Chapter 11

COMPUTERIZED TREATMENT PLANNING SYSTEMS FOR EXTERNAL PHOTON BEAM RADIOTHERAPY

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11.1. INTRODUCTION

Computerized treatment planning systems (TPSs) are used in external beam radiotherapy to generate beam shapes and dose distributions with the intent to maximize tumour control and minimize normal tissue complications. Patient anatomy and tumour targets can be represented as 3-D models. The entire process of treatment planning involves many steps and the medical physicist is responsible for the overall integrity of the computerized TPS to accurately and reliably produce dose distributions and associated calculations for external beam radiotherapy. The planning itself is most commonly carried out by a dosimetrist, and the plan must be approved by a radiation oncologist before implementation in actual patient treatments.

Treatment planning prior to the 1970s was generally carried out through the manual manipulation of standard isodose charts on to patient body contours that were generated by direct tracing or lead wire representation, and relied heavily on the judicious choice of beam weight and wedging by an experienced dosimetrist.

The simultaneous development of computed tomography (CT), along with the advent of readily accessible computing power from the 1970s on, led to the development of CT based computerized treatment planning, providing the ability to view dose distributions directly superimposed upon a patient's axial anatomy.

The entire treatment planning process involves many steps, beginning from beam data acquisition and entry into the computerized TPS, through patient data acquisition, to treatment plan generation and the final transfer of data to the treatment machine.

Successive improvements in treatment planning hardware and software have been most notable in the graphics, calculation and optimization aspects of current systems. Systems encompassing the 'Virtual Patient' are able to display

beam's eye views (BEVs) of radiation beams and digitally reconstructed radiographs (DRRs) for arbitrary dose distributions. Dose calculations have evolved from simple 2-D models through 3-D models to 3-D Monte Carlo techniques, and increased computing power continues to increase calculation speed.

Traditional forward based treatment planning, which is based on a trial and error approach by experienced professionals, is giving way to inverse planning, which makes use of dose optimization techniques to satisfy the user specified criteria for the dose to the target and critical structures. Dose optimization is possible by making use of dose–volume histograms (DVHs) based on CT, magnetic resonance imaging (MRI) or other digital imaging techniques. These optimized plans make use of intensity modulated radiotherapy (IMRT) to deliver the required dose to the target organ while respecting dose constraint criteria for critical organs.

Computerized treatment planning is a rapidly evolving modality, relying heavily on both hardware and software. Thus it is necessary for related professionals to develop a workable quality assurance programme that reflects the use of the TPS in the clinic and that is sufficiently broad in scope to ensure proper treatment delivery.

11.2. SYSTEM HARDWARE

11.2.1. Treatment planning system hardware

The principal hardware components of a TPS include a central processing unit (CPU), a graphics display, memory, digitizing devices, output devices, and archiving and network communication devices. As hardware capabilities tend to change quickly, the general approach is to acquire equipment having the highest current specifications while allowing for future upgrades.

The CPU must have at least the memory and processor speed required by the operating system and treatment planning software. In particular, the specifications for the system speed, random access memory (RAM) and free memory, as well as networking capabilities, must be considered.

The graphics display is normally sufficient for accommodating the patient transverse anatomy on a 1:1 scale, typically 17–21 in. (43–53 cm) or larger. The resolution is submillimetre or better so as not to distort the input. Graphics speed can be enhanced with video cards and hardware drivers.

Memory and archiving functions are carried out through either removable media or networking. Removable media may include floppy disks, rewritable hard disks, optical disks or digital video disks (DVDs). Mass

archiving may also be accomplished with slower digital audio tape (DAT); however, these devices have been reported to suffer from long term instability. Archiving may be carried out over a network on a remote computer or server; these archiving operations may be carried out automatically during low use periods of the day. Archiving operations can include beam data and parameters, patient related data such as CT scans and dose distributions, and data used for setting up the patient for treatment on a linac with record and verify systems.

Digitizing devices are used to acquire manually entered patient data such as transverse contours and BEVs of irregular field shapes. These devices are typically backlit tablets with either a magnetic or acoustic stylus for manually tracing shapes. Scanners, either flatbed or upright, can be used to digitize images from hard copies such as paper or radiographic film. Videoframe grabbers may also be used to digitize images.

Output devices include colour laser printers and plotters for text and graphics. Printers and plotters can be networked for shared access. Hard copies can be in the form of paper or film via a laser camera.

