The MLC leaves must be aligned so that they move parallel to the standard collimator jaws. The centre of the leaf bank must also be coincident with the central axis of the machine. This is principally an issue at commissioning, but with the Varian design where the leaves are mounted on a moving carriage it is possible that they may become misaligned during use. This can be checked on an occasional basis as described in [1.65].

1.8.3.2. Customized blocks

If carrying out 3-D CRT using a cobalt-60 machine or a linear accelerator with a MLC, it is necessary to be able to produce individually shaped customized blocks. If using customized blocks, there is a need to ensure that when the gantry rotates the blocks do not move. For this purpose it is useful to have a block accurately and rigidly mounted so that it blocks one quarter of a 10 cm x 10 cm field. By taking images at different gantry angles it is possible to verify that the block is correctly centred at all gantry angles. It is also essential to have an appropriate quality system to ensure that the correct blocks are used for the correct field. This can be achieved by using blocks fixed to coded polymethylmethacrylate (PMMA) trays.

1.8.4. Patient treatment

1.8.4.1. Patient setup

3-D CRT can only be successful if the patient is set up in the same position for each fraction and should not be carried out unless portal imaging is available (either with film or an EPID). Consideration must also be given to the internal movement of the target tissue associated with respiration [1.45] or with rectal filling. In all cases CTV to PTV margins should be based on a local audit of setup accuracy (see Section 1.5.7).

1.8.4.2. In vivo dosimetry at time of treatment

On treatment there is a need to carry out in vivo dosimetry, although in vivo dosimetry is not a substitute for phantom measurements prior to the introduction of 3-D CRT. Guidance on this can be found in the AAPM Report [1.70]. In vivo dosimetry is particularly important when CRT is being used to allow the dose to the target to be increased.

1.8.4.3. QC of in-vivo dosimetry

An in-vivo dosimetry system is only useful if the accuracy of the dosimetry is better than 5% and ideally better than 3%. To achieve this, a thorough QA programme is required [1.70].

1.9. CLINICAL OUTCOME MONITORING

The aim of 3-D CRT is to offer patients the possibility of local control of their tumour and potentially cure of their cancer. It is important to be able to audit the success of this aim as part of the conformal therapy programme. For example, if planning target volumes do not include a sufficient margin, the likelihood of a recurrence will be increased, while on the other hand if the margin is too large, the normal tissue complications will increase. It is therefore strongly recommended that a database is established when the 3-D CRT programme is initiated so that the impact of the programme on patient outcomes can be monitored. A regular review of these outcome data should be carried out. An indication of the benefits to be expected from such a review can be found in the report of the Scottish Clinical Outcomes Working Group [1.71]

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2. INTENSITY MODULATED RADIOTHERAPY

2.1. INTRODUCTION TO PART 2

This part of the publication describes technological, logistical and personnel requirements to enable the safe and accurate delivery of Intensity Modulated Radiation Therapy (IMRT). IMRT is an evolving technology. It allows the implementation of highly conformal, even concave, dose distributions. Traditional radiation therapy techniques, including three dimensional conformal radiation therapy (3-D CRT) with uniform radiation intensity and/or with simple beam fluence modifying devices like wedges, do not provide a method for sparing critical structures that push into and are partially or fully surrounded by a target or combination of targets. More conformal dose distributions are now possible by continuing advances in computer technology. Largely this has led to the development of sophisticated three-dimensional radiation treatment planning systems (3-D RTPS) with inverse planning capabilities and computer-controlled radiation therapy treatment delivery systems equipped with a multileaf collimator (MLC). Such planning and delivery systems have made possible the implementation of 3-D CRT with modulated radiation fluence, *i.e.* IMRT. The ultimate goal of 3-D CRT is the conformation of the dose distribution to a 3-D target volume (a 3-D region at risk for containing cancerous cells plus a margin for spatial uncertainties), while at the same time minimizing the dose to an acceptable level to the surrounding normal structures.

IMRT involves much more than simply the use of non-uniform beam intensities. Beam modifiers, such as wedges and compensators, have been used for many years to compensate for missing tissue, and in some instances to shape dose distributions, yet they are not IMRT. We define an IMRT treatment plan, for the purpose of this publication, as a dose plan and treatment delivery that is optimized using inverse planning techniques for modulated beam delivery. IMRT can be delivered using either 2-D physical compensators or MLC systems employing: binary delivery; “sliding window” delivery (*i.e.* dynamic MLC or DMLC); or “step and shoot” delivery (static MLC or SMLC [2.1]). An IMRT treatment plan also includes well defined dose planning objectives and constraints and a rationale for target and critical structure expansions. The evaluation of an IMRT treatment plan includes the analysis of 3-D dose distributions, dose-volume histogram (DVH) for targets and critical structures, and patient-specific quality assurance (QA) data. It is important to recognize that IMRT techniques present a set of challenges that are significantly more complex than traditional forms of radiation treatment [2.2].

IMRT improves conformity of dose delivery to the target volume and sparing of normal tissue. Therefore, the highly conformal dose distributions produced by IMRT offer a means of reducing the volume of normal tissue that is irradiated, potentially allowing for dose escalation. Escalating the dose while preserving, or even decreasing, the toxicity rate offers significant potential to improve the therapeutic ratio. Although there have been many institutional reports documenting a significant dosimetric improvement of IMRT over standard 3-D CRT and some preliminary phase II studies show promising results in terms of tumour control and/or reduction in the toxicity profile for selected patients, data from randomized, phase III clinical trials are not yet available.

IMRT techniques are significantly more complex than those described in Chapter 1 and require the close collaboration and expertise of an appropriately trained multidisciplinary team, including radiation oncologists, medical physicists, dosimetrists and radiation technologists [2.3], [2.4]. Due to its complexity, IMRT requires:

- proper patient selection,
- adequate imaging capability,
- appropriate patient immobilization devices,
- a sound knowledge of anatomy, physiology and the natural history of the disease for target and organs at risk delineation,
- advanced and reliable treatment planning software,
- stringent requirements for clinical commissioning of planning and delivery systems,
- increased effort for QA and planning activities,

- careful plan evaluation,
- accurate treatment delivery.

Therefore a strict and comprehensive QA program is essential for safe and accurate treatment delivery and must be established by each and every institution planning to initiate the use of this technique.

The increased conformity of IMRT and the complexity of the isodose volumes may lead to “geographical miss” due to inadequate target delineation, organ motion and patient positioning inaccuracies, while a larger margin may lead to unacceptable high dose to normal critical structures. Extensive research is currently being conducted to define the optimum utilisation of different imaging modalities (computer tomography-CT, magnetic resonance-MR, positron emission tomography-PET-CT, ultrasound - US, MR spectroscopy). International efforts are in progress to understand and minimize the variations in inter-observer target and normal structure delineation through the development of consensus delineation atlases for each disease site. The advancement in 4-D imaging has provided us an opportunity to clearly quantify internal organ motion. Finally, on-board imaging capabilities on the radiation delivery systems provide an opportunity to minimize inter-fraction targeting uncertainties. However, intra-fraction internal organ motion still remains a largely unsolved problem.

There are many important issues related to IMRT, which are required to be seriously considered when implementing this modality: increased costs, increased workload, increased treatment time/delivery, higher integral dose, increased risk of second malignancies, decreased dose rate to some areas of the CTV and low dose hypersensitivity. These issues must be taken seriously by the institution planning to embark on this technique. The final decision to implement IMRT must come from a suitable multidisciplinary committee that is familiar with the institution’s financial capability and well aware of the technical and complex issues involved.

Part 2 of this publication was not produced with the intention of teaching how to perform IMRT. Its aim is to provide guidelines to the Agency and to the Member States (decision makers in Ministries of Health, non-governmental organisations, cancer societies etc) for the necessary foundations needed to allow the transition to IMRT treatment delivery in radiotherapy hospitals and to provide indications for infrastructure and resource requirements for IMRT implementation.

As discussed in Chapter 1 Section 1.1, 3-D CRT delivery relies on a chain of procedures, all of which must be in place if the treatment is to be safe and accurate. The links of the chain for IMRT include all those required for 3-D CRT with, in addition, a computer optimisation algorithm to design the intensity modulated beams. To this end Section 2.3 provides a list of milestones that should be achieved in the project plan in order to set up an IMRT programme. At the publishing of this report, IMRT is a technology with widespread use in North America and Western Europe. In addition it is gradually being adopted in large or leading institutions in the developing world. In this setting, the use of this technology can only be justified through definitive therapeutic gains.

2.2. CLINICAL EVIDENCE RELATING TO IMRT

Multiple institutional studies have been published in recent years demonstrating the dosimetric advantages of IMRT over 3-D conformal radiotherapy in the conformity of the high dose region to the target, and avoidance of high doses to critical neighbouring structures, at the expense of higher tissue volumes receiving low doses and higher dose inhomogeneity within the targets [2.4]. Some examples of anatomical locations in which IMRT may be of dosimetric benefit are:

- head and neck cancer, where the targets are arranged anterior and lateral to the spinal cord and bound externally by the major salivary glands [2.5], [2.6];
- prostate cancer, where the rectum invaginates into the prostate target volume [2.7];
- lung cancer, where mediastinal lymph node targets may lie in front of and lateral to the esophagus,
- esophageal cancer where sparing the lungs from high doses is an objective [2.8];

- gynaecological malignancies, where the lymph node targets are arranged lateral and posterior to the small bowel [2.9], [2.10];
- left-sided breast cancer, in which the target is concave anterior to part of the lung and heart [2.11].

As the volume of adjacent tissue receiving a high dose decreases, it may be possible to deliver a higher-than standard dose to the tumour without increasing toxicity, with the goal of improving local/regional cure rate without increasing toxicity. Furthermore, if specific areas of the tumour that are more resistant to radiation than other parts (e.g. hypoxic tumour sub-volumes), can be identified, it may be possible to use IMRT to deliver higher doses to these parts of the tumour (“dose painting”) [2.12]. These issues are currently subjects for research rather than routine clinical practice.

While dosimetric studies showing an advantage for IMRT have been published in many anatomical tumour sites, studies assessing the clinical benefit arising from the dosimetric advantages are much more limited. Those that have been published constitute phase II or retrospective studies. No large randomized studies have been published, and no study large enough to assess tumour control benefit is currently being conducted. The majority of the clinical studies published thus far using IMRT are in head and neck, prostate and gynaecologic cancer areas.

In head and neck cancer, extensive work has been published on the utility of IMRT to spare the major salivary glands and reduce xerostomia. These studies showed relative sparing of the parotid (but not the submandibular) glands, moderate retention of salivary output, and recovery over time of both salivary output and patient-reported or observer-based assessment of symptoms [2.13]. Retrospective comparison to conventional radiotherapy suggests significant benefit in these regards. The only randomized study presented thus far showed a benefit in saliva sparing but not in quality of life (QOL) [2.14].

