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Optimization of field matching in external photon beam radiation therapy

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A la meva família i als meus amics

Preface

Aim and Scope

Radiation therapy is one of the main modalities used for treating cancer patients, together with surgery and chemotherapy. Radiotherapy treatments can be carried out with a great variety of devices, but most treatments are currently delivered with megavoltage x-ray beams produced by medical linear accelerators (linacs).

Many treatments are carried out with adjacent radiation fields. This situation occurs, for instance, when the length of the target volume is greater than the maximum field size provided by the linac. Sometimes, fields with different orientations are needed to treat different parts of the patient, which also makes it necessary to use adjacent fields. In these cases, fields need to be matched in such a way that their side planes are coincident. Field matching can be performed using a single isocenter technique, where half-fields with no divergence at the central axis are combined, or with a multiple isocenter technique, where fields with different isocenters are matched by rotating the couch and the collimator.

The dosimetry at the junction of abutting fields depends on several factors, including the position and size of fields, the calibration of the jaw positioning and small mechanical inaccuracies of the treatment unit. All these effects limit the homogeneity of the dose distribution at the junction, which can be off by as much as $\pm$30-40%.

This PhD thesis deals with different aspects related to field matching using medical linacs. The aim is to optimize the process in order to improve the accuracy of this technique in clinical practice.

Thesis outline

This thesis is organized in three parts. The first part is an introduction to radiation therapy that provides the background needed for the understanding of the thesis. This introduction includes a brief description of medical linacs, the main steps in radiation therapy and a discussion of the situations where field matching is used. The second part contains the results obtained. They are included in four publications. Two of them focus on the geometrical problem of field matching; the other two on the optimization in single-isocenter half-beam techniques. The third part summarizes the main conclusions, which are also divided in the two topics described above.

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Chapter 1

Introduction

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1.1 Radiation therapy

Radiation therapy consists in the use of ionizing radiation for the treatment of patients with cancer. Its mechanism of action is based on the damage produced to the cell DNA, which can result in cell death or in the loss of the cell capability to reproduce. The aim is to treat the disease with a radiation dose high enough to eliminate the tumor, whilst minimizing the absorbed dose received by the healthy surrounding tissues and organs (M.Washington and Leaver 2009).

Radiation therapy is one of the three main modalities used in oncology, together with surgery and chemotherapy. Most common cancer types are currently treated with radiation therapy, either alone or often in combination with surgery, chemotherapy and hormone therapy. Indeed, approximately 50% of cancer patients benefit from radiation therapy during their treatment courses.

Radiation therapy treatments can be classified in three main types, depending on the position of the radiation source being used:

a) Systemic radioisotope therapy, where radioisotopes (unsealed radioactive sources) are administered to the patient by infusion or oral ingestion.

b) Brachytherapy. One or several sealed radioactive sources are placed next to or directly into the tumor. Radioactive source placement can be temporary or permanent and brachytherapy can be performed with a large variety of techniques.

c) External beam radiation therapy or teletherapy. In this case the radiation source is located outside of the patient. External beam radiation therapy is mainly performed with linear accelerators, but other devices such as tomotherapy and cyberknife units are also commercially available.

The first medical linear accelerator was installed in the 1950s. During the following decades, linear accelerators gradually replaced cobalt units, which use the gamma emissions emitted during the decay of a radioactive cobalt-60 source. Linear accelerators have become widely used in radiation therapy, with thousands of units currently installed around the world. In contrast to Co-60 units, which emit essentially two gamma energies of 1.17 and 1.33 MeV, linear accelerators can produce both megavoltage electron beams and x-ray beams with a range of energies and they offer important technical advantages. Because of these advantages, very few cobalt units are still used in highly developed countries. Cobalt units, however, require lower installation and maintenance costs. For this reason, in developing countries cobalt machines are still in use.

Other particles, such as protons and heavy ions, can also be used in radiation therapy, a modality known as particle therapy. These particles offer biological advantages and improved dosimetric distributions with respect to x-rays. Particle therapy is already being used with cyclotrons, synchrotrons or synchrocyclotrons in a number of centers around the world. However, these facilities are considerably more expensive, which is why their use is still very limited.

This thesis is focused on external photon beam radiation therapy delivered with linear accelerators. Many of the results obtained, however, are also valid for other treatment machines such as cobalt units.

1.2 Medical linear accelerators

1.2.1 Design

Medical linear accelerators (linacs) are built with different designs, but most of the units installed in radiation therapy departments share a similar design (Podgorsak 2005; Khan 2009). Basically, high voltage pulses are sent to both an electron gun and to a klystron. The electron gun supplies the electrons, which are injected into the linear accelerator structure with an initial energy of approximately 50 keV. Pulsed microwaves delivered by the klystron are introduced into the accelerator structure, where they produce stationary electromagnetic waves. Electrons are then accelerated by these waves and directed towards the exit window, where a narrow high energy electron beam is obtained. This beam can be used to deliver an electron beam or it can be directed to strike a target in order to produce an x-ray beam.

In some 'low-energy' linacs (typically 4-6 MV) the accelerator structure is short enough to be placed vertically, in such a way that electrons strike the target directly. However, in most linacs the accelerator structure is horizontal and the produced electrons are turned by a bending magnet an angle of 90^o or 270^o before hitting the target. The target is made of a high atomic number material such as tungsten which, when hit by electrons, generates bremsstrahlung photons. This photon beam has a continuous spectrum with a maximum energy equal to the electron's initial energy and a mean energy of roughly one third of that maximum energy. The photon beam is usually identified by its maximum energy in megavolts. In consequence, a photon beam produced by 18 MeV electrons has a maximum photon energy of 18 MeV, a mean photon energy around 6 MeV and it is referred to as a 18 MV photon beam.

Several types of linacs are available for clinical use. Some of them produce only x-rays in the low megavoltage range (typically 4-6 MV), while others provide both photon and electron beams of several energies. Modern linacs usually provide either a single photon energy (for instance 6 MV) or two photon energies (for instance, 6 and 18 MV), together with several electron energies (for instance 6, 9, 12, 16 and 20 MeV).

1.2.2 Components of medical linacs

The components of clinical linacs are:

- Modulator
- Gantry stand
- Gantry
- Treatment couch
- Treatment room
- Control console

A schematic diagram of a typical modern medical linac and its main components is shown in Fig. 1.1. A description of these components is now presented.

Modulator

The modulator cabinet is located inside the treatment room. Its main purpose is to supply high-voltage electrical pulses to the klystron.