Uninterruptible power supplies (UPSs) are recommended for the CPU, data servers and other critical devices, such as those used for storage and archiving. UPSs can provide backup power so that a proper shutdown of the computer can be accomplished during power failures of the regular power distribution grid, and they also act as surge suppressors for the power.

Communications hardware includes modem or Ethernet cards on local workstations and multiple hubs for linking various peripheral devices and workstations. Large networks require fast switches running at at least 100 Mb/s for file transfer of images. Physical connections on both small and large networks are run through coaxial cable, twisted pairs or optical fibre, depending upon the speed requirements.

The environmental conditions under which the TPS hardware runs may be subject to temperature and humidity requirements. Thus the physical location of the equipment associated with the TPS within a department is of importance.

11.2.2. Treatment planning system configurations

Smaller TPS configurations may have a stand-alone layout whereby one central CPU handles most functions and communications requests. In this configuration there may only a be few users, and access to the peripheral devices used for printing and archiving is not shared. Network requirements may also be limited; however, even stand-alone TPSs now routinely require

network switches to communicate with digital imaging devices such as CT scanners.

Larger systems often operate within a hospital-wide network, and may also make use of Internet based communications systems. Many of the devices operated and accessed by the large TPS configuration will not have a direct connection and must be accessed through a number of network switches using a communications protocol such as transmission control protocol/internet protocol (TCP/IP). These larger systems may also have a remote server for various file handling tasks related to patient data, digital images, beam data and dose calculation. Large area TPS configurations having many users and remote workstations may require the services of an administrator to maintain security, user rights, networking, backup and archiving.

11.3. SYSTEM SOFTWARE AND CALCULATION ALGORITHMS

Dose calculation algorithms are the most critical software component in a computerized TPS. These modules are responsible for the correct representation of dose in the patient, and may be linked to beam time or monitor unit (MU) calculations. Dose calculations have evolved from simple 2-D calculations, to partial 3-D point kernel methods, to full 3-D dose models in which the histories of the primary and scattered radiation in the volume of interest are considered.

11.3.1. Calculation algorithms

There are numerous dose calculation algorithms used by computerized TPSs, and due to the rapidly changing nature of computer power the implementation of these techniques is a constantly evolving process. Specific details of treatment planning dose algorithms can be found throughout the literature, and a small selection is included in the bibliography section of this chapter.

Prior to understanding sophisticated computerized treatment planning algorithms, a proper understanding of manual dose calculations is essential, and there are many texts that adequately discuss these methods, including Johns and Cunningham, Khan, and Hendee and Ibbot.

ICRU Report No. 42 lists the chronological development of dose calculation algorithms for photon and electron beams. It provides representative examples for calculation of the central axis depth dose and the cross-beam or off-axis ratio (OAR) for photon beams. Representative examples of electron beam calculations, including the empirical and semi-empirical

formalism for calculation of the central axis depth dose, and the empirical formalism for calculation of the cross-beam or OARs, are also provided.

Early TPSs generated dose distributions through the manipulation of relatively simple 2-D beam data for a range of square fields in water. These data sets comprised matrices of central axis percentage depth doses (PDDs) and several OARs (profiles) at a number of depths.

To speed up calculation, central axis data were converted and stored as infinite PPD data, while the profiles were stored along ray lines backprojected to an arbitrary source to surface depth (SSD). In this manner, data could be rapidly manipulated using look-up tables to generate dose distributions on to external patient contours. These types of algorithm were used for both photon and electron beam treatment planning and led to very fast dose calculations. However, in general they were not truly representative of the 3-D scattering conditions in the patient.

Prior to the advent of widespread CT use in treatment planning, irregular field dosimetry was accomplished using BEV films of treatment fields obtained with conventional simulators. Using the central axis and profile data sets, the primary and scatter components of the beam could be separated using the zero area tissue–air ratio (TAR) and scatter–air ratio (SAR) at depth to generate Clarkson sector integration calculations for points of interest in the irregular field.

The approach of current beam calculation algorithms is to decompose the radiation beam into primary and secondary or scatter components, and to handle each component independently. In this manner, changes in scattering due to changes in beam shape, beam intensity, patient geometry and tissue inhomogeneities can be incorporated into the dose distribution.

