CHAPTER 11.

COMPUTERIZED TREATMENT PLANNING SYSTEMS FOR EXTERNAL PHOTON BEAM RADIOTHERAPY

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11.1. INTRODUCTION

Computerized Treatment Planning (TP) systems are used in external beam radiation therapy 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 dimensional models. The entire process of treatment planning involves many steps and the medical physicist is responsible for the overall integrity of the computerized treatment planning system 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 treatment.

Treatment planning prior to the 1970s was generally carried out through the manual manipulation of standard isodose charts onto 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 computerized tomography, along with the advent of readily accessible computing power from the 1970s on, lead to the development of CT-based computerized treatment planning, providing the ability to view dose distributions directly superimposed upon patient's axial anatomy.

The entire treatment planning process involves many steps, beginning from beam data acquisition and entry into the computerized planning system through patient data acquisition to treatment plan generation and the final distribution 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 Beams-Eye Views (BEV) of radiation beams, as well as Digitally Reconstructed Radiographs (DRR) for arbitrary dose distributions. Dose calculations have evolved from simple 2D models through 3D models to 3D Monte-Carlo techniques, and increased computing power continues to increase the 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 make use of dose optimization techniques to satisfy user specified criteria for the dose to the target and critical structures. Dose optimization is possible by making use of Dose-Volume Histograms (DVH) based on CT, MR or other digital imaging techniques. These optimized plans make use of Intensity Modulated Radiation Therapy (IMRT) to deliver a required dose to a 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. As such it is necessary for related professionals to develop a workable Quality Assurance (QA) programme that reflects the use of the TP system in the clinic, and is sufficiently broad in scope to ensure proper treatment delivery.

11.2. SYSTEM HARDWARE

11.2.1. TP system hardware

The principal hardware components of a TP system include: CPU, graphics display, memory, digitizing devices, output devices, 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 *Central Processing Unit* (CPU) must have sufficient memory and processor speed as required by the operating system, and the 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 to 21 inches (43 to 53 cm) or larger. The resolution is sub-millimeter 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 either through removable media or networking. Removable media may include floppy disks, re-writable hard-disks, optical disks, or DVDs. Mass archiving may also be accomplished with slower DAT tape, 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, and 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 the linac with record-and-verify systems.

- *Digitizing devices* are used to acquire manually entered patient data such as transverse contours and beams-eye-views of irregular field shapes. These 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 hardcopy such as paper or radiographic film. Video frame grabbers may also be used to digitize images.

- *Output devices* include color laser printers and plotters for text and graphics. Printers and plotters can be networked for shared access. Hardcopy can be to paper or to film via a laser camera.

- *Uninterruptable Power Supplies* (UPS) are recommended for the CPU, data servers, and other critical devices such as those used for storage and archiving. UPSs can provide back-up power so that a proper shut-down of the computer can be accomplished during power failures from the regular power distribution grid, and they also act as surge suppressors for the power.

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

- Environmental conditions under which the TP system hardware runs may be subject to temperature and humidity requirements. Thus the physical location of the equipment associated with the TP system within a department is of importance.

11.2.2. TP system configurations

- Smaller TP system configurations may have a stand-alone lay-out whereby one central CPU handles most functions and communication requests. In this configuration there may be only a few users, and access to peripheral devices used for printing and archiving is not shared. Network requirements may also be limited, however, even stand-alone TP systems 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 communication systems. Many of the devices operated and accessed by the large TP system configuration will not have a direct connection, and must be accessed through a number of network switches using a communications protocol such as 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 TP system configurations having many users and remote workstations may require the services of an administrator to maintain security, user rights, networking, back-up and archiving.

11.3. SYSTEM SOFTWARE AND CALCULATION ALGORITHMS

Dose calculation algorithms are the most critical software component in the computerized TP system. 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 dimensional calculations, to partial 3 dimensional point kernel methods, to full 3 dimensional 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 treatment planning systems, and due to the rapidly changing nature of computer power the implementation of these techniques is a constantly evolving process. Specific details on treatment planning dose algorithms can be found throughout the literature, and a small selection is included in the reference 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 which adequately discuss these methods, including Johns and Cunningham, Khan, and Hendee and Ibbot among others.