Gantry stand

The gantry stand is the structure that mechanically supports the gantry. It includes the following components:

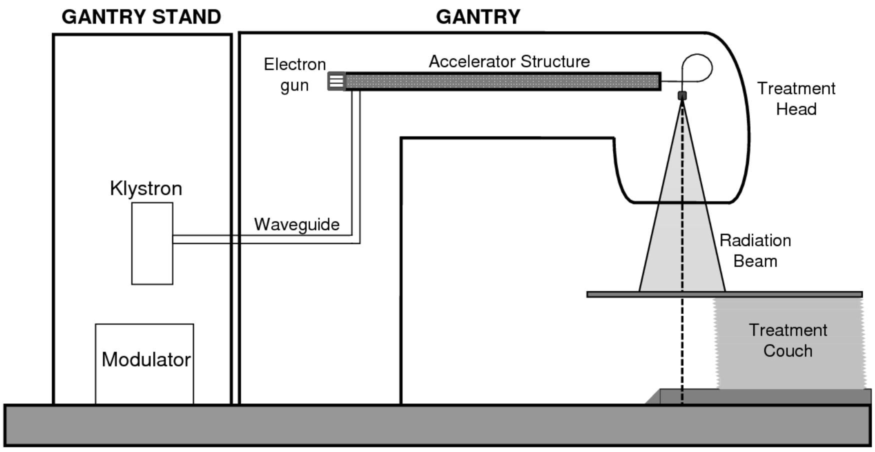

Figure 1.1: Main components of a medical linac.

- The klystron. It is a high power microwave tube that amplifies high frequency waves, which are afterwards directed towards the gantry through the waveguide system.
- The circulator. It leads radiowaves into the waveguide system. The circulator prevents microwaves from reflecting back into the klystron.
- The waveguide. It is a hollow structure that steers microwaves from the klystron to the accelerator structure.
- The pressurizing gas system for the waveguide.
- The cooling water system. It is a thermal stability system that cools down several components of the linac, preventing them from absorbing excess heat because of the linac operation.
- The pressurized air system, used to move the target and the carrousel. The latter contains several components, *e.g.*, the flattening filter and the scattering foil (see below).

Gantry

The gantry is a structure that includes the elements used to accelerate electrons and to generate the clinical beam. It can rotate 360^o to produce radiation fields with different orientations.

The upper part of the gantry contains several components:

- The electron gun. It generates the electrons that are afterwards injected into the accelerator structure.

- The accelerator structure. It accelerates electrons to megavoltage energies by using standing electromagnetic waves. Its length varies depending on the beam energy—the greater the length, the higher the energy.

- The automatic frequency control system (AFC). This system fine tunes the radiofrequency in order to maintain the radiation output stable.

- The vacuum system, which keeps the high vacuum needed in the electron gun and in the accelerator structure.

- The treatment head. It includes the bending magnet, the target, the primary collimator, flattening filters, the secondary collimator, the multileaf collimator, etc. Due to its importance, the treatment head is described in detail in the next section.

The lower part of the gantry usually includes:

- A counterweight to compensate for the weight of the treatment head and allow an accurate rotation of the gantry. In Varian linacs the weights of the treatment head and the counterweight are about 7 and 4 tonnes, respectively. These relatively large weights introduce mechanical torsions and deflections.

- An imaging system (portal imager). This system, mounted on a retractable arm, provides images that are produced by the same megavoltage x-ray beam that is used for the treatment. Portal images can be used to verify the beam shape, the patient positioning and even for dosimetry purposes.

Modern accelerators offer the possibility to incorporate an additional kV x-ray tube (similar to the ones used in diagnostic radiology) and an amorphous silicon flat panel, each in one side of the gantry. These systems improve the image quality for patient positioning verification and allow the acquisition of cone beam computed tomography scans of patients at the treatment position.

Treatment couch

Medical linacs include a treatment couch, the patient positioning support where patients are lying during treatment. To facilitate the patient positioning, the treatment couch permits the following movements:

- Longitudinal: In the direction towards or away from the gantry.

- Lateral: Perpendicular to the longitudinal direction and parallel to the floor.

- Vertical: Up (away from the floor) and down (towards the floor).

- Rotation: The treatment couch can rotate about a fixed vertical axis.

The treatment couch must support up to 200 kg without bending significantly and, furthermore, it must provide accurate movements to allow for precise patient positioning. It is usually made of carbon fiber to minimize the photon beam attenuation caused by the couch and to reduce scattered radiation. An image of a modern linac is given in Fig. 1.2 where the gantry, the gantry stand, the treatment head and the treatment couch are shown.

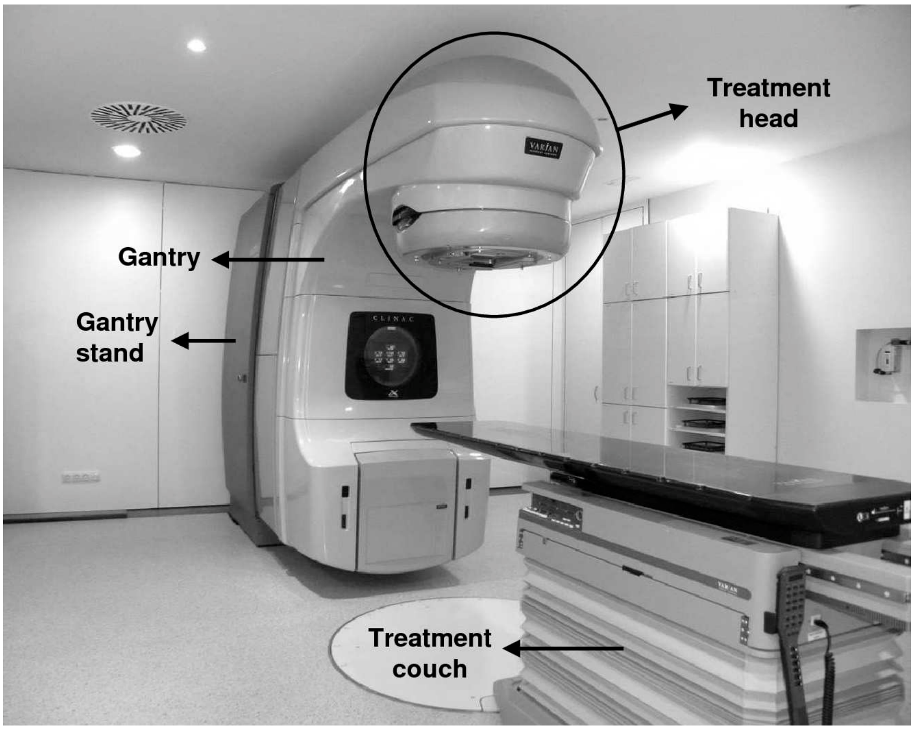

Figure 1.2: Medical linac with the gantry at 0^o.

Treatment room

Linacs are installed in shielded rooms for radiation safety considerations, that is, to minimize the radiation exposure in adjacent areas. Concrete (normal or high-density) is commonly used as the shielding material, and large thicknesses are required. Thick motorized doors are also necessary, especially when high energy photon beams are used, to block scattered radiation and to shield secondary neutrons produced in the treatment head. These rooms are often known as bunkers.

Treatment rooms are equipped with lasers that project lines from the walls and from the ceiling along horizontal and vertical orthogonal planes. These lines intersect at a point called the isocenter of the treatment unit (see below) to provide a visual reference for patient positioning.

Control console

The control console is the system that monitors and controls the linac operation. It includes the computers, monitors, cameras and other devices that allow the appropriate delivery of treatments.

The control console is located outside the treatment room and it usually includes computer software to manage patient information (treatment plans, patient images, record and verify system, etc). It also contains TV cameras to keep visual and audio contact with the patient during treatment delivery.