One such model uses convolution methods whereby the dose at any point in the medium can be expressed as the sum of the primary and scatter components. These models use superposition principles to account for both local changes in the primary fluence and changes in the spread of energy due to local scattering caused by the patient and beam geometry. Under specific conditions of non-divergent sources and homogeneous phantoms, convolution type integrals can be used to simplify and speed up these calculations.

Monte Carlo or random sampling techniques are used to generate dose distributions by following the histories of a large number of particles as they emerge from the source of radiation and undergo multiple scattering interactions both inside and outside the patient.

Monte Carlo techniques are able to accurately model the physics of particle interactions by accounting for the geometry of individual linacs, beam shaping devices such as blocks and multileaf collimators (MLCs) and patient surface and density irregularities. They allow a wide range of complex patient

treatment conditions to be considered. In order to achieve a statistically acceptable result, Monte Carlo techniques require the simulation of a large number of particle histories, and are only now becoming practical for routine treatment planning as computing power reduces the calculation time to an acceptable level, of the order of a few minutes for a given treatment plan.

Pencil beam algorithms are common for electron beam dose calculations. In these techniques the energy spread or dose kernel at a point is summed along a line in a phantom to obtain a pencil type beam or dose distribution. By integrating the pencil beam over the patient's surface to account for changes in primary intensity and by modifying the shape of the pencil beam with depth and tissue density, a dose distribution can be generated.

As pointed out by Cunningham, treatment planning algorithms have progressed chronologically to include analytical, matrix, semi-empirical and 3-D integration methods.

The analytical technique as developed by Sterling calculated the dose in the medium as the product of two equations, one of which modelled the PDD, while the other modelled the beam's off-axis component. The model has been extended to incorporate field shielding and wedge hardening.

Treatment planning computer systems developed in the 1970s began using the diverging matrix method of beam generation based on measured data.

The Milan–Bentley model was used to calculate diverging fan lines that radiate from a source and intersect depth lines located at selected distances below the patient's surface. Dose distributions are made by rapidly manipulating measured data sets consisting of central axis PDD and OAR data sets stored as a function of field size. These techniques continue to be used in treatment planning algorithms (Storchi and Woudstra), although they suffer from the perceived disadvantage of requiring large amounts of measured data, and from their limited ability to properly model scatter and electron transport conditions.

Semi-empirical dose calculation methods model the dose to a point by considering the contribution from the primary and scattered radiation independently. Based originally on the Clarkson scatter integration technique, these models have been refined by combining the formalism of basic physics with data derived from measurement. Correction factors to account for penumbra, block transmission and flattening filters have improved in these models.

These methods have been further refined by applying differential SAR techniques to allow for variations in the intensity of scatter radiation throughout the field due to the presence of wedges or non-uniform surface contours.

3-D integration methods represent the transport of electrons and photons away from the primary site of interaction so as to have an accurate description of the deposition of absorbed energy while considering the geometry and composition of the entire volume being irradiated. Monte Carlo techniques for computing dose spread arrays or kernels used in convolution–superposition methods are described by numerous authors, including Mackie, and in the review chapters in Khan and Potish, and Van Dyk provides a detailed summary of treatment planning algorithms in general.

11.3.2. Beam modifiers

Treatment planning software for photon beams and electron beams must be capable of handling the many diverse beam modifying devices found on linac models. Some of these devices are generic to all linacs, whereas others are specific to certain manufacturers. Some of these devices and specific considerations for incorporation into the TPS are listed below, separated into two main groups: photon beam modifiers (consisting of jaws, blocks, compensators, MLCs, wedges) and electron beam modifiers (consisting of cones, blocks, bolus, etc.).

11.3.2.1. Photon beam modifiers

Jaws: The field size is defined by motorized collimating devices (jaws). Jaws can move independently or in pairs and are usually located as an upper and lower set. Jaws may over-travel the central axis of the field by varying amounts. The travel motion (transverse or arced) will determine the junction produced by two abutting fields. The TPS will account for the penumbra produced by the location of these jaws, and differences in radial and transverse open beam symmetry due to the jaw design may also be considered.

Blocks: Field shielding is accounted for in the TPS by considering the effective attenuation of the block to reduce the total dose under the shielded region. The dose through a partially shielded calculation volume, or voxel, is calculated as a partial sum of the attenuation proportional to the region of the voxel shielded. The geometry of straight edge and tapered blocks can be considered separately so as to more accurately model the penumbra through the region of the block edge. TPSs are able to generate files for blocked fields that can be exported to commercial block cutting machines.