- The ICRU Report 42 lists the chronological development of dose calculation algorithms for photon and electron beams. It provides representative examples for the calculation of central axis depth dose and cross beam or off-axis ratios for photon beams. Representative examples for electron beam calculations including empirical and semi-empirical formalism for the calculation of central axis depth dose and empirical formalism for the calculation of cross beam or off-axis ratios are also provided.

- Early TP system generated dose distributions through the manipulation of relatively simple 2D beam data for a range of square fields in water. These data sets comprised matrices of central-axis (CAX) percent depth-dose (*PDD*) and several off-axis ratios (profiles) at a number of depths.

- To speed up the calculation, CAX data was converted and stored as “infinite PPD” data, while the profiles were stored along ray-lines back-projected to an arbitrary SSD. In this manner, data could be rapidly manipulated using look-up tables to generate dose distributions onto external patient contours. These types of algorithms were used for both photon and electron beam treatment planning and lead to very fast dose calculations. However, in general they were not truly representative of the 3D scattering conditions in the patient.

- Prior to the advent of widespread CT use in treatment planning, irregular field dosimetry was accomplished using Beams-Eye View films of treatment fields obtained with conventional simulators. Using the CAX and profile data sets, the primary and scatter components of the beam could be separated using the zero area Tissue-Air-Ratio and Scatter-Air-Ratio 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 the 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 as well as changes in the spread of energy due to local scattering caused by 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 linear accelerators, 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 on 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 phantom to obtain a pencil-type beam or dose distribution. By integrating the pencil beam over the patient's surface to account for the 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 three-dimensional integration methods.

    - The *analytical* technique as developed by Sterling calculated the dose in the medium as the product of two equations, one of which modeled the percent depth dose, the other modeled 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 surface. Dose distributions are made by rapidly manipulating measured data sets consisting of central axis percent depth dose and off-axis ratio 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 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 on these models.

- These methods have been further refined by applying differential scatter-air ratio 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.

- *Three-dimensional 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 the review chapters in Khan and Potish, and Van Dyk provide a detailed summary of treatment planning algorithms in general.

11.3.2. Beam modifiers

Treatment planning software for photon beams as well as electron beams must be capable of handling many diverse beam modifying devices found on specific 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 TP system are listed below, separated into two main groups: photon beam modifiers (consisting of jaws, blocks, compensators, MLCs, wedges and) and electron beam modifiers (consisting of cones, blocks, bolus, etc.).

Photon beam modifiers

- ***Jaws****:* Field size is defined with 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 TP system will account for penumbra produced by location of these jaws, and differences in radial and transverse open beam symmetry due to jaw design may also be considered.

- ***Blocks****:* Field shielding is accounted for in the TP system 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 by 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. TP systems are able to generate files for blocked fields that can be exported to commercial block-cutting machines.

- ***MLC**:* The multileaf collimator (MLC) is a beam-shaping device which 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 on the order of 0.5 to 1.0 cm at isocenter are typical, MLCs providing smaller leaf widths are referred to as microMLCs. The MLC may be able to cover all or part of the entire field opening, and leaf design may be incorporated into the TP system to model transmission and penumbra. The MLC may also have varying degrees of dynamic motion that can be invoked during beam-on to enhance dose delivery.

- ***Wedges***: Static wedges remain the principal devices for modifying dose distributions. The TP system can model the effect of the dose both along and across the principal axes of the physical wedge, as well as account for any percent depth dose change due to beam hardening and/or softening along the central axis ray-line. The clinical use of wedges may also 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 during the beam-on condition.

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

Electron beam modifiers

- Electron beams use external collimating devices known as *cones* or *applicators* that reduce the spread of the electron beam in 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 alloy inserts. These shielding inserts can have significant effects upon the electron beam dosimetry (especially *PDD* and output), and these effects may be modeled by the TP system.

- 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 TP system.

- Bolus may be used to increase the surface dose for both photon and electron treatments. Bolus routines, incorporated into TP system 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 TP system can distinguish between bolus and patient so that bolus modifications and removal can be achieved with ease.