1.2.3 Treatment head

The treatment head incorporates several components for the production, collimation, localization and monitoring of the beam. Its main components are:

- Bending magnet. It turns the electron beam from the horizontal to the vertical direction (for gantry at 0^o), producing a beam that points to the patient. Some low energy linacs (with one single x-ray energy) are designed with a vertical accelerator structure; in that case, the bending magnet is not necessary.

- X-ray target. Accelerated electrons are directed to hit the target and thus produce a photon beam by means of bremsstrahlung interactions. The target is usually a small cylinder made of a high atomic number material, for instance, a copper and tungsten alloy. The area where the electron beam impacts the target is called the focal spot, also known as radiation source or focus.

- Primary collimator. It is a shielding block made of tungsten with a conical opening. It is located immediately after the target and it limits the maximum field size of the beam.

- Flattening filters. The photon beam generated in the target has a higher flux density in the forward direction. This beam is modified with a filter to obtain a beam as uniform as possible in the plane perpendicular to the beam axis. Flattening filters can be made of various materials such as lead, tungsten, steel, lead, copper and aluminum.

- Monitoring ionization chambers. They are sealed ionization transmission chambers that monitor the dose rate, integrated dose and symmetry of the field while the beam is being delivered, allowing for real-time adjustments and safety checks.

- Jaws or secondary collimators. They comprise two pairs of lead or tungsten blocks, which can collimate the beam to an arbitrary rectangular field size. The two pairs move in directions perpendicular to each other. The movement of these jaws follows the divergence of the beam, which means that for all jaw positions the field side planes contain the focal spot. One pair of jaws,

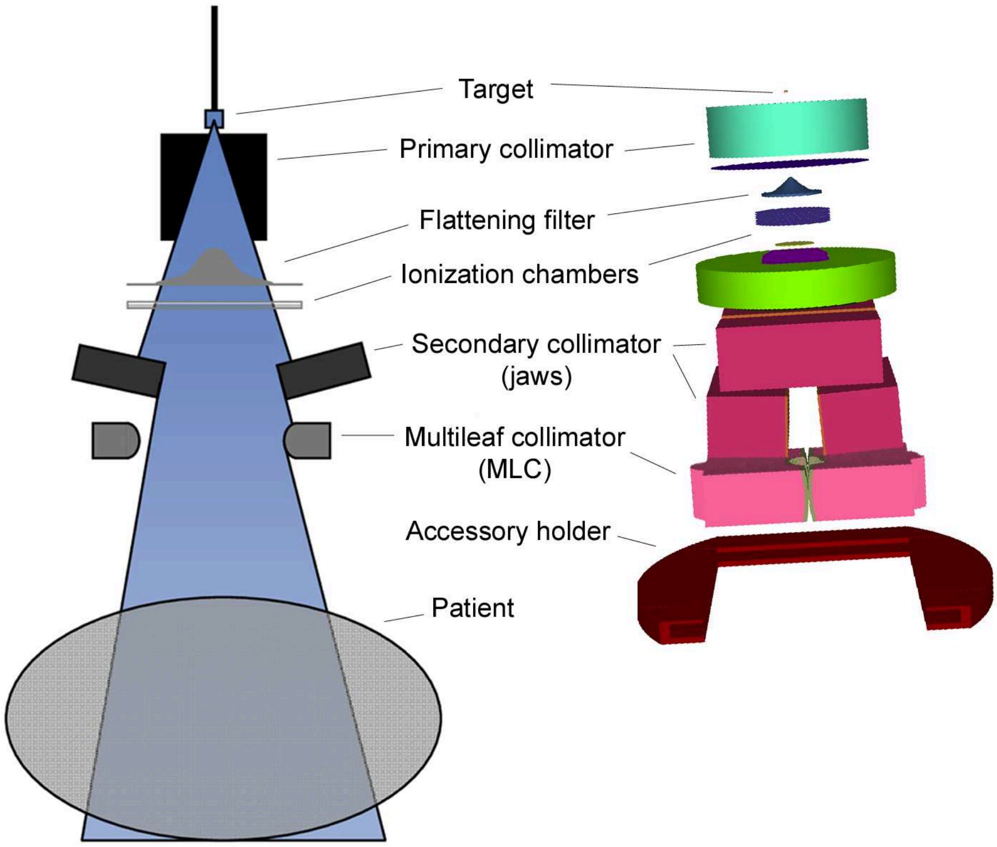

Figure 1.3: Components of the treatment head of a medical linac in photon mode. The photon beam is represented in blue.

located closer to the target, is called the upper jaws, while the others are named lower jaws. The jaws can produce rectangular fields with a maximum size of 40x40 cm^2 measured in a plane placed at a distance of 100 cm from the source.

When each jaw is capable of moving independently from the other jaw in the pair, the system is said to be formed by asymmetric (or independent) jaws. Nowadays most jaws are asymmetric.

- Light field and a range finder. A mirror placed between the ionization chambers and the jaws projects a light field that mimics the radiation field coming from the x-ray source. This light field is visible on the patient and it shows the shape and size of the radiation field. For this purpose, the light field and the radiation field must be aligned in such a way that they are coincident. A visible range finder is also projected to show the distance at the field central axis from the source to the entrance surface. This distance is called the source-to-surface distance and it is usually abbreviated as SSD.

- Multileaf collimator (MLC). It consists of a number of thin shielding blocks, called leafs, which can move independently from each other in order to define arbitrary field shapes. The leaf width is measured in the isocenter plane (that is, at SSD=100 cm) and it limits the conformality of the treatment field. For this reason the leaf width in commercial MLCs has been constantly decreasing in new models (and the number of leafs increasing). Currently, models with 120 leafs are widely used, where 60 pairs of leafs (with widths of 0.5 cm or 1 cm at the isocenter level) are used. Reduced MLC models (called micro or high definition MLCs) are also available. These models use smaller leaf widths (around 0.25 cm at the isocenter level), which can be useful in certain cases, for instance in stereotactic radiation therapy treatments, although the maximum field size is decreased.

  The main advantage of MLCs is that they make possible the delivery of multiple fields without re-entering the treatment room and that they eliminate the need for ad-hoc heavy blocks. Another major advantage of MLCs is that they allow the delivery of intensity modulated radiation therapy (IMRT). Indeed, multileaf collimators make it possible to use techniques such as step and shoot (multiple static field segments), sliding window (continuous dynamic dose delivery) and VMAT (volumetric modulated arc therapy).

- Accessory holder. It can be attached to the treatment head in order to hold optional accessories such as hard wedges, block trays or other add-ons.

For electron beams, the x-ray target and the flattening filter are retracted from the beam path. Instead, the beam passes through a scattering foil which consists of one or several thin metal sheets that scatter the beam to increase its usable size. A so-called electron applicator is attached downstream of the treatment head to define the final shape of the field. Therefore, the characteristics of the beam are not defined by the jaws and the MLC as in the photon case, but by the electron applicator, which can include an additional customized block.

1.2.4 Linac movements and geometrical issues

The gantry can rotate 360^o about a horizontal axis. The two pairs of jaws can also collectively rotate about an axis, the collimator rotation axis, which is perpendicular to the gantry axis. The collimator rotation axis is vertical when the treatment head is in its upper position (that is, the gantry set to 0^o) and, as the gantry rotates, so does the collimator rotation axis. The gantry and collimator rotation axis intersect at a point, called the isocenter, located at a distance of 100 cm from the linac focus.