MLC: An MLC is a beam shaping device that can replace almost all conventional mounted blocks, with the exception of island blocking and excessively curved field shapes. Most modern linacs are now equipped with MLCs. There are various designs; however, MLCs with a leaf width of the order

of 0.5–1.0 cm at the isocentre are typical: MLCs providing smaller leaf widths are referred to as micro MLCs. The MLC may be able to cover all or part of the entire field opening, and the leaf design may be incorporated into the TPS to model transmission and penumbra. The MLC may also have varying degrees of dynamic motion that can be invoked while the beam is on in order to enhance dose delivery.

Wedges: Static wedges remain the principal devices for modifying dose distributions. The TPS can model the effect of the dose both along and across the principal axes of the physical wedge, as well as account for any PDD change due to beam hardening and/or softening along the central axis ray line. The clinical use of wedges may be limited to field sizes smaller than the maximum collimator setting. More recently, wedging may be accomplished by the use of universal or sliding wedges incorporated into the linac head, or, even more elegantly, by dynamic wedging accomplished by the motion of a single jaw while the beam is on.

Custom compensators may be designed by TPSs to account for missing tissue or to modify dose distributions to conform to irregular target shapes. TPSs are able to generate files for compensators that can be read by commercial compensator cutting machines.

11.3.2.2. Electron beam modifiers

Electron beams are used with external collimating devices known as cones or applicators that reduce the spread of the electron beam in the air. The design of these cones is dependent on the manufacturer and affects the dosimetric properties of the beam.

Electron shielding for irregular fields may be accomplished with the use of thin lead or low melting point alloy inserts. These shielding inserts can have significant effects upon the electron beam dosimetry (especially the PDD and output), and these effects may be modelled by the TPS.

The design of the linac head may be important for electron dosimetry, especially for Monte Carlo type calculations. In these conditions particular attention is paid to the scattering foil. The effective or virtual SSD will appear to be shorter than the nominal SSD, and may be taken into consideration by the TPS.

Bolus may be used to increase the surface dose for both photon and electron treatments. Bolus routines incorporated into TPS software will usually permit manual or automatic bolus insertion in a manner that does not modify the original patient CT data. It is important that the TPS can distinguish between the bolus and the patient so that bolus modifications and removal can be achieved with ease.

11.3.3. Heterogeneity corrections

Heterogeneity or inhomogeneity corrections generally account for the differences between the standard beam geometry of a radiation field incident upon a large uniform water phantom and the beam geometry encountered by the beam incident upon the patient's surface. Beam obliquity and regions where the beam does not intersect the patient's surface will affect the dose distribution. Inside the patient, the relative electron density of the irradiated medium can be determined from the patient CT data set.

Most TPS algorithms apply either a correction factor approach or a model based approach. Generalized correction factors, such as the power law or the equivalent TAR methods, lead to fast calculations, but are based on a correction of the initial dose calculated in water. Model based approaches such as the differential SAR approach and Monte Carlo based algorithms consider the transport and scatter in the irradiated medium directly, but have historically involved longer calculation times. Most methods are still having difficulties with dose calculations at tissue interfaces.

11.3.4. Image display and dose–volume histograms

BEVs and room eye views (REVs) are used by modern TPSs. The BEV is often used in conjunction with DRRs to aid in assessing tumour coverage and for beam shaping with blocks or an MLC.

The REV gives the user a perception of the relationship of the gantry and table to each other and may help in avoiding potential collisions when moving from the virtual plan to the actual patient set-up. DRRs are projection images generated by mathematically passing ray lines through the patient CT data. Digitally composite radiographs (DCRs) may be generated by differentially weighting ranges of CT numbers to selectively discriminate between tissue densities on the projected image.

Portal image generation can be accomplished by TPSs by substituting energy shifted attenuation coefficients for CT data sets. These virtual portal images with the treatment field superimposed can be used for comparison with the portal images obtained with the patient in the treatment position on the treatment machine.

Image registration routines can help match simulator, MR, positron emission tomography (PET), single photon emission computed tomography (SPECT), ultrasound and other image sources to planning CT and treatment acquired portal images.