11.3.3. Heterogeneity corrections

Heterogeneity or inhomogeneity corrections generally account for 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 surface. Beam obliquity and regions where the beam does not intersect the patient 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 TP system algorithms apply either a correction factor approach or a model-based approach. Generalized correction factors, such as the *Power Law* or the *Equivalent Tissue-Air-Ratio* 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 scatter-air ratio and Monte Carlo-based algorithms consider the transport and scatter in the irradiated medium directly, but have historically involved larger calculation times. Most methods are still having difficulties with dose calculations at tissue interfaces.

11.3.4. Image display and dose volume histograms

- Beams-Eye-Views (BEVs) and Room-Eye-Views (REVs) are used by modern TP systems. The BEV is often used in conjunction with Digitally Reconstructed Radiographs (DRR) to aid in assessing tumour coverage, and for beam shaping with blocks or an MLC.

    - The REV gives the user a perception of the relation of the gantry and couch 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 (DCR) may also 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 the TP systems by substituting energy shifted attenuation coefficients for the CT data sets. These virtual portal images can be used to compare the expected portal image with field superimposed to that taken with the patient on the machine.

    - Image registration routines can help match simulator, MR, PET, SPECT, ultrasound and other image sources to planning-CT and treatment acquired portal images.

- Dose Volume Histograms (DVHs) are calculated by the TP system with respect to target and critical structure volumes in order to establish 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 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. TP systems can employ logic to help define volumes when dealing with overlapping structures. For example, when a volumetric margin is defined around a target, the TP system 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

- Optimization routines including inverse planning are provided by TP systems with varying degrees of complexity. Algorithms can modify beam weights and geometry or calculate beams with 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 pre-defined beam geometry specific to clinical sites (e.g., prostate, etc.) to shorten calculation times.

- Beam time and monitor unit calculation by TP systems is optional. The calculation process is directly related to the normalization method. Relative field size output factors, wedge factors, tray factors and other machine specific factors are required. 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 (RV) systems

Networked TP systems 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 TP system manufacturer, the linac manufacturer, or through third party software. They may require a mapping between various accessories on the linac and the TP system so that devices such as the jaws and wedges are oriented correctly with respect to the patient anatomy. Communication between the TP system and the linac avoids the errors associated with manual transcription from paper print-out to the linac, and can help in the treatment of complex cases involving asymmetric jaws, and custom MLC shaped fields.

11.3.7. Biological modeling

Distributions modeled 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 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 TP systems, the various mechanical components of the treatment machines must be obtained so that the TP system model of the machine agrees with the possible mechanical motions and limits of the machine. The gantry, couch and collimator rotation conventions used in a particular institution must be described accurately, and the angle convention fully understood. The TP system must also be able to distinguish between jaw pairs and accurately model the limits of the jaw over-travel.

- Static and virtual wedge use by the TP system 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 that are used by the linac to generate jaw movements, such as Segmented Treatment Tables (STT), may also be used directly by the TP system.

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

- Linacs that are capable of producing IMRT fields may do so via step-and-shoot or fully dynamic techniques. For these types of treatments the TP system requires data regarding maximum leaf speed, 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 TP system, and physical data related to the attenuation coefficients of materials used to fabricate physical compensators is required.

- Electron cone design varies from one linac manufacturer to another. The TP system may require information regarding the distance from the cone to the nominal SSD as well as the external dimensions of the electron cone to produce rooms-eye-view so as to avoid potential patient-machine collisions.

11.4.2. Beam data acquisition and entry

- The beam data required by the TP system 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 ionisation chambers or diodes), and any geometrical correction factors that must be applied to the data. Beam data is often smoothed and re-normalized both following measurement and prior to data entry into the TP computer.

- Typical photon beam data sets include central axis *PDD*s and off-axis ratios (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.

- 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 TP systems. These values are used both in treatment time calculations and in the calculation of dose distributions involving dynamic beams (dynamic wedge, dynamic MLC, etc). 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 Monitor Unit calculations. Central axis wedge factors, tray factors and other accessory factors (normally the ratio of dose with and without the accessory) are also required by the TP system.

- 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 ionisation 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 direct reading in dose.

- Monte Carlo TP systems 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 ionisation 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. Hardcopy 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 keyboard. This may be required for text, parameters such as transmission and field size factors, or for more detailed data sets such as *PDD* and profiles. Other parameters may be required on a trial and error nature by the TP system 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 TP system is common. The digital nature of the computer-acquired beam data makes it readily available to the TP system; 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 TP system. 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 and this mode of radiation treatment planning is referred to as conventional 2-D treatment planning.