Series reporting tumour control rates following head and neck IMRT suggest better loco regional control rates compared to similar series of conventional radiotherapy, especially for nasopharyngeal and oropharyngeal cancer [2.15]. However, issues of potential patient selection bias for IMRT and lack of randomized studies bar any definitive conclusion. For example, in a series of IMRT for nasopharyngeal cancer from the University of California-San Francisco, more than half of the patients had tumour stage T1-2 and all had World Health Organization (WHO) type III (undifferentiated cancer), which is associated with favourable loco-regional control rates. None of the series of IMRT for head and neck cancer reported how many patients were treated with conventional radiotherapy during the same time period. It is likely that patients with low performance status, patients who could not tolerate long treatment time or those requiring urgent treatment starts were selected for conventional radiotherapy rather than IMRT. This potential selection bias limits the ability to compare the results of published IMRT series with previous series using conventional radiotherapy. In addition, the introduction of image guided radiotherapy (IGRT) which improves the geometric accuracy of radiotherapy treatment may also be responsible for some of the reduction in the side effects of treatment.

Few series assessed the pattern of loco regional recurrences following IMRT for head and neck cancer. These series showed that the large majority of recurrences were in-field with only a few recurrences being marginal or out-of-field [2.16]. However, these series were published by centers with large patient numbers and experience. It is not known if this is the case in institutions treating smaller patient numbers. At this time we can only state that there is no evidence that IMRT compromises loco-regional tumour control.

The delivery of high fraction doses to the gross tumour volume (GTV) in head and neck cancer, resulting in high biologically effective doses, has been published [2.17]. However, only one phase I trial has been conducted assessing the safety and dose limiting toxicity of such an approach [2.18]. As expected, the dose limiting toxicity was severe mucositis. The main problem is that the heterogeneity of tumour sites and GTVs, which probably have a considerable effect on toxicity, have not been taken into account in these studies. In addition, concurrent chemotherapy, standard of care for advanced head and neck cancer, was not administered in these studies and would be expected to increase toxicity even further. In summary, dose escalation for head and neck cancer using IMRT, in an effort to improve tumour control rates, should only be done in a carefully controlled clinical study setting and is not considered standard care.

In prostate cancer, partial sparing of the rectal wall seems to be the major advantage of IMRT. Reducing rectal toxicity, a major dose-limiting factor in the therapy of prostate cancer, may allow dose escalation and the potential for improved cure rates. The largest experience in this regard has been accumulated at Memorial Sloan Kettering Cancer Centre in more than 700 patients [2.19], [2.20]. This group reported that when doses of 81 Gy were delivered, IMRT resulted in significantly less acute and late rectal toxicity compared with previous techniques of 3-D CRT. Data suggesting improved tumour control rates for high-risk prostate cancer using higher doses are emerging [2.20], [2.21]. In this regard, IMRT seems to be essential in securing low rates of rectal toxicity while higher-than-standard total doses (>76 Gy) are delivered to the prostate, but not when lower doses are prescribed.

In gynaecologic cancer, benefits in dosimetric sparing of the small bowel and bone marrow have been demonstrated in the postoperative treatment of endometrial and cervical cancer. Clinical studies at the University of Chicago demonstrated, in a retrospective comparison, significantly reduced rates of grade 2 and 3 gastrointestinal toxicities in patients treated with IMRT compared with similar patients treated in the past with conventional techniques, and the data also suggested reduced low/moderate severity urinary symptoms [2.22]. In this regard, the benefits from IMRT seemed to be especially important in patients requiring extended-field radiotherapy (pelvis and para-aortic irradiation), whose treatment with IMRT resulted in a very low incidence of acute toxicity [2.23]. This group reported an additional benefit for IMRT in reducing bone marrow toxicity, especially in patients receiving radiation concurrent with chemotherapy [2.24]. Sparing the bone marrow was facilitated by SPECT bone marrow imaging, which allowed specific avoidance by IMRT of the bone marrow-forming parts of the pelvic bones [2.25], [2.26].

Several potential negative aspects of IMRT exist, for which there is as yet no clinical validating information [2.27], [2.28]. While IMRT reduces the tissue volumes receiving high doses, larger tissue volumes receive low doses compared with standard radiotherapy or 3-D CRT due to the larger number of beams and increased leakage through the collimator leaves. This may increase the risk of radiotherapy-related malignancies, as the risk of radiotherapy-related mutations and carcinogenesis increases at intermediate, rather than at high doses. This risk is especially relevant for young patients. As the risk of radiotherapy-related malignancies increases usually after 5-10 years following therapy, clinical data are not expected to be available in the near future

2.3. MILESTONES FOR IMRT

An IMRT programme should be built on a firm foundation of expertise in conventional and three-dimensional radiotherapy. The questionnaire given in Appendix A provides a checklist of steps in the process. Before any resources are committed to the establishment of an IMRT programme, the following milestones have to be fulfilled. Numbers in brackets refer to the questions in the Appendix A.

Milestones that must be passed before resources are committed to the establishment of IMRT:

- Facilities should be in place for the provision of conventional radiotherapy and 3-D CRT.
- Adequate diagnostic imaging facilities are in place.
- Adequate imaging facilities are in place for planning CT-scans.
- There is a sizeable population of patients with an indication for curative radiotherapy and IMRT.
- Previous 1-2 years experience with 3-D CRT (51).

Milestones in the process once the project has started:

- IMRT Committee and Programme including budget plan (52).
- Appointment of sufficient staff so that conventional radiotherapy treatments are not compromised (53).
- Adequate maintenance facilities to ensure that the calibration of the MLCs can be maintained (54).
- Academic training of the staff in IMRT (55).
- Specification and purchase of IMRT-specific additional equipment (56).
- Practical clinical training of radiation oncologists and medical physicists (55).
- Commissioning of Radiation Treatment Planning System (RTPS) and treatment machines (57-62).
- Establishment of protocols for IMRT for defined anatomical sites (58, 59).

2.4. APPROACHES TO IMRT

IMRT and other advanced technologies should be planned taking into account an assessment of the specific local needs. Given the lack of level 1 evidence, the introduction of IMRT should not compromise standard care provided to the whole population of patients in the institution at the national level the establishment of IMRT, in selected institutions, should not be done at the expense of the adequate basic radiotherapy services to the cancer patient population.

2.4.1. Building an IMRT team

The institution must set up an IMRT committee including a radiation oncologist, medical physicist, radiation therapy technologist (RTT) and hospital administrator(s) to plan and decide on the implementation of the IMRT program. The planning aspects should include appropriate allocation of resources with a well-defined budget, an assessment of the population needs, an established time-frame to launch the program and a clearly elaborated action plan with suitable distribution of responsibilities among the members of the committee. The team, including radiation oncologists, medical physicists, dosimetrists and RTTs should be “comfortable and familiar” with the 3-D approach in various anatomical sites. Previous experience and an ongoing program in 3-D CRT is a must before implementing an IMRT program. Given the complexity of the technique and its possible associated difficulties, full-time coverage by at least one fully trained radiation oncologist is essential. Each radiation oncologist should ideally have not more than 30 patients under treatment at any given time. The role and responsibilities of each IMRT team member are described in Section 2.6.

2.4.2. Equipment

The implementation of IMRT requires substantial investment in material and manpower and can be associated with extra major capital expenditure. IMRT requires a controlled and adequate environment, regular preventive maintenance and engineering support. Given the complexity of the technique and its associated costs, it is mandatory that the primary focus of implementing such a program is not only related to the potential clinical benefit patients may receive from it but also to its impact on the institution as well. Thus a comprehensive budget plan needs to be properly elaborated and fully discussed by the IMRT committee. The budget must include capital costs for equipment, additional shielding (if necessary), new staff, training, spare parts and maintenance. Apart from the material costs for the acquisition of relatively expensive equipment, there will be changes in patient scheduling, as well as an increase in the time for preparation for the IMRT procedure and treatment delivery. All of these may cause a negative impact on patient flow that will affect the department as a whole (physicians, dosimetrists, therapists and physicists).

Appendix B provides indicative equipment costs. These costs do not include the costs associated with linac bunkers. In addition, because the beam-on time is greater with IMRT, the shielding necessary for leakage radiation will be greater than for standard therapy and this may require some modifications to the shielding [2.29].

While it is easier to carry out IMRT with a linear accelerator and a MLC, these are not essential. Adequate IMRT treatments can be achieved using solid compensators fabricated with a milling machine and this technique is equally suited to cobalt-60 therapy [2.30].

2.4.3. IMRT process

The process of IMRT includes patient immobilization, 3-D imaging, inverse planning, leaf sequencing, plan verification, patient setup verification, and treatment delivery. IMRT requires more stringent tolerance limits for patient immobilization than 3-D CRT. This is because IMRT treatment delivery may take a longer time, thus increasing the potential for intra-fraction patient motion. Moreover, the computer optimization process in inverse planning depends on the accurate delineation of target volume and critical structures, and their spatial integrity relative to each other. In inverse planning, the clinical objectives are described mathematically and a computer optimization algorithm is used to determine optimal beam intensities that lead to the desired conformal dose distribution.

The complexity of radiotherapy is constantly increasing and involves many groups of professionals. IMRT is significantly more complex than 3-D CRT, delivering very conformal dose distributions to the target with sometimes sharp dose gradients. Special attention is needed by the different radiotherapy staff members to the different steps involved towards treatment such as: image acquisition, patient positioning, equipment and patient QA, etc. Moreover, from a dosimetric point of view this technique utilizes dose depositions obtained by small field sizes (SMLC) or dynamic field sizes (DMLC), requiring a careful analysis of the dosimetry data and sometimes specific dosimetry equipment. Overall, IMRT is an integrated process that uses very sophisticated equipment and methods, requiring sufficient staff with specialized training and education before its clinical implementation. Responsibilities are shared between the different disciplines and must be clearly identified and defined. Each group has an important part in achieving the output of the entire process; their specific QA roles, as well as and their overall roles are interdependent, requiring close cooperation. The training requirements for all staff groups are considered in Section 2.6.

2.4.4. Resource requirements for IMRT

IMRT is an evolving technology. In order to ensure that IMRT services consistently meet the highest clinical standards, each institution must invest in a comprehensive QA program for IMRT planning and delivery. Besides a large initial investment in the IMRT hardware and software, adequate qualified personnel resources are necessary for the initial commissioning and ongoing QA of IMRT systems. Current estimates of additional resources necessary for the implementation and maintenance of an IMRT program (40 IMRT patients out of a total of 300 patients treated per year on a single machine) are 550 hours, which includes the following: 100 additional hours for machine QA, 50 additional hours for treatment planning QA, 200 hours for patient-specific QA, and 200 additional hours for IMRT treatment planning. It should also be noted that IMRT decreases the daily throughput on a machine. The maximum machine workload is expected to go down from 32 to 27 patients per day (8-hour shift). Also, the machine uptime may go down from 99% to 95% due to more wear and tear of delivery equipment hardware and complexity of the control software.