DVHs are calculated by the TPS with respect to the target and critical structure volumes in order to establish the adequacy of a particular treatment

plan and to compare competing treatment plans. DVHs may be displayed as differential DVHs, whereby the ordinate represents the volume receiving the dose specified on the abscissa, or as cumulative DVHs, whereby the ordinate represents the volume or percentage volume receiving a dose equal to or greater than that indicated on the abscissa. Overlapping DVHs aid in evaluating different treatment plans, although no information with respect to the dose location is presented.

The natural DVH is encountered more commonly in brachytherapy, whereby the inherent effects of the inverse square law are reduced in the display to aid in DVH interpretation. TPSs can employ logic to help define volumes when dealing with overlapping structures; for example, when a volumetric margin is defined around a target, the TPS can establish a volume equal to the margin minus the target, and DVHs can be calculated for this virtual volume around the target.

11.3.5. Optimization and monitor unit calculations

Optimization routines including inverse planning are provided by TPSs with varying degrees of complexity. Algorithms can modify beam weights and geometry or calculate beams with a modulated beam intensity to satisfy the user criteria. These criteria may be based on a number of discrete points of interest or be specified as minimum/maximum doses to targets and critical structures. DVHs are used in optimization routines to specify the required dose criteria for various volumes. These routines can make use of 'class solutions' using a predefined beam geometry specific to a clinical site (e.g. prostate) to shorten calculation times.

Beam time and MU calculation by TPSs is optional. The calculation process is directly related to the normalization method. Relative field size output factors, wedge factors (WFs), tray factors and other machine specific factors are required. The absolute output at a reference point (e.g. SSD of 100 cm, depth of dose maximum for a reference field) will be required, as well as decay data for cobalt units. Total prescription dose and fractionation information can be incorporated.

11.3.6. Record and verify systems

Networked TPSs allow for interface between linac record and verify systems, either through a direct connection or through a remote server using fast switches. Record and verify systems may be provided by the TPS manufacturer, the linac manufacturer or third party software. They may require a mapping between various accessories on the linac and the TPS so that devices such as the jaws and wedges are orientated correctly with respect to the

patient's anatomy. Communication between the TPS and the linac avoids the errors associated with manual transcription of paper printouts to the linac and can help in the treatment of complex cases involving asymmetric jaws and custom MLC shaped fields.

11.3.7. Biological modelling

Distributions modelled on biological effects may in the future become more clinically relevant than those based upon dose alone. Such distributions will aid in predicting both the tumour control probability (TCP) and the normal tissue complication probability (NTCP). These algorithms can account for specific organ dose response and aid in assessing the dose fractionation and volume effects. Patient specific data can be incorporated in the biological model to help predict individual dose response to a proposed treatment regime.

11.4. DATA ACQUISITION AND ENTRY

11.4.1. Machine data

Prior to entering radiation data into the TPSs, the various mechanical components of the treatment machines must be obtained so that the TPS model of the machine agrees with the possible mechanical motions and limits of the machine. The gantry, table and collimator rotation conventions used in a particular institution must be described accurately and the angle convention fully understood. The TPS must also be able to distinguish between jaw pairs and to accurately model the limits of the jaw over-travel.

Static and virtual wedge use by the TPS will be limited to field sizes that correspond to the maximum field setting in both the transverse and longitudinal directions. Dynamic wedge use may also be limited by the jaw over-travel and by the maximum dose rate available on the linac. Specific files used by the linac to generate jaw movements, such as segmented treatment tables (STTs), may also be used directly by the TPS.

The TPS models the MLC leaf design and leaf motion. Blocking trays may reside at several distances, and this is accounted for by the TPS for penumbra generation. Blocks with straight or tapered edges may be modelled separately.

Linacs capable of producing IMRT fields may do so via step and shoot or fully dynamic techniques. For these types of treatment the TPS requires data regarding the maximum leaf speed and the characteristics of the maximum rise in the beam-on time and information on maximum dose rates.

Missing tissue compensators and dose compensators can be calculated by the TPS, and physical data related to the attenuation coefficients of the materials used to fabricate physical compensators are required.

The electron cone design varies from one linac manufacturer to another. The TPS may require information regarding the distance from the cone to the nominal SSD, as well as the external dimensions of the electron cone, in order to produce REVs so as to avoid potential patient–machine collisions.