The patient is positioned and immobilized on a horizontal couch that can rotate about a vertical axis. This axis intersects the gantry and collimator rotation axes at

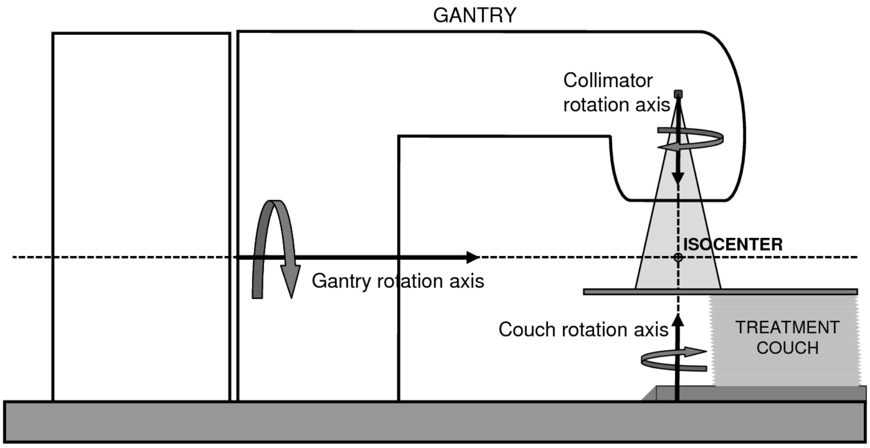

Figure 1.4: Schematic cross sectional view of a linac where the gantry (at 0^o), the collimator and the couch rotation axes, as well as the isocenter, are illustrated.

the isocenter. Hence, the couch rotation axis coincides with the collimator rotation axis when the gantry is at 0^o (treatment head in its upper position).

This design facilitates the use of isocentric techniques, where multiple fields with different orientations are used without moving the patient. These techniques make it feasible to use complex field arrangements, providing good accuracy and reproducibility of treatments in clinical practice.

In summary, medical linacs are mounted isocentrically. This design determines the type of techniques that can be implemented in clinical practice and influences the treatment planning process. It is also key to understand the framework of the present thesis. An image of a modern linac is given in Fig. 1.5 where the three axes mentioned above are shown. Notice that the gantry and couch axes are fixed in space, whereas the collimator axis and the treatment head rotate jointly.

1.3 Clinical process in radiation therapy

The process of radiation therapy involves many steps, from patient data acquisition to treatment delivery (M.Washington and Leaver 2009; Podgorsak 2005; P Mayles and Rosenwald 2007). This process can be divided into three main categories:

- Simulation and patient data acquisition.
- Treatment planning.
- Treatment delivery.

Each one of these categories is explained in the following sections.

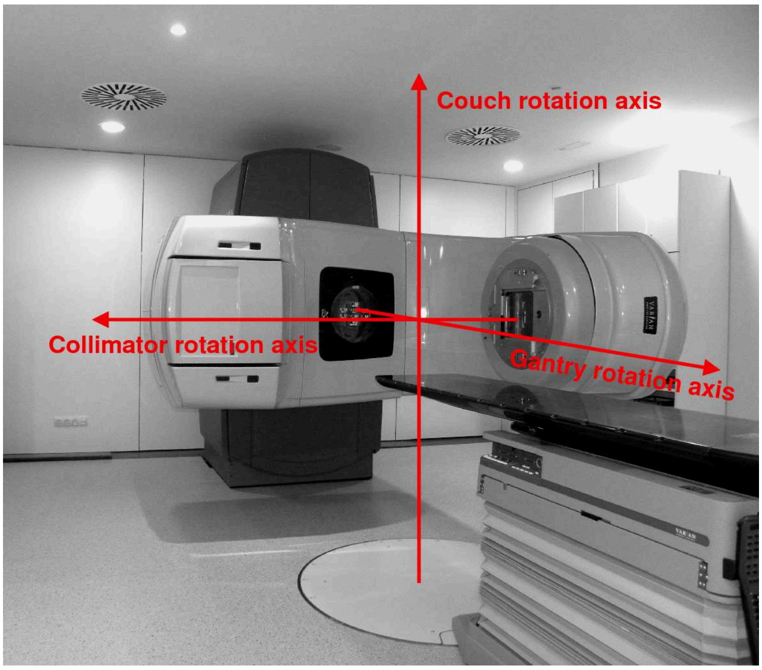

Figure 1.5: Medical linac with the gantry at 90^o. The gantry, collimator and couch rotations axes are represented in red.

1.3.1 Simulation and patient data acquisition

The so-called 'simulation' is the first step in the clinical process. During this step the patient position is determined, patient data is documented and reference marks are applied. This step is fundamental, since it is absolutely necessary for accurate treatment planning and delivery.

First, the position for treating the patient is decided taking into account the area to be treated as well as the protection of normal tissues. Once the treatment position is established, immobilization devices such as masks and breast boards are used to fix the patient and to ensure reproducibility during the different treatment sessions. Reference marks and tattoos can also be used to ensure proper positioning during the treatment. At this point, patient data is acquired. To this end, either a treatment simulator or a computed tomography (CT) simulator can be used.

a) Treatment simulator The treatment simulator is a device similar to a conventional x-ray diagnostic unit that simulates the treatment machine. It can mimic the movements of the linac and it includes features such as:

   - A laser system mounted in the room that allows to set references for the patient's treatment position.
   - Movable wires. These wires simulate the linac jaws, making treatment fields visible in the patient's skin and in the acquired x-ray images.

- Crosshair, which shows the field central axis.
- Patient positioning couch. This couch must have the same characteristics as the linac's treatment couch, including rotation and longitudinal, lateral and vertical movements.

The simulator head contains an x-ray tube with fluoroscopic capabilities, facilitating the determination of the treatment fields to be used (that is, field orientations and field sizes). This makes it possible to define the treatment fields taking into consideration each individual patient's anatomy. Apart from x-ray images, additional information is usually needed for treatment planning. Indeed, other image techniques such as CT scans are commonly used.

b) CT simulator CT simulators are dedicated CT scanners designed for radiotherapy treatment simulation and planning. They include:

- A large bore CT scanner with a wide opening. This opening permits the placement of immobilization devices during CT scanning. It also permits a large variety of patient positions.
- An in-room laser system, needed for patient positioning and to set references on the patient.
- A flat couch that reproduces the treatment couch.

CT scanners supply anatomical images related to the local electron density, measured in the so-called Hounsfield units, with a typical spacing between 2 and 5 mm. These images, which are essential for accurate dose calculation, allow to delineate contours of the patient for both tumor volumes and normal tissues. This step, called 'volume definition', is necessary for 3D treatment planning.

After volume definition, field design and virtual simulation is performed. The software used to this end is capable of producing digitally reconstructed radiographs (DRRs) which mimic conventional x-ray images. DRRs can be obtained for arbitrary fields; thus, simulation can be performed with the CT information (without the patient being present), which is the reason why this process is usually known as 'virtual simulation'.