2.5. CLINICAL IMPLEMENTATION OF IMRT

2.5.1. Patient assessment and decision to treat with radiation

The clinical and dosimetric advantages detailed in Section 2.2 suggest that patients likely to benefit from IMRT are, for example:

- Patients with head and neck cancer in whom conventional radiotherapy would encompass the majority of both parotid glands; patients with tumours near the base of skull, whose irradiation would deliver a high dose to the optic pathways; and patients requiring re-irradiation, where IMRT may facilitate an avoidance of critical structure, like the spinal cord
- Patients with prostate cancer in whom a dose of >76 Gy is considered
- Patients with gynaecologic tumours requiring extended field radiotherapy, especially when concurrent with chemotherapy
- In pediatric patients, for cochlea sparing in the treatment of medulloblastoma, and in other similar situations. However, these advantages need to be balanced with the theoretical risk of a higher rate of future second malignancies, which may be associated with the higher tissue volume receiving a low dose in IMRT compared with 3-D CRT.

2.5.2. Definition of the target volume

The dosimetric advantages of IMRT need to be balanced with the potential pitfalls related to the production of tight dose distributions around the targets. The most important issue is the reliability and reproducibility of outlining the targets. For the purposes of treatment planning, the targets are outlined on a CT scan obtained while the patient lies in the exact position required for treatment. The GTV is outlined on the treatment planning CT scan using clinical and radiological information. In many sites, CT is not the best imaging modality for the definition of the extent of the macroscopic tumour. MRI is superior to CT in delineating brain tumours, head and neck tumours near the base of skull and pelvic tumours, for example. PET may be superior to CT in defining the extent of lung cancer [2.31], and studies of its utility relative to CT/MRI in other sites are ongoing.

Future improvements in the anatomic and metabolic imaging of tumours are expected to improve the uncertainties in outlining the GTV for determining the volume receiving high radiation doses. However, the definition and outlining of the tissue volumes at risk of harbouring sub clinical disease (clinical target volumes or CTVs) depends on clinical judgment alone. It is not surprising, therefore, that large inter-observer differences have been noted in outlining these volumes [2.32], [2.33]. The uncertainties in outlining the target volumes raise concerns about the potential of highly conformal radiotherapy to miss disease while striving to spare organs adjacent to the targets. Anatomical guidelines to help proper definition of volumes-at-risk for sub-clinical disease are available for head and neck cancer [2.34], [2.35] breast cancer [2.36], gynaecological cancer and other sites [2.37].

Additional factors confounding treatment based on a single pre-therapy planning CT scan are inter- and intra-fraction set-up uncertainties and organ and tumour movement. These include, for example, chest motion due to breathing, daily variations in rectal and bladder filling and motion due to swallowing during therapy. (Bortfeld et al [2.38] have argued that these movement problems even out if multiple fractions are used.) These issues may be addressed by increasing planning target volumes (PTVs) to accommodate uncertainties and tumour movement. However, larger PTVs reduce the ability of IMRT to spare neighbouring tissues. Recently, techniques like controlled breathing, gating treatment to a specific breathing cycle, reducing variations in rectal volume with the help of an intrarectal balloon, and tracking tumour movement, especially in prostate cancer via implanted seeds, to adapt radiotherapy to the daily changing position of the target, are currently being investigated. Another important issue is the possible change in tumour volume and position relative to organs-at-risk, like the parotid glands, during the course of radiation therapy for head and neck cancer [2.39]. It is not clear yet which strategy should be employed to best accommodate these changes and they currently remain subjects for clinical research

2.5.3. IMRT treatment planning requirements

The non-uniform beam intensities in IMRT are determined by various computer-based optimization techniques driven by clinically defined planning objectives and constraints. IMRT dose distributions are calculated by dividing each beam into smaller sections, called beamlets that can have varying intensities. Since these beamlets can be very small in size, typically 1 cm x 1 cm, a small error in the size of the beamlet can result in a large change in the radiation output. Accurate modelling of

beam parameters such as transmission through the collimators, penumbra, and dose outside the field is much more significant for IMRT than for 3-D CRT. The accuracy with which the planned intensity distribution is reproduced on a delivery system depends on parameters such as collimator transmission, shape and size of the leaves, interleaf leakage, and mechanical limitations on the motion of the MLC. Idealized intensity patterns are almost never delivered exactly. IMRT treatment planning systems are also different in that the commissioning and QA process must include determining the effect of the input parameters on the optimized dose distribution. There are currently no established criteria for testing the quality and acceptability of the dose distributions produced by automated optimization. It is expected that a standard set of phantoms with defined geometries and planning objectives will enable meaningful comparison between different IMRT planning systems and the development of criteria for acceptance testing, commissioning and QA.

2.5.4. The class solution concept

The design of an IMRT treatment plan can be very time consuming, especially, if for every patient, one were to start from scratch. In order to facilitate the more rapid development of treatment plans the concept of the class solution has been developed. For particular common situations, such as the treatment of prostate cancer, a set of beam orientations together with dose objectives are developed that can be used for many patients [2.40]. An advantage of this approach is that considerable effort can be applied to the development of the class solution and subsequent individual patient plans are then much quicker. It also gives the opportunity to check that there are no particular problems with the delivery of the class solution.

2.5.5. Intensity modulation

Intensity modulated distributions cannot be delivered directly by the IMRT delivery systems. They are first converted into an MLC leaf sequence. The leaf sequencing algorithms need to account for the mechanical limitations of the delivery system, beamlet size, leaf end leakage, leaf transmission, and leaf travel. Each one of these parameters has tolerance limits that impact the overall accuracy of the beam intensity delivery. The non-intuitive nature of the beam intensity patterns makes it necessary to verify each IMRT treatment plan on a hybrid phantom. The sharp dose gradients in IMRT warrant much tighter tolerance limits in the verification of patient set up for treatment delivery. Finally, the accuracy of IMRT delivery depends on the mechanical accuracy and integrity of the MLC system. IMRT places much greater mechanical demands on the MLC and can result in accelerated wear and tear of the system. Therefore, periodic QA test procedures with appropriate tolerance limits and action levels are crucial in the planning and delivery of IMRT. The most comprehensive guidance to date on IMRT QA, tolerance limits, and action levels for planning and delivery of IMRT can be found in the American Association of Physicists in Medicine (AAPM) summer school proceedings [2.3].

2.5.6. IMRT treatment delivery

The three most important characteristics of the MLC-based IMRT delivery system include: mechanical integrity of the delivery system, precise spatial and temporal positioning of the MLC system and radiation beam fidelity for small number of monitor units (MUs). The mechanical demands on the delivery system components, especially the MLC system, are an order of magnitude more for IMRT than the 3-D CRT. The wear and tear of the mechanical system may also be accelerated. Therefore, special QA tests are required in addition to those necessary for 3-D CRT using an MLC, to ensure the delivery system continues to meet the functional performance specifications. It is important to recognize that both the hardware and software control of the current IMRT delivery systems are relatively new and the potential for error is not completely understood at this time. Therefore, the testing of the IMRT delivery system needs to be more comprehensive and more frequent until it can be demonstrated with extended monitoring that a given parameter does not change over a period of time. The component of the IMRT delivery system requiring the most vigilance at this time is the MLC system. The MLC performance characteristics that require continuous monitoring include the following:

- the leaf position accuracy and reproducibility
- the leaf gap width reproducibility
- the leaf speed accuracy.

There are a number of IMRT delivery techniques. Techniques in which the gantry rotates while the radiation beam is delivered include Tomotherapy with a binary MLC modulating the beam from a 6 MV linear accelerator mounted on a CT scanner type gantry and IMAT (Intensity Modulated Arc Therapy) which can be carried out with a conventional linear accelerator. More widely used at present are techniques in which the linear accelerator gantry moves to a number of fixed beam orientations. In each of these an intensity modulated beam is delivered either with a “step-and-shoot” system (in which a number of shaped field segments are delivered sequentially with the beam turned off between segments) and DMLC techniques in which the leaves are moved continuously with the beam on while the gap between the leaves changes in such a way as to deliver the desired intensity modulated field. All the IMRT delivery techniques require a computer-controlled linear accelerator with a fast-responding control system, which precisely synchronizes the motion of the intensity modulation subsystem (MLC or binary collimator) and the radiation output from the accelerator.

Sharp dose gradients, which are typical of an IMRT delivery, mandate better mechanical accuracy of the delivery equipment to realize its full clinical potential. Both the SMLC- and the DMLC-IMRT delivery techniques have relatively small gaps between opposed leaves while the radiation is delivered at each gantry position. The radiation output for small gap widths is very sensitive to the size of the gap width, which changes the magnitude of the extra-focal radiation. In addition, leaves shield most regions most of the time during radiation delivery. Therefore, the delivered dose is very sensitive to the transmission through the leaves and the rounded leaf ends. The requirements for MLC positional accuracy are more stringent for DMLC than for step-and-shoot because the gap between the opposing leaves tends to be much smaller for DMLC delivery. A variation of ± 0.2 mm in gap width for a 1.0 cm nominal gap can result in a dose variation of $\pm 3\%$ for each DMLC field. Other factors impacting the accuracy of dynamic IMRT delivery include leaf speed, dose rate of the linear accelerator, and, for step-and-shoot, the fidelity of the delivery control system for small numbers of MU at high-dose rates. The accuracy of dose output and beam stability for small MU cannot be overlooked in IMRT because a large fraction of the total MU for each IMRT field is delivered with field segments that have a very small number of MU.

2.5.7. Individual patient quality assurance of IMRT

The QA for 3-D CRT planning and delivery typically relies on the performance evaluation of individual parameters of the system only. It is not necessary to perform patient-specific QA except when a clinical situation warrants the monitoring of dose to a specific area of interest with in-vivo dosimeters. This assumes that once the system is properly commissioned, the periodic QA checks of the subsystems will guarantee that all patients are treated with accuracy that is within the limits of established QA criteria. For IMRT, the traditional QA is not sufficient. It is very difficult to anticipate all likely problems in IMRT. There is little correlation between the MU and the delivered dose from each intensity-modulated field. Therefore, direct measurements are commonly made of a “hybrid plan” which is generated by applying the intensity-modulated field from a patient plan to a CT study of a geometric phantom. The computed dose distributions are then compared with the measured dose distributions with either a film or a diode array device. Often, an ion chamber is also used to measure the dose in a high-dose, low-dose-gradient region in the phantom. One must recognize that the patient-specific QA is only a check of the dose calculation and delivery systems. It does not tell anything about the accuracy with which the patient receives an IMRT treatment. The accuracy of the patient treatment is strongly dependent on the accuracy of patient positioning, internal organ motion, and the presence of heterogeneities. Once a large number of patients have been treated using a particular class solution it may be appropriate to omit the individual patient measurements in favour of regular quality control (QC) of a standard IMRT patient [2.41]. However, whenever a radically different plan is done, individual QC is essential.