11.4.2. Beam data acquisition and entry

The beam data required by the TPS must be well understood. This is especially true when acquiring beam data from the treatment units. Special consideration must be given to the geometry of the radiation detector (typically ionization chambers or diodes) and to any geometrical correction factors that must be applied to the data. Beam data are often smoothed and renormalized both following measurement and prior to data entry into the treatment planning computer.

Typical photon beam data sets include central axis PDDs and OARs (profiles) for open and wedged fields for a range of square fields. Diagonal field profiles to account for radial and transverse open beam asymmetry and wedged field lateral profiles to account for the variation in wedge hardening off-axis may also be required. In the case of diagonal profiles it may only be possible to acquire half-field scans, depending upon the size of the water tank.

The penumbra may be fitted to, or extracted from, measured data. In either case it is important that scan lengths be of sufficient length, especially for profiles at large depths, where field divergence can become considerable.

Relative or absolute field size factors are required for TPSs. These values are used both in treatment time calculations and in the calculation of dose distributions involving dynamic beams (e.g. dynamic wedges, dynamic MLCs). Particular care must be taken with respect to the reference field size, reference depth and nominal SSD, as these will have a global effect on time and MU calculations. Central axis WFs, tray factors and other accessory factors (normally the ratio of dose with and without the accessory) are also required by the TPS.

Measured beam data relevant to the MLC can include transmission through the leaf, inter-leaf transmission between adjacent leaves and intra-leaf transmission occurring when leaves from opposite carriage banks meet end on.

Beam measurement for electrons is more difficult than for photons because of the continuously decreasing energy of the beam with depth. Electron beam data measured with ionization chambers must be first converted to dose with an appropriate method, typically using a look-up table of stopping

power ratios. Measurements with silicon diodes are often considered to be tissue equivalent and give a reading directly proportional to dose.

Monte Carlo TPSs require accurate information concerning the geometry and composition of linac beam line components such as the waveguide exit window, target, flattening filter, scattering foil, transmission ionization chamber, jaws, MLC, blocks and trays, and any other items the electron or photon beam is likely to encounter.

Beam data acquired from a linac may be entered manually using a digitizer tablet and tracing stylus. A hard copy of beam data is used, and it is important that both the beam data printout and the digitizer be routinely checked for calibration.

Beam data may also be entered via a keyboard. This may be required for text, parameters such as transmission and field size factors, or for more detailed data sets such as the PDD and profiles. Other parameters may be required on a trial and error basis by TPSs that fit beam models to measured data. Keyboard data entry is inherently prone to operator error and requires independent verification.

Beam data entry via file transfer from the beam acquisition computer to the TPS is common. The digital nature of the computer acquired beam data makes them readily available to the TPS; however, careful attention must be paid to the file format. File headers contain formatting data concerning the direction of measurement, SSD, energy, field size, wedge type and orientation, detector type and other relevant parameters. Special attention must be paid to these labels to ensure that they are properly passed to the TPS. Data transfer can also occur via removable media or over a network.

11.4.3. Patient data

The patients' anatomical information may be entered via the digitizer using one or more contours obtained manually or it may come from a series of transverse slices obtained via a CT scan. In both cases, isodose distributions are calculated and displayed in patient transverse planes; this mode of radiation treatment planning is referred to as conventional 2-D treatment planning.

Three dimensional treatment planning delivers tumouricidal doses in volumes of tissue rather than in individual planes. The 3-D information data required to localize the tumour volume and normal tissues may be obtained from various imaging modalities. The patient's volumetric anatomical information is likely to be derived from multislice CT or MR scanning. It may also be the result of image registration and fusion techniques in which the volume described in one data set (MRI, PET, SPECT, ultrasound, digital

subtraction angiography (DSA)) is translated or registered with another data set, typically CT.

The patient image data may be transferred to the TPS via the DICOM 3 (Digital Imaging and Communications in Medicine) or DICOM RT (radiotherapy) format. Both formats were adopted by the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) in 1993.

To ensure accurate dose calculation, the CT numbers must be converted to electron densities and scattering powers. The conversion of CT numbers to electron density and scattering power is usually performed with a user defined look-up table, which in turn is generated using a water equivalent circular phantom containing various inserts of known densities simulating normal body tissues such as bone and lung.