The process of virtual simulation can be summarized in the following steps:

- Determination of the patient's treatment position.
- Setting references on the patient's skin.
- Acquisition of CT data and transfer to the virtual simulation workstation.
- Volume definition, which consists of delineation of target volumes (tumors) and of healthy surrounding structures (normal tissues and organs at risk).

- Determination of the treatment isocenter with respect to the references.
- Choice of plan parameters such as number of fields, energy, field size and orientation.

Modern treatment planning systems (TPSs) incorporate packages for virtual simulation. In consequence, it is possible to transfer the CT data to the TPS and carry out the volume definition, virtual simulation and treatment planning in a single integrated system.

CT simulators offer important advantages over conventional simulators, allowing for complex and accurate treatment planning based on 3D data sets.

1.3.2 Treatment planning

The primary goal of treatment planning is to achieve tumor control while minimizing normal tissue complications, fulfilling the dose constraints imposed by the radiation oncologist. Normally, the strategy is to deliver a dose distribution as homogeneous as possible to the planning target volume (PTV), whilst minimizing the dose delivered to normal tissues and organs at risk. Usually, a computerized TPS is used to determine the treatment fields and to estimate the dose distribution in the patient. Medical physicists are responsible for TPSs and for obtaining appropriate dose distributions.

The calculated dose distribution is typically represented by isodose lines, *i.e.*, curves that connect points with equal dose, superimposed on the CT image. Isodoses are displayed with different colors depending on the dose value. Dose histograms and statistical information in the delineated volumes (PTVs and organs at risk) are also provided to summarize the 3D distribution. When a plan is approved, it is transferred to the treatment unit for delivery.

Many treatments involve more than one radiation field. In theses cases, two types of techniques are commonly employed:

- Fixed SSD techniques, where the distance between the radiation source and the patient's skin is constant for all fields. Thus, these techniques require moving the couch for each field.
- Isocentric techniques, where the couch can be rotated but not shifted. These techniques provide improved accuracy in treatment delivery.

Isocentric techniques present a number of important advantages over fixed SSD techniques, such as avoiding the need to enter the treatment room for patient repositioning. Therefore, the patient position can be accurately verified and the whole treatment carried out with no interruptions. Thus, most treatments involving multiple fields are nowadays delivered with isocentric techniques. Despite this fact, fixed SSD techniques still play an important role in old cobalt units with a source-to-isocenter distance of 80 cm, due to their reduced clearance between the treatment head and the patient's skin.

During treatment planning, a reference system attached to the patient is commonly used. In this reference system, different couch positions imply different isocenter coordinates. For this reason, treatment techniques where the couch is shifted are called multiple isocenter techniques. Notice that, since the couch axis contains the isocenter, couch rotations do not involve a change of isocenter coordinates.

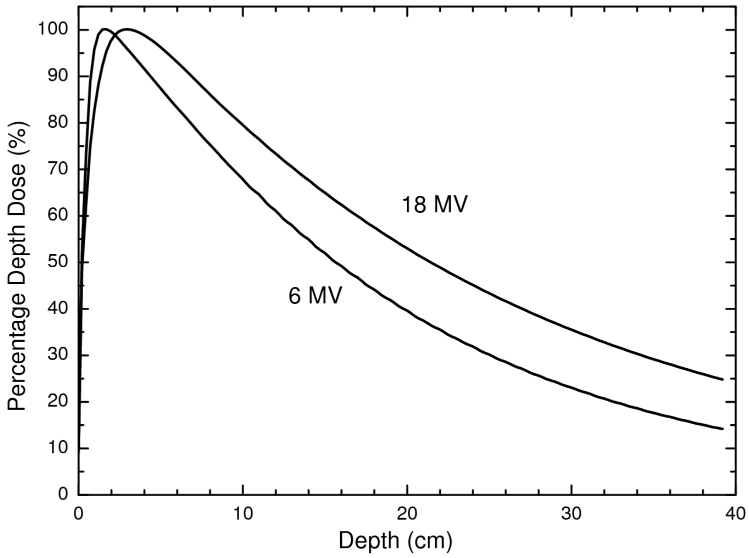

Figure 1.6: Percentage depth dose curves for 6 MV and 18 MV photon beams.

1.3.2.1 Single field

Various photon beam energies are used in clinical practice, usually a 'low-energy' photon beam of 4-6 MV and a 'high-energy' photon beam with nominal energy around 18 MV. The energy of the photon beam determines the penetration of the beam, *i.e.*, how the dose is distributed at different depths.

It is to note that with megavoltage photon beams the dose at the surface is rather low, especially for high energies. This is known as the skin sparing effect, since it prevents the patient's skin from receiving high doses. As depth increases, the dose gradually raises (build-up region) due to progressive generation of secondary electrons until electronic equilibrium is achieved. At greater depths the dose decreases due to tissue attenuation and to the increase in the distance from the radiation source. As a result of these effects, there is a maximum dose at a given depth. This depth is approximately 1.5 cm for the 6 MV photon beam and 3.3 cm for the 18 MV photon beam. The latter produces a more pronounced skin sparing effect and it is relatively less attenuated in depth. This is illustrated in Fig. 1.6, where the dose curves along the field central axis are shown. In Fig. 1.7 isodose lines for a single photon field of 6 and 18 MV incident upon a flat surface are presented.

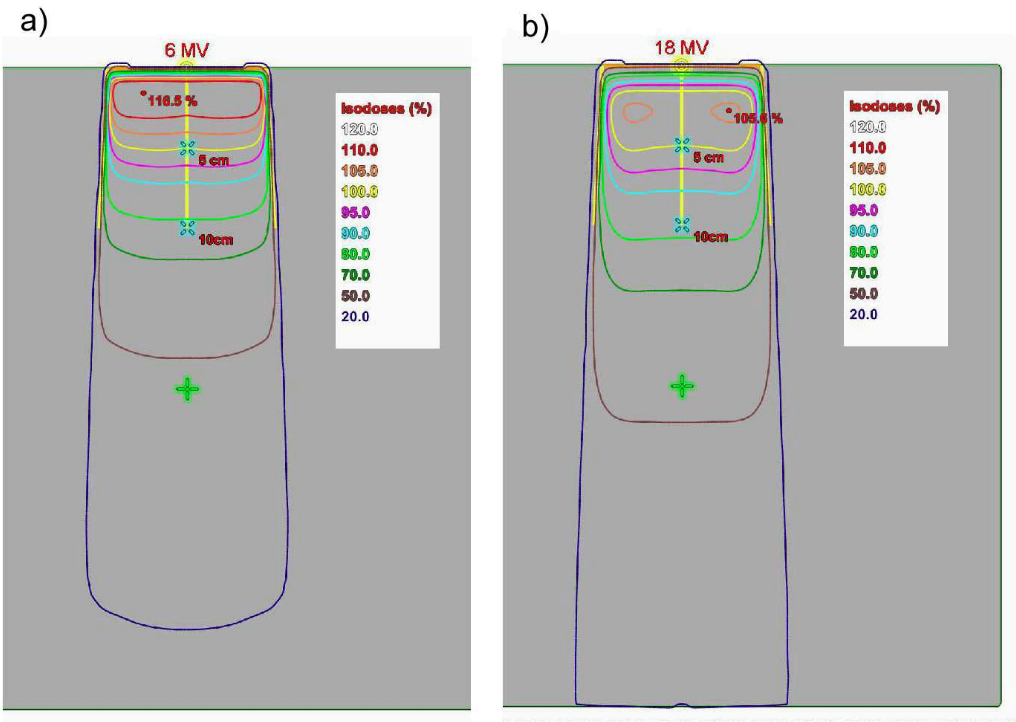

Figure 1.7: Isodose curves for a photon beam of 6 MV (left) and 18 MV (right) from a typical Varian linac incident on a water phantom.