2.5.8. Sources of error in the IMRT process

The IMRT process as described previously has multiple steps with a potential to incur in small errors at each step along the way. Most of the treatment delivery errors occur to a different extent for each treatment fraction and are classified as *random* errors. There are other errors such as organ motion that can occur both during imaging for treatment planning and treatment delivery. The errors that occur only during treatment planning are classified as *systematic* errors. It should be noted that the systematic errors are the most significant in terms of undesirable clinical outcome in IMRT. It is generally believed that the total error in clinical practice of IMRT has a normal distribution and that errors in each step can be added quadratically. The total error can then be obtained by adding the standard deviations of each error in quadrature. It is quite obvious that the overall error is dominated by the error in a step with the largest magnitude. Therefore, every attempt should be made to reduce that error. Errors cannot be eliminated completely and the only way to account for errors without compromising a positive clinical outcome is to select margins around the clinical target volumes and organs at risk judiciously.

The error analysis should be done for each disease site specifically because, as described earlier, the internal organ motion and target delineation uncertainties can vary from site to site and each one of these has a much greater impact on the overall uncertainty. The impact of the spatial uncertainties on delivered dose to a patient depends strongly on the local dose gradients of isodose distributions. Therefore, it is fairly easy to convert spatial uncertainties into dose uncertainties. One other parameter that can impact the overall uncertainty is the target and critical structure delineation. Several studies have shown that physician-to-physician variability in target delineation can also be significant. Having explicit delineation protocols, adequate training, and frequent consultations with the diagnostic imaging experts can reduce the uncertainties in target and critical structure delineation.

2.5.9. Quality assurance and quality control in the IMRT process

A quality system is the organizational structure, responsibilities, procedures, processes and resources required for implementing quality management. In respect to such a quality system in radiotherapy, a QA committee must be appointed. This committee is composed as an integrated team from all groups of staff involved in the process, including radiation oncologists, medical physicists, radiotherapy technologists, dosimetrists, service engineers, etc., as all areas of the process should be covered. Also, for a new IMRT program the establishment of an IMRT quality team is mandatory. The team members should consist of representatives from the above groups and certainly should as a minimum include a radiation oncologist, a medical physicist and a radiation therapist. Each member should be clear about his or her responsibilities and be adequately trained to perform them, and should also know which actions are to be taken in the event that any result is observed outside the limits of the established acceptance criteria. As a group, they are responsible for the establishment and implementation of the present guidelines and should report to the QA committee of the radiotherapy department.

2.6. TRAINING REQUIREMENTS FOR IMRT

Each staff member must have qualifications (education, training and experience) in respect to his or her role and responsibility, and have access to appropriate opportunities for continuing education and development. QA programs for IMRT will require a great effort of all team members and consequently require significant human resources. Therefore all centres introducing IMRT should review their staffing needs and foresee at least one specifically trained staff member for the professions listed below.

Although the nomenclature of the different professionals can be different for different countries, the following list of radiotherapy team members is essential for the initiation of an IMRT programme.

2.6.1. Radiation oncologists

Radiation oncologists are clinicians, almost always certified (or accredited) in the speciality of radiation oncology by recognized national boards and are at least responsible for:

- Consultations;
- Assessment of the appropriateness of the use of IMRT for the individual patients;
- Dose prescriptions;
- On-treatment supervision and evaluations, supportive management during the IMRT;
- Treatment summary reports;
- Follow-up monitoring and evaluation of treatment outcome including assessment of acute and late morbidity.

IMRT starts from a different principle than 3-D CRT with respect to optimization of the treatment plan. At the start, the planning goals and objectives must be defined and dose constraints must be given to the different volumes (PTV, OAR). The use of an inverse optimization tool requires a learning process for the radiation oncologist in order to adjust the different optimization parameters to obtain the best acceptable solution with respect to the objectives. IMRT requires full 3-D information with respect to volumes. While this is also the case for 3-D CRT, IMRT will be used in more critical cases where tumours are in the proximity of or surrounded by critical structures. Experience with 3-D CRT is a prerequisite for starting IMRT allowing the radiation oncologist to build up experience at the level of 3-D image interpretation. Several imaging techniques are used in IMRT to obtain the most precise information on the anatomy and treatment region. Not only CT and anatomy atlases are used but also new imaging techniques such as MRI, functional MRI and PET. Registration of the images obtained by these different techniques plays a very important role. This registration can be rigid or non-rigid, introducing 3-D segmentation methods for automatic registration. The training of the radiation oncologist must focus on these different imaging and registration techniques in order to be capable of evaluating the clinical impact of all these methods used for delineation of the target and critical structures.

IMRT will produce treatment plans with high dose gradients and sometimes less homogeneous dose distributions in the target. In addition, the application of slightly adapted fractionation schedules and the understanding of biological equivalent dose concepts are a matter of concern in IMRT. The radiation oncologist must critically evaluate the impact of these issues on outcome and tissue tolerances.

Training of the radiation oncologist with respect to the above concepts is essential before the start of an IMRT program. This training can be obtained at specialized workshops and/or IMRT scientific meetings but also at specialized courses organized by the equipment supplier.

2.6.2. Medical physicists

Medical physicists (or radiation oncology physicists, clinical physicists) are specialists who in many countries are certified by a recognized national board. They are generally responsible for:

- Specification, acceptance, commissioning, calibration and QA of all radiotherapy equipment;
- Measurement of beam data;
- Calculation procedures for the determination and verification of patient doses;
- The physics content of treatment planning and patient treatment plans;
- Supervision of therapy equipment maintenance, safety and performance;
- Establishment and review of QA procedures;
- Radiation safety and radiation protection in the radiotherapy department.

In view of these responsibilities, the introduction of IMRT is very challenging for the medical physicist who also plays a more direct and significant role in the preparation of the treatment plan (e.g. commissioning, treatment planning and QA of equipment and treatment plans). IMRT requires a much higher level of QA (both at the machine level and at the patient level) than 3-D CRT. The whole infrastructure for IMRT (e.g. treatment equipment and dosimetry equipment, treatment planning and associated algorithms, positioning devices and R&V systems, etc.) is required to be at a very high

technological standard. Vigilance is needed both during the acceptance and commissioning process and during the quality control process. Tests should be performed following well established protocols applying recommended tolerances and frequencies. The medical physicist must therefore have experience with MLCs and their respective quality control procedures. The testing regime should include MLC positioning precision, MLC control software and its integration with the linac control software and the data transmission from the original CT scan right through to treatment delivery.

Optimization and treatment planning algorithms are an essential part of the IMRT process. Medical physicists must acquire a profound understanding of the role played by the different constraints on the volumes during the optimization process as well as of the mathematical and physical principles involved in 3-D dose calculation and beam modelling. This is important during the treatment planning commissioning which should include several special issues for IMRT such as:

- small field size and low MU delivery and calculations,
- the effect of heterogeneity corrections,
- the effect of interfaces and lack of dose equilibrium,
- absolute and relative dose measurements in small fields, modulated fields, dynamic fields and high dose gradients.

Quality assurance for IMRT not only includes quality control (QC) at the level of the equipment (machine output and treatment planning) but also at the patient level. Medical physicists should be familiar with the recommendations for patient-specific QC procedures that are part of the quality control process of IMRT.

The use of 3-D treatment techniques needs also experience with 3-D image acquisition and transfer. In radiology, the communication protocol allowing image transfer is called DICOM (Digital Imaging and Communications in Medicine). For radiotherapy this protocol has been extended to include the transfer of structures and dose volumes. (This extension of the DICOM protocol is called DICOM-RT). This protocol plays a very important role during image and contour transfer both from the imaging device to the planning computer and then, to the treatment unit. All treatment parameters determined during the planning process must be accurately transferred to the treatment unit using DICOM-RT. (In some instances company specific protocols are used instead). Sometimes when the different systems (treatment planning, optimization, linac, Record and Verification (R&V) system) are made by different companies, there can be conflicts of interpretation of the DICOM standard, producing connectivity problems. The medical physicist together with the field engineer must be able to install and interpret these protocols during the commissioning and quality control phase.

It is especially important that training of the medical physicist takes place before the start of the IMRT program, because the physicist has an important role in the acceptance and commissioning of the equipment. This training can be obtained either from courses organized by the equipment supplier or from training courses in the form of IMRT workshops or scientific meetings.

2.6.3. Treatment planning staff

Depending on the national arrangements treatment planning may be carried out variously by physicists, dosimetrists, medical physics technicians or technologists, radiation dosimetry technicians or technologists, radiotherapy technologists or therapy radiographers. In what follows the term “dosimetrist” is used for all such staff. Whatever the background of the IMRT planner is, special training is needed. This includes experience in 3-D image acquisition, use of MLCs, IMRT application of R&V systems and 3-D treatment planning including optimization techniques and QA techniques. Dosimetrists may be involved in machine calibrations and regular equipment QA under the supervision of a medical physicist and may construct immobilization and other treatment devices. The tasks of these staff may include:

- accurate patient data acquisition;
- radiotherapy treatment planning;
- dose calculations and verifications;
- patient measurements.

Like medical physicists, dosimetrists need to understand the special requirements of IMRT planning (e.g. dose constraints and optimization methods) and the implications of exact positioning for treatment accuracy. Dosimetrists can also contribute to patient specific quality control. When IMRT is used, there is less requirement for beam shaping devices. Dosimetrists can best be trained on site by medical physicists or the equipment supplier.

2.6.4. Radiation therapy technologists

Radiation therapy technologists (RTTs) — sometimes referred to as radiation therapists, therapy radiographers, radiation therapy technologists, radiotherapy nurses — are responsible for:

- clinical operation of simulators, CT scanners, treatment units;
- accurate patient set-up and delivery of a planned course of radiation therapy prescribed by a radiation oncologist;
- documenting treatment and observing the clinical progress of the patient and any signs of complications;

RTTs may also often be involved in:

- treatment planning;
- construction of immobilization devices;
- imaging for treatment planning.

This group plays also a vital role in the IMRT process. They are responsible for the daily correct positioning of the patient utilizing the appropriate immobilization devices. The RTTs must be familiar with routine radiotherapy treatment methods and with 3-D CRT before embarking on an IMRT program. In particular they must be familiar with patient immobilization, setup and position verification. They also need specific training in relation to the IMRT components (e.g. MLC, Linac control, R&V). Some of these are common to 3-D CRT but some, for example the linac control systems for IMRT delivery, are specific to IMRT. Most of their training can be organized on site by medical physicists or the company that installed the equipment. Some immobilization devices may also require specific training in their use.