Patient data can undergo image segmentation whereby the region within an image data set that belongs to an organ or tumour is defined. Manual contouring on the TPS can be achieved by using copy and edit tools for convenience. Automatic contouring routines can help in outlining organs or regions of bulk density.

Standard volumes, such as those defined by the ICRU Report No. 50 and the ICRU Report No. 62, including the gross target volume (GTV), clinical target volume (CTV) and planning target volume (PTV), are used by the TPS, along with automatic margin generation. Image segmentation is used in the determination of the beam geometry to irradiate the target volume while sparing normal tissues and in the evaluation of treatment plans using DVHs.

Patient anatomy may be displayed using the BEV capability of the TPS. The rendering of patient anatomy from the point of view of the radiation source is useful in viewing the path of the beam, the structures included in the beam and the shape of the blocks or MLC defined fields.

11.5. COMMISSIONING AND QUALITY ASSURANCE

11.5.1. Errors

Uncertainties and errors in TPSs may arise from any of the many steps involved in the treatment planning process. Expected and acceptable errors may be expressed either as a percentage error in high dose regions of the dose distribution such as the irradiated volume or as distance in high dose gradient regions such as the buildup or penumbra regions of the distribution. A statement of acceptable uncertainty should also address the probability of practically achieving these levels.

11.5.2. Verification

Data verification entails a rigorous comparison between measured or input data and data produced by the TPS. Standard test data sets such as the AAPM TG 23 data set can be used to assess TPS performance. TPS data can also be compared with published data, although this can only serve as an approximation. AAPM TG 53 provides a detailed description of quality assurance tests that may be carried out by the clinical physicist.

Hard copy plots of basic TPS data and measured beam data are kept in logbooks for ready access. Comparisons for situations of varying degrees of complexity such as open and wedged fields with and without blocks can be used to initially assess TPS performance. More complex set-ups involving partial fields and inhomogeneous phantoms may also be considered. Geometrical verification of the accuracy of the TPS to produce shielded regions, as either blocks or apertures, can be performed by overlaying a hard copy. When designing shields with an MLC, the leaf intersection on the region of interest may occur on the outer corner, centre or inner corner. This must be verified in order to assess the amount of over- or undershielding that occurs.

Certain 3-D beam algorithms are not based on directly measured beam data but are based on the linac design and component composition. Verification with respect to the stated manufacturers' specifications will therefore be necessary.

The digitizer and plotter (printer) can be verified by using the digitizer to enter a contour of known dimensions and comparing it with the final hard copy.

Commissioning tests will include geometry with oblique fields and fields using asymmetrical jaws. Beam junctioning as calculated by the TPS, for either abutting fields or those junctioned with independent jaws, can be compared with test cases measured with film or detector arrays.

Calculations of rotational beams for both photons and electrons can be compared with measured or published data. Special attention must be given to the beam weighting and normalization used for rotational and arced beams.

To confirm file compatibility between the CT scanner and the TPS, a file transfer process must be performed. CT using helical scans may require separate transfer software.

The transfer of image data is checked by performing an analysis of the input data for a known configuration and density, such as a phantom, to detect any error in magnification and in spatial coordinates. Special attention should be given to the pixel values, scan size and matrix size. The images must be checked for the integrity of surface rendering, especially for unlinked structures such as arms.

The large amount of data used by a TPS can make routine verification of all data difficult or impossible. Scheduled checks of dose distributions and beam time/MU calculations using a standard geometrical phantom with a variety of fields and beam modifiers are recommended for all TPSs; the frequency and scope of these procedures are described in the publications in the bibliography. The use of check sum programmes can ensure file and data integrity and alert the user to the possibility of inadvertent data changes or file corruption.

11.5.3. Spot checks

Spot checks of measured data versus those obtained from the TPS are required; these spot checks can involve calculations of fields shielded by blocks or MLCs. Spot checks of static and dynamic wedged fields with respect to measured data points are also recommended. A detector array may be used to verify wedged and, even more importantly, dynamically wedged dose distributions produced by the TPS. Wedge distributions produced by the TPS must be verified for identification, orientation, beam hardening and field size limitations.

11.5.4. Normalization and beam weighting

Dose normalization and beam weighting options vary from one TPS to another and have a direct impact on the representation of patient dose distributions. Normalization may be referred to a specific point such as the isocentre, to the intersection of several beam axes or to a minimum or maximum value in a slice or entire volume. Normalization can be referred to an arbitrary isodose line in a volume or to a minimum or maximum isosurface or related to a target or organ. Beam weighting may depend on whether the technique is SSD or source to axis distance (SAD).