1.3.2.2 Multiple fields

Radiation therapy with megavoltage photon beams is usually carried out with multiple fields in order to achieve a uniform dose distribution inside the target volume while maintaining the dose to surrounding healthy tissues as low as possible. Multiple fields use different machine parameters such as gantry angles, collimator angles, beam energies, field sizes, etc. These fields overlap in the region where a high dose is to be delivered, whereas much lower doses are given elsewhere.

Typical field arrangements

Some simple plans corresponding to different arrangements with multiple fields are commented below (Khan 2009; P Mayles and Rosenwald 2007).

a) Parallel opposed pair

The most basic multiple field technique is the parallel opposed pair, where two fields directed to each other from opposite sides are combined. This field arrangement yields a dose distribution more uniform than that of a single field, giving a similar dose to all the tissues included in the beams path.

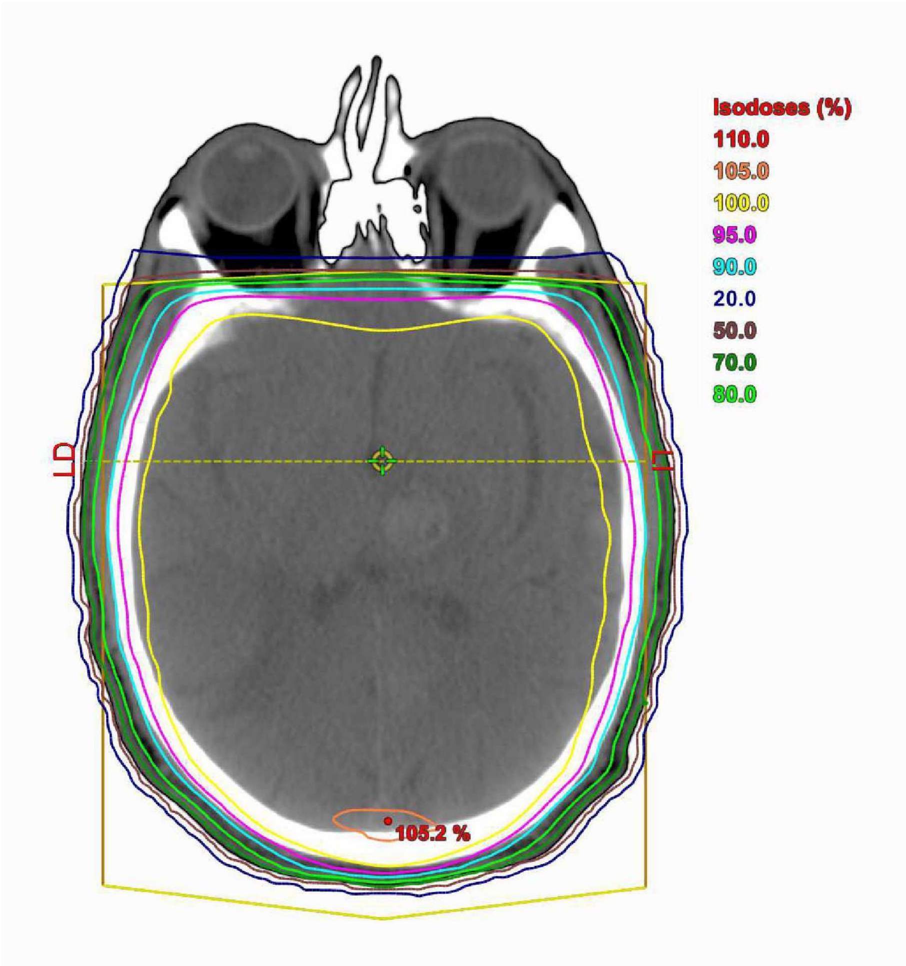

Figure 1.8: Isodose curves for two lateral fields in a whole brain irradiation.

Parallel opposed pairs are used in many situations. Some typical arrangements are:

- Anterior and posterior fields. This technique is used in many palliative cases due to its simplicity.
- Right and left lateral fields. Opposed lateral fields are commonly used in head and neck treatments and in whole brain irradiations. An example of a dose distribution corresponding to a whole brain irradiation is given in Fig. 1.8.

b) Four field technique

Increasing the number of beams permits to reduce the dose to normal tissues compared with parallel opposed pairs, because entrance and exit doses do not coincide. In this case all beams irradiate the target volume, while some of the beams avoid the different organs at risk.

The four field technique includes four fields with a gantry angle difference of 90°: an opposing anteroposterior pair together with two opposing lateral fields. This arrangement is commonly used in the treatment of deep tumors located in the pelvis, where most lesions are central (e.g. prostate, bladder and uterus). This technique is sometimes known as four-field box, because it produces a relatively high dose box-shaped region. A dose distribution corresponding to a prostate case treated with a four field technique is given in Fig. 1.9.

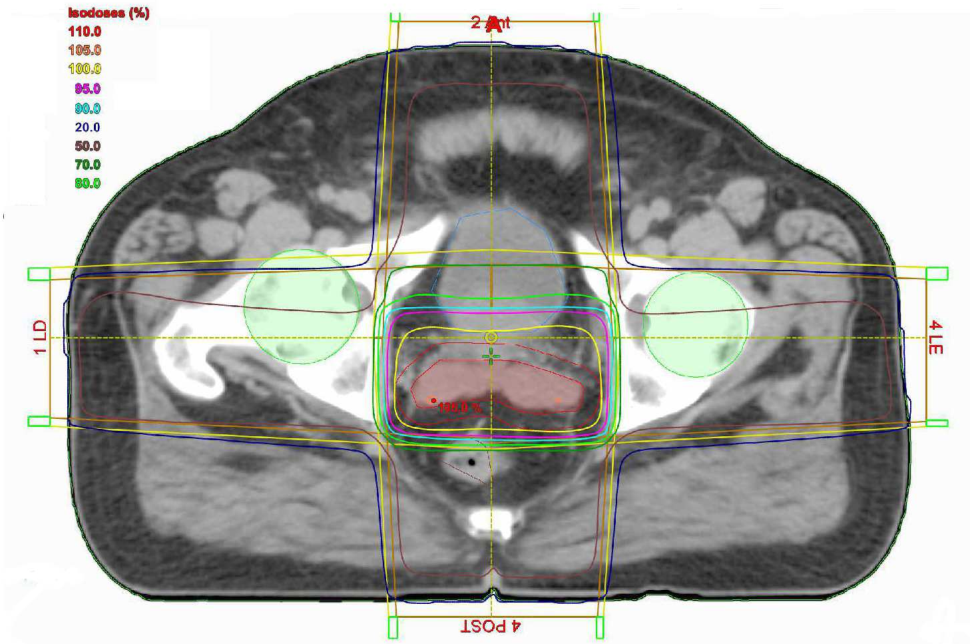

Figure 1.9: Isodose curves for a prostate cancer planned with a four-field technique.

c) Tangential fields

In breast treatments two opposed oblique fields, named tangential fields, are commonly used to treat the patient's breast or chest wall (post mastectomy). These fields irradiate beyond the patient's surface to allow for geometrical changes such as those corresponding to respiratory movements. Sometimes the difference in gantry angle between the two tangential fields varies slightly from 180° to make the edges of the two fields coincident in the lung region– thus avoiding innecessary irradiation of the lung.