2.6.5. Support engineers

Support engineers (service technicians, electronic engineers or electronic technicians) have specialized expertise in the electrical and mechanical maintenance of radiotherapy equipment. The increased accuracy requirements for the delivery of IMRT place a greater emphasis on regular maintenance of the equipment than is the case for 3-D CRT. Maintenance services may be in-house or via a service contract for equipment maintenance. In each case, the local support engineer must be familiar with the entire radiotherapy infrastructure and must be fully trained in all the issues relating to setting up IMRT equipment. The engineers can also fabricate specialized patient related devices and may also administer the local network. Local support engineers are mostly supervised by medical physicists. If an in-house maintenance service is to be provided it is essential that the maintenance staff receive training from the equipment supplier, although it might be appropriate for the medical physicist to receive the training and then to train the other members of the staff.

2.6.6. Administrative staff

Administrative staff in an IMRT facility take care of all project planning, organizing and other management functions. Critical issues like equipment procurement and maintenance, budgeting and financial management, human resource functions such as training and recruitment, and overall supervision of the workplace are just some of the key responsibilities of an administrator. The administrative staff ensures that the facility complies with the highest standards of safety and patient care and that the delivery of radiotherapy services is both efficient and effective.

2.7. SUMMARY OF RECOMMENDATIONS FOR THE IMPLEMENTATION OF IMRT

Intensity-modulated radiation therapy (IMRT) represents a new paradigm in radiation therapy that requires knowledge and understanding of patient immobilization, volumetric imaging, patient setup and internal organ-motion uncertainties, three-dimensional (3-D) heterogeneous dose calculation, large-scale optimization, and dynamic beam delivery of non-uniform beam fluences. IMRT practice is continuing to develop and evolve with the addition of multi-modality and functional imaging, tumour control and normal tissue complication probability modelling, and image-guidance. This new process of planning and treatment delivery shows significant potential for further improving the therapeutic ratio. It is important to understand that IMRT techniques present a set of challenges that are significantly more complex than traditional forms of radiation treatment [2.42]. These include: the following:

- IMRT requires a detailed understanding of radiographic anatomy, as well as, other developing 3- and 4-D representations of the patient in order to correctly delineate both tumour/target volume(s) and organs-at-risk (critical structures). With IMRT using inverse planning, the target must be outlined precisely or it might not be treated to the prescribed dose. More importantly, if a critical structure is not outlined, it might not be spared.
- The conformal dose distribution and high dose gradients in IMRT mandate improved patient immobilization as well as quantitative assessment of target and organ motion detection and control.
- IMRT dose distributions are often more inhomogeneous within the target than traditional conformal therapy. It has been observed that dose inhomogeneity increases:
 - as the required dose gradient between the target and an adjacent critical structure increases;
 - the concavity of the required dose distribution increases;
 - the distance between the target and a critical structure decreases;
 - and the number of available beam directions decreases.

Therefore, volume dose prescriptions are required for IMRT and prescribing dose to a single point is unacceptable.

- IMRT doses are often calculated by dividing beams into smaller sections, called sub-fields, which have varying amounts of uniform fluence. Therefore, the mechanical accuracy of the IMRT delivery system and accurate modelling of the delivery machine dosimetry characteristics, such as head scatter, penumbra, and transmission, become very important. Also, these sub-fields often have small areas and can be problematic for dose computation algorithms. Thus additional patient-specific QA tests are required.
- Accounting for heterogeneities is important for IMRT because they can affect some sub-fields more than others, giving rise to localized dose differences in distribution that may be significant.
- IMRT plan evaluation requires more diligence than does traditional 3-D CRT planning.
- IMRT can create cold spots or hot spots in unexpected locations, which are not easily appreciated on DVHs. IMRT plan evaluation requires inspection of isodose distributions on each image slice.
- Respiratory motion can cause far more problems for IMRT treatments than for traditional treatments. The effect of breathing motion and other patient motions can be significant for the summation of sub-fields with different intensities calculated based on a static image. Care must be taken in the acquisition of the CT dataset used in the planning process to avoid motion artefacts while being representative of the average location of the anatomy.
- The expansion of target contours in 3-D to account for uncertainties in treatment planning and delivery may result in the overlap of two or more structures. In some commercial systems, this creates problems in inverse-planning optimization and in storage of the original structure contours. Expansion into air or into the build-up region may also cause problems.

- IMRT plans that allow simultaneous treatment of gross and sub-clinical disease at different doses per fraction can have radiobiological consequences that differ from those of traditional plans delivered with a uniform dose-per-fraction. The longer treatment times typical of some IMRT treatments may also be radiobiologically relevant [2.43].
- IMRT results in a higher whole-body dose due to leakage radiation because IMRT plans often require substantially more monitor units (MU) to deliver the prescribed dose.

Currently, most published reports on the clinical use of IMRT are single institution studies, and are either treatment planning studies for a limited number of cases showing the improvement in dose distributions generated by IMRT, or dosimetric studies confirming IMRT treatment. There are no published reports at present of prospective randomized clinical studies comparing the efficacy of IMRT to traditional treatment, and this lack of information clearly limits our knowledge of the impact of the use of IMRT on clinical outcomes. It is clear that IMRT offers the opportunity of more conformal dose distributions and for increasing the daily treatment dose to the target volume with a decreased dose to normal tissues. Although most agree with these potential advantages in physical dose distribution with IMRT, and therefore the potential for improvement in patient outcomes, there exists concern for actual IMRT treatment execution, including proper plan optimization, as optimization algorithms and QA procedures for this new modality are still evolving. The Radiological Physics Center has reported that over 30% of centres wishing to enter clinical trials involving IMRT in the USA did not initially meet the QA criteria [2.44]. Specific concerns include the potential to miss the tumour (or at least underdose a portion of the tumour) and/or to have significant high dose volumes in the normal tissues. There is also the additional concern that the widespread use of IMRT could lead to an increased incidence of radiation therapy associated carcinomas due to the larger volume of normal tissue exposed to low doses and the increase in whole body doses as a result of the increased MU required for the delivery of IMRT. This may be especially important in the pediatric and young adult patient populations.

Specifying and planning a dose distribution that provides a high dose to the target volume and a lower dose to organs-at-risk requires careful accounting for geometric uncertainties when IMRT is used. The reality is that over the course of treatment, the patient's target volume will vary from the geometry captured at the initial imaging study for treatment planning, due to organ movements and daily patient setup variations, as well as possible changes in both the patient's physical dimensions and the tumour volume over the course of the radiation therapy. In such situations, the physician must evaluate a computed dose distribution based on a patient image that can be substantially different from the dose distribution actually delivered. In addition, one must fully appreciate that IMRT, depending on how it is implemented, can be "less forgiving" than conventional radiation therapy in regard to the effects resulting from geometric uncertainties. IMRT dose distributions are shaped to conform more closely to the tumour volume and avoid normal tissues, introducing large gradients near the perimeter of both the target volume and normal structures. Also, because IMRT techniques (unlike conventional 3-D CRT) treat only a portion of the target volume at a particular time, there is the potential for significant dosimetric consequences if the patient and/or the target volume move during treatment (known as intra-fraction geometric uncertainties). Respiratory-related excursions of a target volume could potentially cause the tumour to be grossly under-dosed despite an apparently satisfactory dose distribution in a static plan. Furthermore, since IMRT treatments typically take longer than conventional radiation therapy treatments, the patient must remain in a fixed position for a longer period of time, increasing the vulnerability to intra-fraction geometric uncertainties. Hence, it is clear that IMRT imposes more stringent requirements than conventional radiation therapy requiring an accounting for both intra-fraction and inter-fraction patient position variations and organ motions.

In summary, it is apparent that comprehensive QA is vital for the safe practice of IMRT due to the high dose gradients and non-intuitive nature of the treatment planning. It is not guaranteed that all institutions that may wish to use IMRT in a routine practice perform adequate QA.

Taking the above into account the following recommendations are made:

- (1) The introduction of IMRT should not be allowed to compromise standard care provided to the whole population of patients in the institution and at the national level.

- (2) Only radiation oncology departments that have sufficient experience with 3-D CRT are in a position to transition to IMRT.
- (3) Adequate training in IMRT technology for all members of the team is essential prior to the initiation of the program. Ideally, the team members are best trained on equipment that they plan to use for IMRT in their department.

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APPENDIX A

SELF ASSESSMENT QUESTIONNAIRE

This questionnaire is designed to assist centres that plan to embark on a programme of 3-D conformal radiotherapy to check that they have all the necessary requirements. By the time the first patient is to be treated the answers to all the questions should be “Yes”. Where gaps are identified they will need to be corrected. The questionnaire begins with the staffing and equipment requirements and then looks at the process of conformal radiotherapy planning and treatment to identify the issues that need to be addressed. Items indicated with an asterisk (*) are optional for 3-D CRT. Questions 50-62 cover additional issues required for IMRT, for which the items marked with an asterisk should be regarded as essential.