Common TPS weightings for SSD set-ups relate the 100% value to the given dose at the depth of dose maximum per beam. SAD set-up options employ either an isocentric type weighting, whereby the beam weight is summed at the isocentre, or a tissue–phantom ratio (TPR) weighting, whereby a 100% beam weight produces a distribution having a value at the isocentre in the patient equal to the sum of the beams' TPRs.

Manual checks of all dose distributions as well as beam time or MU calculations used for treatment are recommended. Since many treatment plans involve complex beam delivery, these manual checks do not need to be precise, yet they serve as a method of detecting gross errors on the part of the TPS.

11.5.5. Dose–volume histograms and optimization

DVHs must be verified for both geometric and calculative accuracy. By drawing geometric targets such as spheres or cubes in a phantom, volume calculations can be verified. A dose distribution displaying a single beam passing through the sphere or cube can be used to verify the DVH calculation for both the differential and cumulative representations.

Optimization routines are provided by many TPSs, and intensity modulated beams having complex dose distributions may be produced. As these set-ups involve partial or fully dynamic treatment delivery, spot checks of absolute dose to a point, as well as a verification of the spatial and temporal aspects of the dose distributions using either film or detector arrays, are a useful method of evaluating the TPS beam calculations.

11.5.6. Training and documentation

Training and a reasonable amount of documentation for both the hardware and software are essential. Typically the training is given on the site and at the manufacturer's facility. Ongoing refresher courses are available to familiarize dosimetrists and physicists with 'bug fixes' and system upgrades. Documentation regarding software improvements and fixes is kept for reference by users at the clinic. TPS manufacturers have lists of other users and resource personnel to refer to.

Most manufacturers of TPSs organize users' meetings, either as stand-alone meetings or in conjunction with national or international scientific meetings of radiation oncologists or radiation oncology physicists. During these meetings special seminars are given by invited speakers and users describing the particular software systems, new developments in hardware and software as well as problems and solutions to specific software problems.

11.5.7. Scheduled quality assurance

Following acceptance and commissioning of a computerized TPS a scheduled quality assurance programme should be established to verify the output of the TPS (see also Section 12.3.7).

The frequency of these tests and the acceptance criteria should be established based on the user's specific needs or on national or international norms. Owing to the complexity and changing nature of TPSs, quality assurance tests found in the literature (suggested in the bibliography) may not be sufficient; however, they can give the basis for a scheduled programme.

Scheduled quality assurance tests for TPSs will validate data relating to routine treatments using photon beams, electron beams and brachytherapy programmes. The tests should not only verify the output of physical data (such as PDDs, TPRs, OARs, the effects of blocked fields, the inverse square law, decay and half-life), but should also verify the final machine monitor or time settings. The tests must also consider the role of the CT scanner or CT simulator in the planning process and as much as possible should mimic the use of the TPS in determining the use of the therapy unit for delivering patient treatments.

Particular attention may be paid to tests for TPSs that deal with specialized techniques such as stereotactic and 3-D TPSs. In addition, care must be given to in-house systems that are undocumented and undergo routine development. These TPSs may require quality assurance tests at a higher frequency.

There is a common thread of continuity that runs from machine acceptance and commissioning to data acquisition, data entry into the TPS, the production of patient specific dosimetry and treatment delivery. The medical physicist must be able to link all these steps together, and a well planned and scheduled set of quality assurance tests for the TPS is an important link in the safe delivery of therapeutic radiation.

11.6. SPECIAL CONSIDERATIONS

TPSs can be dedicated for special techniques as stand-alone systems. In addition, there are various clinical procedures that require careful consideration, owing to their inherent complexity.

A list of techniques that require special consideration and that may result in dedicated TPSs includes:

- Brachytherapy;
- Orthovoltage radiotherapy;
- IMRT;
- Dynamic MLC;
- Total body irradiation (TBI) (photon and electron);
- Micro MLC;
- Stereotactic radiosurgery with a linac or Gamma Knife;
- Tomotherapy;
- Intraoperative radiotherapy;
- D shaped beams for choroidal melanoma;
- Electron beam arc therapy;
- Total skin electron irradiation (TSEI).

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