In most breast treatments the maximum dose would appear where the breast is thinnest, that is, in the external part of the breast. Wedges, beam modifiers with a triangularly shaped section, are introduced to compensate for this missing tissue and to achieve a more homogeneous dose distribution. In Fig. 1.10 the dose distribution of a breast treatment with two wedges, one for each field, is presented.

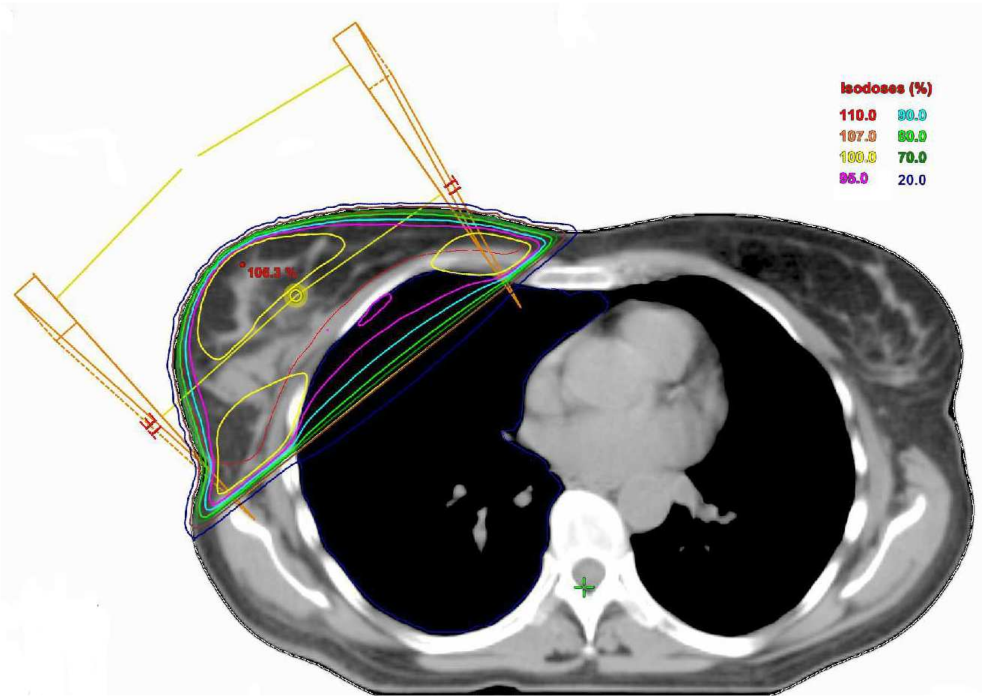

Figure 1.10: Isodose curves for a breast plan with two tangential fields with wedges.

1.3.2.3 Non-coplanar fields

When the treatment couch rotation angle is constant for all the fields involved, the fields are called 'coplanar', since their central axis remain on the same plane (a vertical plane perpendicular to the gantry rotation axis). In cases where multiple fields with different couch rotations are used, fields are called 'non-coplanar'. In Fig. 1.11 two views of a case with 4 non-coplanar fields are shown.

Non-coplanar fields are useful when there is inadequate sparing of organs at risk with a conventional coplanar field arrangement. With non-coplanar fields the doses at the entrance of the fields are distributed over a larger volume, which can help to prevent surrounding tissues from receiving high doses. In these cases care must be taken to ensure that no collisions occur between the treatment head and either the couch or the patient. Indeed, the use of non-coplanar fields is often limited by mechanical restrictions. In brain treatments the limitations due to potential collisions are reduced and the target volume is frequently surrounded by critical structures.

For this reason non-coplanar fields are most often used in brain treatments, where they provide a high potential benefit.

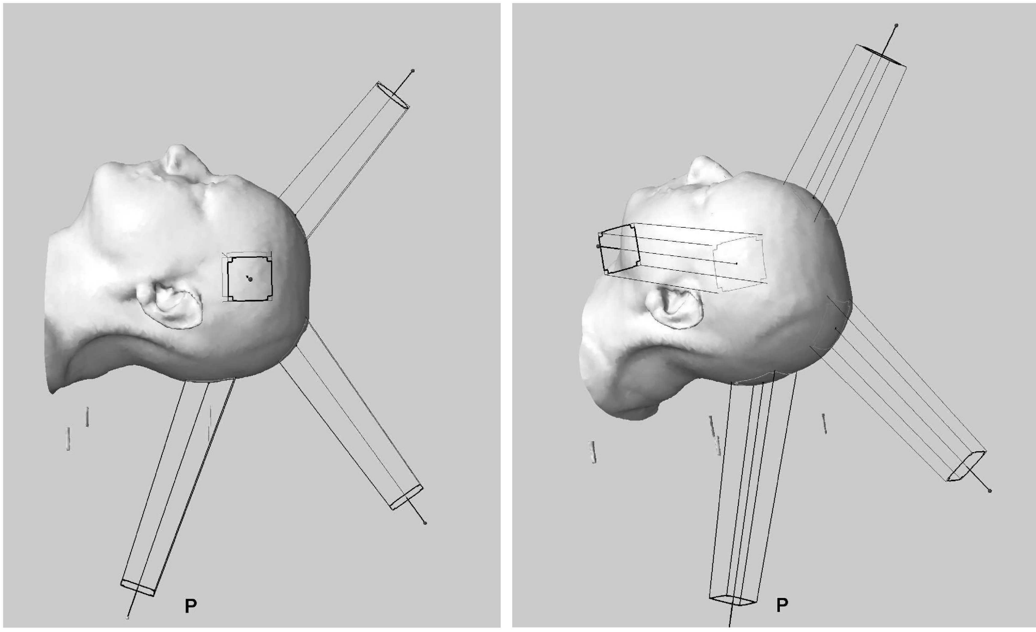

Figure 1.11: Example of a technique with non-coplanar fields.

1.3.2.4 Treatment techniques

1. Conformal Radiation Therapy

   In conformal radiation therapy treatment fields are shaped to conform to the target volume in order to reduce the dose to normal tissues. Relatively uniform radiation intensities are delivered over the beam's aperture and organs at risk are protected by adequate selection of beam orientations. Thus, a high dose is delivered to the target volume, where all treatment fields overlap, while lower doses are given to regions avoided by some of the fields (Podgorsak 2005; P Mayles and Rosenwald 2007).

   In the past, fields were shaped by means of customized blocks that were fixed to trays and placed in the accessory holder, at the end of the treatment head. However, the construction of these individualized blocks was tough and time consuming. Moreover, their use reduced the clearance between the treatment head and the patient's skin and introduced interruptions between treatment fields, since blocks had to be placed manually. Nowadays, MLCs have replaced these customized blocks, avoiding the need for mould room time, for carrying heavy trays and for interrupting treatment sessions.