STAFFING

- (1) Do you have a radiation oncologist who is trained and experienced in the practice of conventional radiotherapy?
- (2) Does the radiation oncologist have the academic knowledge necessary for 3-D CRT:
 - Cross sectional anatomy, surface and radiological anatomy
 - Target volumes and critical structures
 - Dose response data
 - Understanding of beam shaping methodologies – leaf fitting
 - Linear accelerators, basic understanding especially choice of energy, choice of modality
 - Immobilization methods for CRT
- (3) Has the radiation oncologist had practical training in contouring of target volumes and critical structures?
- (4) Is the radiation oncologist (or a radiologist who has time available) familiar with CT scanning procedures?
- (5) Has the radiation oncologist had practical training in the operation of the RTPS for contouring, image registration*, treatment planning, BEV planning for MLCs (or customized blocks)?
- (6) Do you have a medical physicist who is trained and experienced in the practice of conventional radiotherapy?
- (7) Has the medical physicist the academic knowledge necessary for 3-D CRT:
 - Basic understanding of cross sectional anatomy, surface and radiological anatomy as it relates to radiotherapy planning and understanding of treatment plans;
 - Target volumes and critical structures
 - Dose response data
 - Understanding of beam shaping methodologies – MLC and customized blocks
 - Understanding of Linear accelerator concepts, commissioning and acceptance of linacs
 - Portal imaging systems
 - Random and systematic errors in radiotherapy treatment
 - In-vivo dosimetry
 - QC for MLCs, portal imaging, in-vivo dosimetry

- Commissioning and acceptance of a image-based 3-D RTPS
 - Immobilization methods for CRT
 - QC of CT (and MR*) scanners especially in relation to geometry and Hounsfield units
- (8) Has the medical physicist had practical training in contouring of critical structures?
- (9) Has the Medical Physicist had practical training in the operation of the RTPS for beam data modelling, contouring, image registration*, treatment planning, BEV planning for MLCs (or customized blocks)?
- (10) Has the medical physicist had practical training in QC for CRT?
- (11) Do other treatment planning personnel have the academic knowledge necessary for 3-D CRT:
- Basic understanding of cross sectional anatomy, surface and radiological anatomy as it relates to radiotherapy planning and understanding of treatment plans;
 - Target volumes and critical structures
 - Understanding of beam shaping methodologies – leaf fitting methodologies
 - Immobilization methods for CRT
 - Basic understanding of the physics of treatment planning dose calculation
- (12) Have other treatment planning personnel had practical training in planning 3-D-CRT?
- (13) Is there a medical physicist (or other IT expert) with knowledge of networking and DICOM protocols?
- (14) Are there sufficient RTTs trained and experienced in conventional radiotherapy treatment to cope with the workload?
- (15) Are the RTTs trained and experienced in the additional requirements for 3-D CRT:
- Basic understanding of cross sectional anatomy, surface and radiological anatomy as it relates to radiotherapy planning and understanding of treatment plans;
 - Immobilization techniques
 - Portal imaging and registration techniques
 - MLC operation
 - Daily QC for MLCs
 - R&V systems
 - CT operation for radiotherapy planning

EQUIPMENT

- (16) Is there a CT scanner with a flat top couch and alignment lasers suitable for radiotherapy planning with time available?
- (17) Is there a linear accelerator with an MLC (or block cutting facilities)?
- (18) Is there an electronic portal imaging system available on the linear accelerator (or facilities for portal films)?
- (19) Is there an image-based TPS with sufficient spare capacity, which is capable of the following:
- 3-D display
 - 3-D dose calculation
 - BEV display with facility for field shape design

- Dealing with many CT slices
 - Image fusion*
 - DVH calculation and display;
 - Non-coplanar beams including display, inhomogeneity correction, DRRs, and DRR export
- (20) Is there a Record and Verification system with a networked connection to the RTPS and CT scanner?
- (21) Is there appropriate measurement equipment in addition to that required in IAEA-TECDOC-1040
- Dose plotting tank with detectors
 - Anthropomorphic phantom
- (22) Is there an appropriate immobilization system for all relevant disease sites?

COMMISSIONING PROCEDURES

- (23) Have measurements of geometric accuracy been made on the linear accelerator to demonstrate that conformal treatment fields can be delivered accurately?
- (24) Has a check of the CT scanner geometric and CT number accuracy been carried out?
- (25) Have the appropriate parameters been entered into the RTPS physics database to ensure that the MLC (or blocking system) parameters (e.g. transmission factors and position in space) are taken into consideration?
- (26) Has the dose calculation for MLC (or block) shaped fields been verified in terms of its geometric and dosimetric accuracy?
- (27) Is there a system in place to ensure that an independent check calculation of the dose delivered by a treatment plan for the given monitor units is carried out before each patient treatment course? Has it been verified that this system is using an independent algorithm and can correctly calculate the dose for a simple shaped field on a phantom to better than 2% accuracy at a non standard SSD and field size?
- (28) Have all the network connections been set up and have the transfer protocols been verified for accuracy using realistic data?
- (29) Have dose volume histogram algorithms been tested?

3-D CRT PLANNING AND TREATMENT PROCESS

CT scanner

- (30) Is a system for identifying skin marks (e.g. isocentre indication) on CT scans (and for the establishment and marking of the isocentre*) in place?
- (31) Is there a system in place for geometric QC of the CT scanner in place and is the CT scanner geometry within 1 mm?
- (32) Has the CT number to relative electron density conversion been measured and the results input to the TPS translation table?
- (33) Has the CT scanner couch deflection under load as defined by the IEC been measured and is it <5 mm?

- (34) Has electronic transfer from the CT scanner to the RTPS been established and the results of the data transfer been verified (for geometric and CT number accuracy).

MR scanner*

- (35) Has electronic transfer from the MR scanner to the RTPS been established and the results of the data transfer been verified (for geometric and CT number accuracy)?
- (36) Is a system for image registration of MR and CT scans in place?

Target and Normal Tissue Segmentation

- (37) Has a protocol been written to cover the definition of the GTV, CTV and ITV?
- (38) Has a protocol been written to cover the definition of normal tissue structures including the identification of staff authorised to carry this out?
- (39) Has an audit been carried out to establish the magnitude of setup uncertainties (both random and systematic) and is it established that setup within 5 mm can be achieved?
- (40) Has a protocol been written to cover the volume growing procedures from GTV/CTV to PTV and of OARs to PRVs and are the margins based on the audit of setup uncertainties?

Treatment Planning

- (41) Has QA involving phantom measurements of planned shaped fields been carried out on the RTPS to verify that dose calculations for MLC (or blocked) fields are carried out accurately both geometrically and dosimetrically?
- (42) Are appropriate treatment planning protocols in place giving details of appropriate techniques (including beam energies) and dose calculation algorithms, including specification of inhomogeneity correction policies, for particular sites?
- (43) Has a policy been established regarding leaf fitting methodologies for MLCs including when and how to make manual adjustments of automated field shaping?
- (44) Have dose prescription protocols for all the relevant sites been produced and do they include dose constraints for normal tissues?
- (45) Is there a protocol in place for the evaluation of treatment plans, including 3-D visualisation of the target volumes compared to the calculated doses and DVH analysis?

Patient Treatment

- (46) Is there a tested protocol for the transfer of patient data from the planning system to the treatment machine verification system and have appropriate responsibilities for the data accuracy and integrity been assigned to the relevant personnel?
- (47) Has a system been set up for the checking of the individual patient field shape against a printed template of the treatment fields to check that the correct patient and plan data are in place?
- (48) Is there a portal imaging verification protocol in place that takes appropriate account of the effects of random and systematic errors?
- (49) Is there a system in place for carrying out beam entry in-vivo dosimetry on one fraction for every patient and for evaluation of the results?

IMRT specific issues

- (50) Are items marked with an asterisk in questions 1 – 49 available?
- (51) Have all groups of staff had at least one year experience in the planning and delivery of 3-D CRT?
- (52) Has an IMRT committee been established to oversee the introduction of IMRT?
- (53) Are there sufficient radiation oncology, medical physics and RTT staff to ensure that the introduction of IMRT does not compromise other radiotherapy treatment including 3-D CRT?
- (54) Are there satisfactory service support arrangements to ensure that the MLC can be maintained at the required level of accuracy?
- (55) Have all groups of staff had additional training in the planning and delivery of IMRT?
- (56) Is there a 3-D dosimetry system available (e.g. using film) and are anthropomorphic phantoms available for IMRT verification?
- (57) Have QC measurements been made on the linear accelerators to ensure that the MLC is set up to the required higher level of accuracy?
- (58) Has a system of dose constraints for different organs-at-risk been established?
- (59) Have class solutions been developed for the anatomical sites to be treated and have the dose distributions been compared to those obtained using 3-D CRT?
- (60) Have phantom measurements been made to verify the accuracy of IMRT including geometric accuracy in three dimensions?
- (61) Have tests been carried out to ensure that the R & V system is reliable when delivering IMRT beams?
- (62) Have tests been carried out to ensure that if an IMRT beam is interrupted, the treatment can be completed accurately?

APPENDIX B PROCESS DETAILS FOR THE DELIVERY OF CONFORMAL THERAPY IN HEAD AND NECK CANCER

A flowchart given in Section 1.5 (Figure 1) shows the steps of a typical 3D-CRT process. This Appendix is designed to illustrate details of the different steps for the delivery of 3-D CRT in head and neck cancer. It should be understood that these details may vary from one institution to another and are presented here as an example.

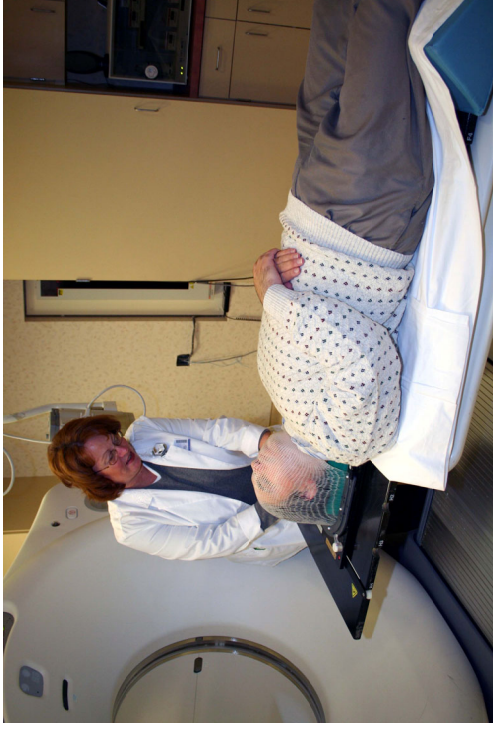
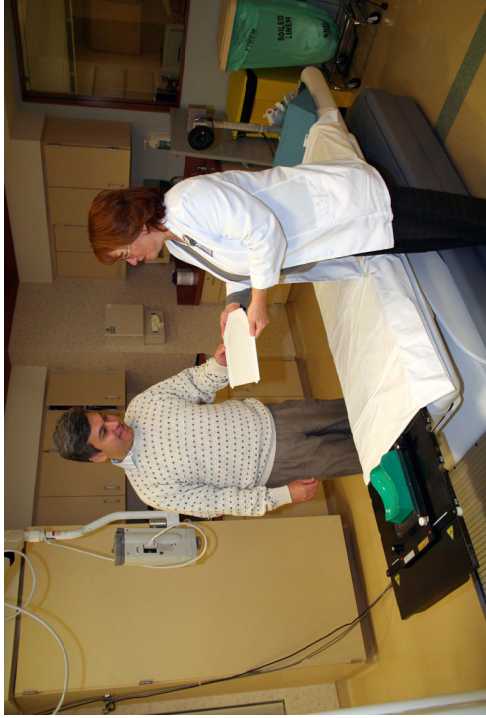


Figure B.1 Left: RTT explains immobilization procedure to the patient; Right: RTT applies mask for patient immobilization.