- 3-D 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 patients' volumetric anatomical information is likely to be derived from multi-slice 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 (MR, PET, SPECT, Ultrasound, DSA) is translated or registered with another data set, typically CT.

- The patient image data may be transferred to the treatment planning system via DICOM 3 (Digital Imaging and Communications in Medicine) format or DICOM RT 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 dataset that belongs to an organ or tumour is defined. Manual contouring on the TP system 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 ICRU 50 and ICRU 62, including the gross tumour volume (GTV), clinical target volume (CTV) and planning target volume (PTV) are used by the TP system 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 dose-volume histograms (DVH).

- Patient anatomy may be displayed using the BEV capability of the TP system. 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 treatment planning systems 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 build-up 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 TP system. Standard test data sets such as the AAPM TG-23 data set can be used to assess the TP system performance. TP system data can also be compared to 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.

- Hardcopy plots of basic TP system 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 the TP system performance. More complex set-ups involving partial fields and inhomogeneous phantoms may also be considered. Geometrical verification of the accuracy of the TP system to produce shielded regions, either as blocks or apertures, can be performed by overlaying hardcopy. When designing shields with an MLC, the leaf intersection on the region of interest may occur on the outer corner, center or inner corner. This must be verified in order to assess the amount of over- or under-shielding that occurs.

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

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

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

- Calculations of rotational beams for both photons and electrons can be compared to 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 treatment planning system, a file transfer process must be performed. Computerized tomography using helical scans may require separate transfer software.

- The transfer of image data is checked by performing 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 pixel values, scan size and matrix size. The images must be checked for the integrity of surface rendering especially for unlinked structures like arms.

- The large amount of data used by a TP system 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 on all TP system, and the frequency and scope of these procedures are described in the references. The use of checksum 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 TP system are required, and these spot checks can also involve calculations of fields shielded by blocks or MLC. 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 TP system. Wedge distributions produced by the TP system 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 TP system to another and have a direct impact on the representation of patient dose distributions. Normalization may be referred to: (i) a specific point such as the isocenter or to (ii) the intersection of several beam axes, or to (iii) a minimum or maximum value in a slice or entire volume. Normalization can be 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 *SAD*.

- Common TP system weighting 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 isocenter or a *TPR* weighting whereby a 100% beam weight produces a distribution having a value at isocenter in the patient equal to the sum of the beams' *TPR*s.

- Manual or hand 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 hand checks do not need to be precise, yet they serve as a method of detecting gross errors on the part of the TP system.

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 TP systems, 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 TP system beam calculations.

11.5.6. Training and documentation

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

Most manufacturers of TP systems 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 computerised treatment planning system a scheduled quality assurance (QA) program should be established to verify the output of the TP system (see also 12.3.7).

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

- Scheduled quality assurance tests for TP systems will validate data relating to routine treatments using photon beams, electron beams and brachytherapy programs. The tests should verify not only the output of physical data (such as *PDD*, *TPR*, off-axis ratios, effects of blocked fields, inverse square law, decay and half life-considerations), 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 TP system in determining the use of the therapy unit for delivering patient treatments.

- Particular attention may be paid to tests for TP systems that deal with specialized techniques such as stereotactic and 3D treatment planning systems. In addition care must be given to "in-house" systems that are un-documented and undergo routine development. These TP systems may require QA 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 TP system, 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 TP system is an important link in the safe delivery of therapeutic radiation.

11.6. SPECIAL CONSIDERATIONS

Treatment planning systems can be dedicated for special techniques as stand-alone systems. In addition there are various clinical procedures that require careful consideration because of their inherent complexity.

A partial list of techniques that require special consideration and may result in dedicated TP systems include:

- *Brachytherapy*
- *Orthovoltage raditherapy*
- *Intensity Modulated Radiation Therapy (IMRT)*
- *Dynamic MLC (dMLC)*
- *Total Body Irradiation (photon and electron)*
- *MicroMLC*
- *Stereotactic Radiosurgery with linacs or Gamma Knife*
- *Tomotherapy*
- *Intraoperative Radiotherapy*
- *D-shaped-beams for choroidal melanoma*
- *Electron beam arc therapy*
- *Total Skin Electron Irradiation*

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