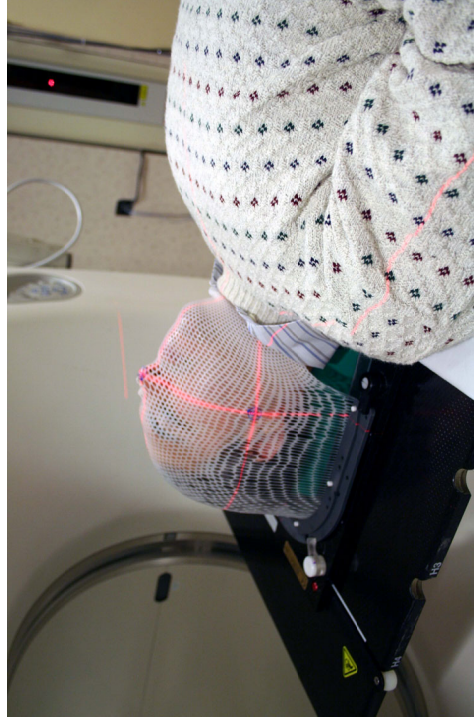


Figure B.2 Left: Patient alignment using lasers; Right: CT images acquisition.



Figure B.3. Evaluation of CT images and transfer the data to RTPS

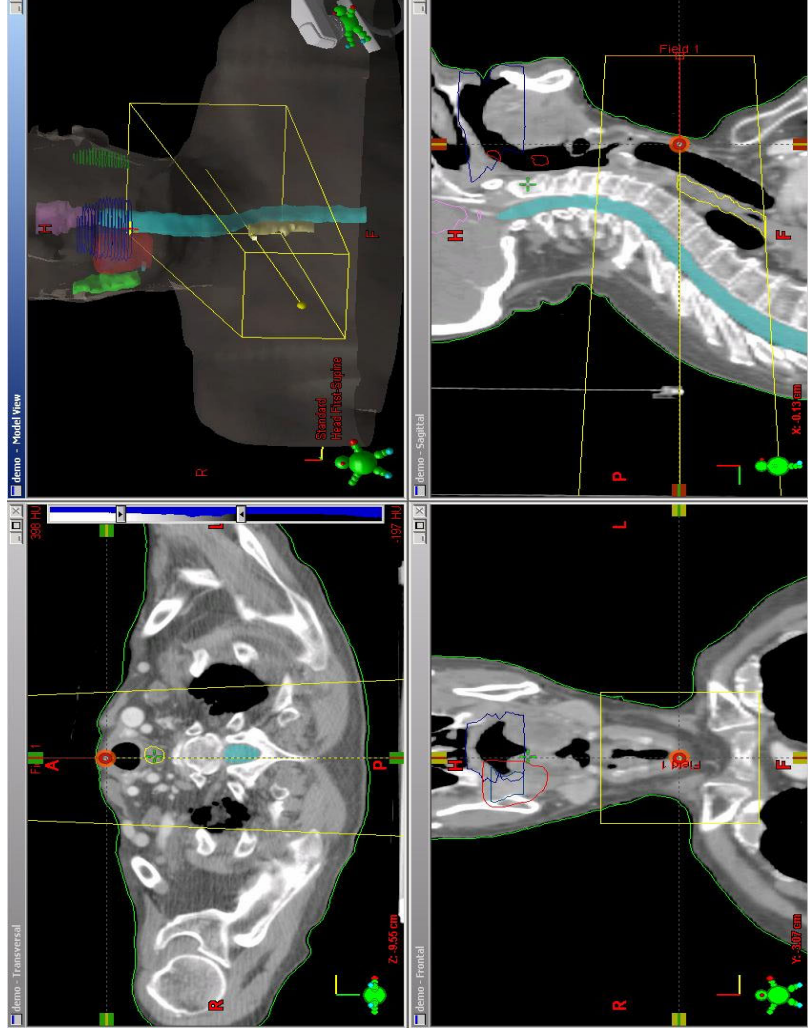


Figure B. 4. Treatment planning: selection of the isocenter

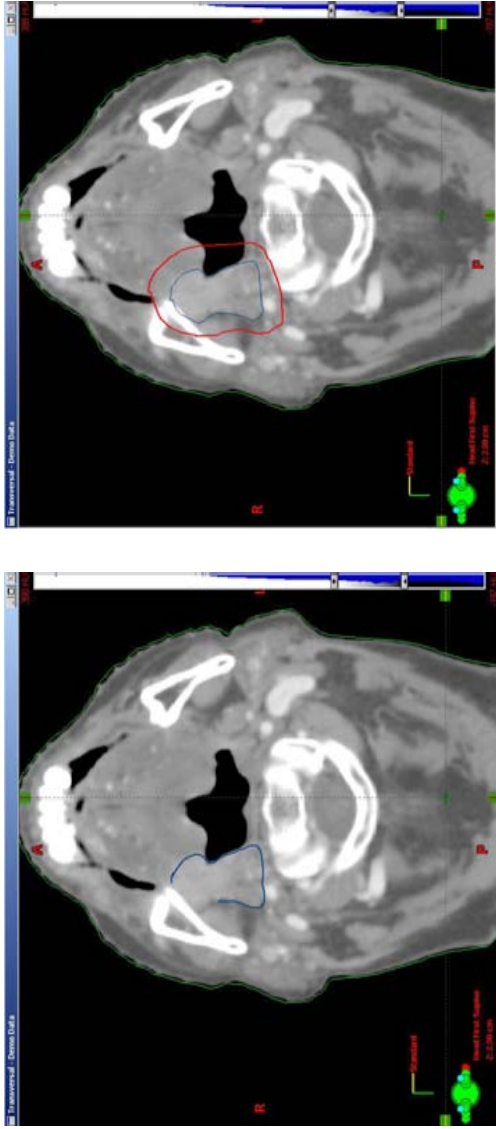


Figure B. 5. Left: Drawing clinical target volume (CTV); Right: created planning target volume (PTV).

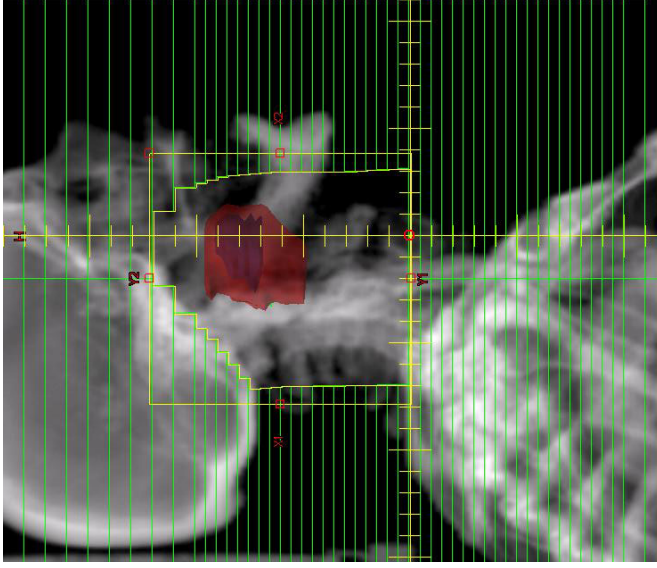


Figure B. 6. Digitally reconstructed radiograph (DRR)

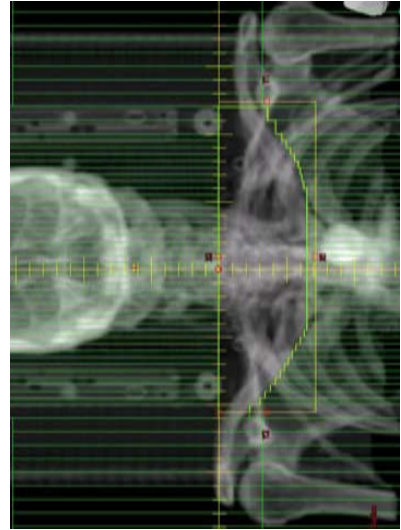


Figure B. 7. Digitally reconstructed radiograph (DRR) for the supraclavicular field

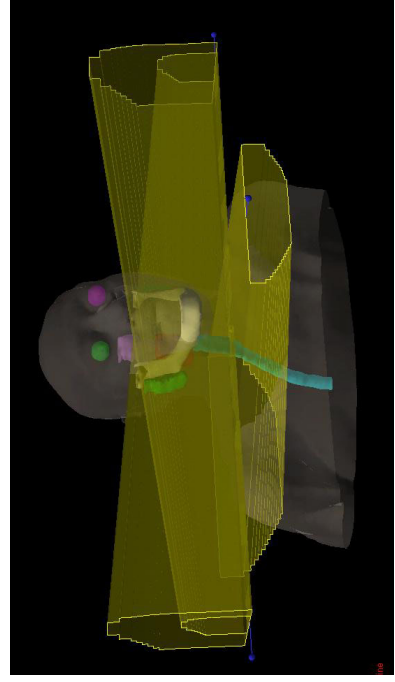


Figure B. 8. 3-D view of treatment beams

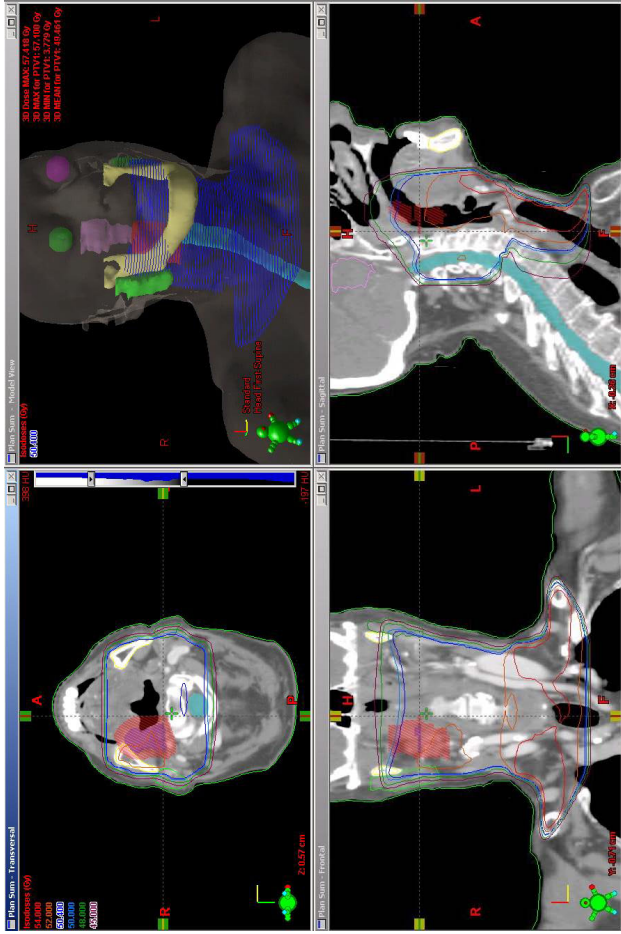


Figure B.9. Resulting dose distributions for the selected plan



Figure B.11. Patient set up and alignment on the treatment machine

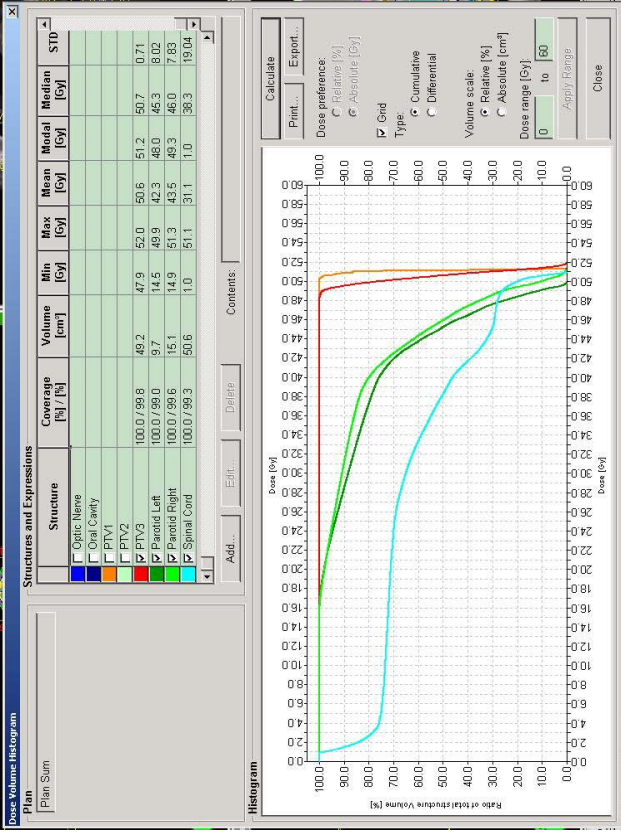


Figure B.10. Dose-volume histograms for the selected plan



Figure B.12. Patient in treatment position

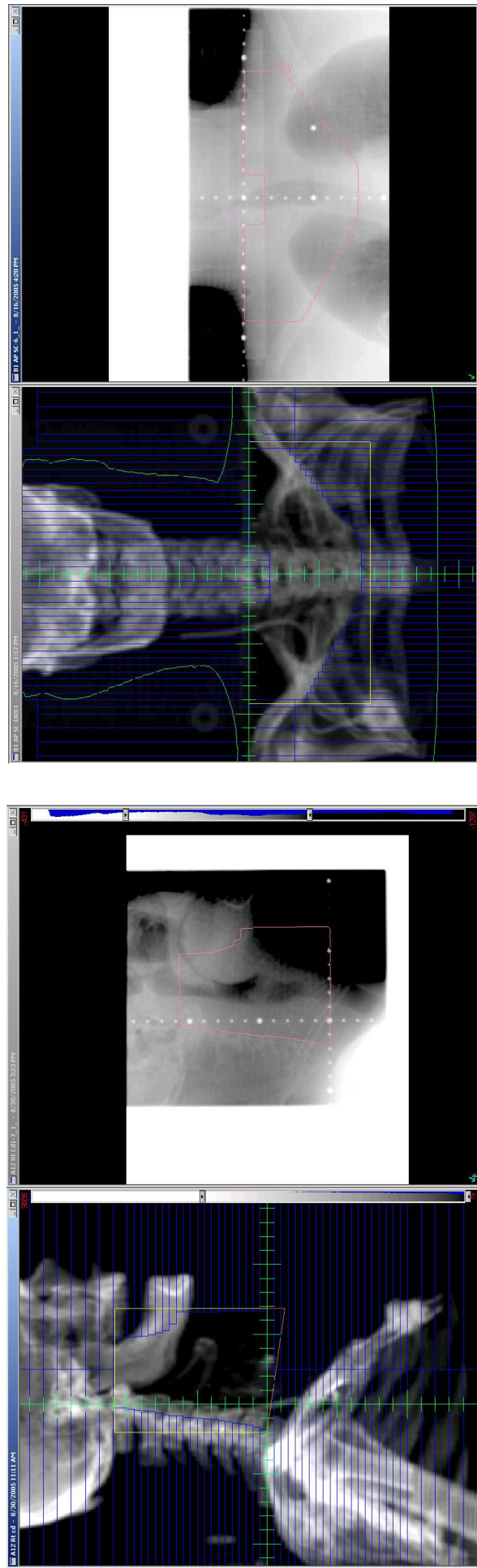


Figure B.13. Position verification using portal imaging - left for the lateral field, right for the supraclavicular field

APPENDIX C INDICATIVE EQUIPMENT COSTS (2008)

RADIOTHERAPY EQUIPMENT

Treatment Delivery

Linear accelerator (with EPID and R&V system)

Low energy (IMRT ready)	\$ 2 million
IMRT option	\$ 30,000
Dual energy – 6 & 18 MV – (IMRT ready)	\$ 4 million
IMRT option	\$30,000

Imaging/Treatment Simulation

CT simulator	\$ 1-3 million
Workstation (x2)	included
Immobilization	\$ 10-100,000

Planning

TPS workstation (x2)	\$100-500,000
IMRT software	\$100,000

DOSIMETRY AND QA EQUIPMENT

Film dosimetry system for IMRT	\$ 20,000
Phantoms	\$ 20,000
IMRT phantom	\$ 30,000
2D Array detectors (ion chambers or diodes)	\$ 25,000 – 40,000
Ion chambers and electrometers	\$ 15,000

MAINTENANCE COSTS

First year – maintenance contract	included in price
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ABBREVIATIONS

The following abbreviations have been used in the text and are collected here for easy reference.

3-D CRT	Three Dimensional Conformal Radiotherapy
AAPM	American Association of Physicists in Medicine
BEV	Beam's Eye View
CNS	Central Nervous System
CT	Computed Tomography
CTV	Clinical Target Volume (see Figure 1.2)
DICOM	Digital Imaging and Communications in Medicine
DICOM-RT	DICOM with Radiotherapy Extensions
DMLC	Dynamic Multileaf Collimation
DRR	Digitally Reconstructed Radiograph
DVH	Dose Volume Histogram
EPID	Electronic Portal Imaging Device
GTV	Gross Tumour Volume (see Figure 1.2)
IGRT	Image Guided Radiotherapy
IMAT	Intensity Modulated Arc Therapy
IMRT	Intensity Modulated Radiotherapy
IPEM	Institute of Physics and Engineering in Medicine
ITV	Internal Target Volume
MLC	Multileaf Collimator
MRI	Magnetic Resonance Imaging
MU	Monitor Unit
NTCP	Normal Tissue Complication Probability
PET	Positron Emission Tomography
PRV	Planning (organ-at-) Risk Volume
PTV	Planning Target Volume (see Figure 1.2)
PSA	Prostate Specific Antigen
QA	Quality Assurance

QC	Quality Control
QOL	Quality of life
R&V	Record and Verification system
RTPS	Radiation Treatment Planning System
RTT	Radiation Therapy Technologist
SFPM	Société Française des Physiciens Médicaux
SPECT	Single Photon Emission Computed Tomography
TCP	Tumour Control Probability

GLOSSARY

4D imaging	A technique form of tomographic imaging in which image data collection is synchronised to patient respiration. This makes it possible to have one or more complete data sets at particular phases in the breathing cycle.
Beam's Eye View	A view of the target and other tissues as seen from the source of the treatment machine. This permits the design of appropriate shielding to reduce the amount of normal tissue irradiated.
Conformal blocks	A system of cast blocks of low melting point alloy used to shape the radiation field based on a beam's-eye-view (BEV) of the patient.
Digitally Reconstructed Radiograph	Planar image similar to a radiograph, but derived from a CT data set.
Dose Volume Histogram	A method of displaying the volume of tissue treated to a certain dose level.
Dynamic Multileaf Collimation	A form of IMRT in which the MLC leaves move continuously during the irradiation in order to produce intensity modulated beam.
Electronic Portal Imaging Device	A device mounted on a linear accelerator directly in line with the radiation source but beyond the patient which forms an image electronically based on the distribution of radiation leaving the patient.
Forward Planning	The traditional process of treatment planning whereby the planner tries a particular beam arrangement and subsequently adjusts beam weights and orientations until a satisfactory plan is obtained.
Internal Target Volume Image Guided Radiotherapy	A CTV with an additional allowance for intrafraction tumour movement.
Intensity Modulated Arc Therapy	A term generally used to reflect the use of various imaging modalities to help define the target volume. More specifically it refers to the possibility of obtaining CT data (or diagnostic quality planar images) on a linear accelerator with the patient in the treatment position).
Intensity Modulated Radiotherapy	A form of IMRT in which the linear accelerator gantry rotates around the patient while the beam intensity is modulated. The ultimate implementation of this technique is Tomotherapy.
Intensity Modulated Radiotherapy	A method of treating which involves the use of deliberately non uniform beams to provide the required dose distribution, allowing conformation to concave targets and deliberately inhomogeneous dose distributions.
Inverse Planning	The process whereby the doctor defines the objectives of a treatment plan and these are programmed into a computer which computes the beam arrangements that will most closely meet the doctor's specification.
Magnetic Resonance Imaging	Imaging system based on properties of matter in a magnetic field which produces particularly good soft tissue contrast.

Monitor Unit	A unit of radiation as measured by the in-beam ionisation chamber of a linear accelerator. Usually this represents the dose in cGy measured for a particular field size (usually 10 cm square) in a particular geometry (often at 100 cm source surface distance).
On-board imaging	A term used to describe linear accelerator systems in which a diagnostic x-ray tube is also mounted to allow high quality patient images to be taken.
Planning (organ-at-risk) Volume	A volume around organs-at-risk allowing for setup errors in an analogous way to the PTV.
Positron Emission Tomography	Imaging system for radionuclides which is based on the fact that when certain radionuclides decay they emit two positrons in directly opposite directions. This allows tomographic images to be produced representing the concentration of the radionuclide.
Quality Assurance	All those planned and systematic actions necessary to provide adequate confidence that a structure, system or component will perform satisfactorily in service, or will satisfy given requirements for quality.
Quality Control	The regulatory process, through which the actual quality performance is measured, compared with existing standards and finally the actions necessary to keep or regain conformance with the standards.
Radiation fluence	The intensity of the flow of radiation through a plane.
Record and Verification System	Electronic control system for a linear accelerator.
Single Photon Emission Computed Tomography	A method of obtaining three dimensional images of the radionuclide distribution within a patient by combining the images obtained from multiple orientations of a gamma camera.
Step and Shoot	The IMRT delivery technique in which the treatment is given using a succession of small radiation fields each given a particular number of monitor units (MU). All these small fields add together to give the composite dose distribution. The beam is turned off while the collimator and gantry positions are adjusted.
Ultrasound	High frequency sound used to obtain sonar images from inside a patient. It is particularly suited to imaging in the pelvis.

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