The treatment planning process involves trying different number of fields and field parameters. Dose distributions for each plan are calculated and the final distribution is manually optimized. Thus, several field arrangements are tested by trial and error until a satisfactory dose distribution is produced. This approach is known as 'forward planning', because beam parameters are first decided and the dose distribution is calculated subsequently. This process can be very complex in some cases, demanding a great expertise.

Some linacs have the capability to rotate the gantry during treatment, while radiation is delivered (beam on). This technique is called arc therapy, because the gantry describes one or several arcs during the treatment. In arc therapy the MLC can move (while the gantry rotates) to dynamically adapt the beam shape to the varying projection of the target volume. Thus, the dose outside the target is spread over a larger volume, decreasing the dose received by healthy surrounding tissues. However, similar dose distributions can be achieved with a large number of static conformed fields.

2. Intensity Modulated Radiation Therapy (IMRT)

   IMRT is an advanced form of 3D conformal technique which uses a new approach. In IMRT the radiation intensity over the beam's aperture is modulated to protect normal tissues. Regions in the target volume with lower doses from one field are then compensated by higher doses delivered from other fields in such a way that a homogeneous dose distribution to the target volume with a steep dose gradient to adjacent normal tissues is obtained. Thus, the use of multiple beams with non uniform intensity profiles permits the production of more conformed dose distributions, better adapting the dose to the target volume. The purpose of IMRT is to allow the escalation of the dose given to the tumor while minimizing the dose received by the surrounding tissues (Podgorsak 2005; P Mayles and Rosenwald 2007).

   There are several possibilities available for IMRT delivery. In linear accelerators the beam intensity is usually modulated by means of a MLC. The following strategies are used:

   (a) Step-and-shoot. The IMRT fluence is divided into a number of uniform subfields (also known as 'segments'), each one with its corresponding static MLC position. While the MLC is being set to each one of these positions the radiation beam is turned off. Once the MLC reaches one of its static configurations the beam is turned back on. This process continues until all segments are delivered.

   (b) Sliding window or dynamic MLC. Leaves of the MLC move while the beam is on to produce the desired intensity profile. This method is faster and more efficient than step-and-shoot, but it requires an MLC with dynamic capabilities.

Generally speaking, treatment planning in IMRT is too complex for the application of the 'forward planning' method described above because the number of degrees of freedom is too large. Instead, an alternative approach known as 'inverse planning' is used. In inverse planning a number of dose constraints are introduced in the system and the TPS determines the optimal beam parameters that best fulfill them. The considered parameters include field size, intensity profile and MLC configuration, but they can also include the number and orientation of the treatment fields. Thus, conceptually, inverse planning is the reverse of forward planning, since beam parameters are determined from the clinical objectives.

A technique called 'Volume Modulated Arc Therapy' (VMAT) has been recently developed. VMAT uses arc therapy with intensity modulated arcs, where the gantry rotates about the patient while the beam is on and the MLC is dynamically moving to modulate the beam intensity. Moreover, both the dose rate and the gantry rotating speed are adjusted to reach an optimal dose distribution in the shortest possible elapsed time.

Other advanced techniques such as treatments delivered with tomotherapy, Cyberknife ®, protons or heavy ions are available. Notwithstanding, nowadays most patients receiving radiation therapy are treated with a linac.

1.3.3 Treatment delivery

Treatments are delivered in multiple sessions (also called fractions) in order to optimize the clinical efficacy of radiation therapy. Daily fractions are commonly used, although other fractionation schemes such as hyperfractionation (more than one fraction per day) or hypofractionation (higher daily doses distributed in fewer fractions) are used in certain cases. These fractionation schemes make it necessary to ensure patient positioning and treatment reproducibility throughout the entire treatment course (M.Washington and Leaver 2009).

Prior to treatment delivery, reference images provided by the treatment planning system are used to check the patient positioning. Control images are afterwards obtained in the treatment unit with the patient on the treatment position and they are compared to reference images for verification purposes. Computer assisted treatment delivery, as well as record and verify systems, greatly reduce errors when treating patients, allowing for faster and more reliable procedures.

1.4 Field matching

The radiation field originates from a point in the treatment head called the 'focus'. The field can be conceived as a pyramid of rectangular base whose sides are limited by the two jaw pairs. These sides, called field side planes, are depicted in Fig. 1.12.

Adjacent fields are commonly used in radiation therapy for two main reasons:

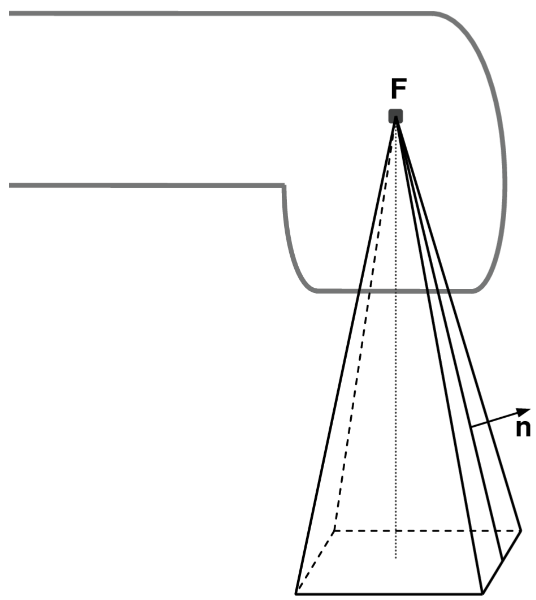

Figure 1.12: Sketch showing the pyramidal shape of the radiation field. The focus (F) and the normal vector (**n**) perpendicular to one of the field side planes are represented.

a) The extension of the region to be treated (PTV) is greater than the maximum field size produced by the linac, which is of 40×40 cm^2 at a distance from the focus of 100 cm.

b) Fields with different gantry angles are required in different parts of the PTV in order to protect organs at risk and to adapt to the patient's anatomy.

If field matching is not correctly performed a non uniform dose distribution across the junction is produced. Overlapping of fields results in overdosage and may cause unacceptable fibrosis or normal tissue complications (Datta *et al* 1979; Chiang *et al* 1979; Podgorsak *et al* 1984; Rosenow *et al* 1990), while a gap produces underdosage and reduces tumor control probability. One might think that field side planes can be visually matched at the patient's skin and field parameters decided by visual inspection of the field entrance at the skin, while the patient is lying on the treament couch. This approach to field matching was historically used in many centers, but it has some major drawbacks. Indeed, it is not possible neither to see the edges of the treatment fields inside the patient nor to visually manage the multiple variables involved in this three dimensional problem. Therefore, this method may lead to a sizeable overdosage or underdosage, which renders it inappropriate for clinical practice.

The simplest field matching technique is to match the field side planes at a certain depth (Podgorsak 2005). A simple case with two anterior fields matched at a depth d is shown in Fig. 1.13. Note that at a depth smaller than d there is a region where no field contributes, whereas at depths greater than d fields partially overlap. This originates undesired high dose inhomogeneities in the junction region.

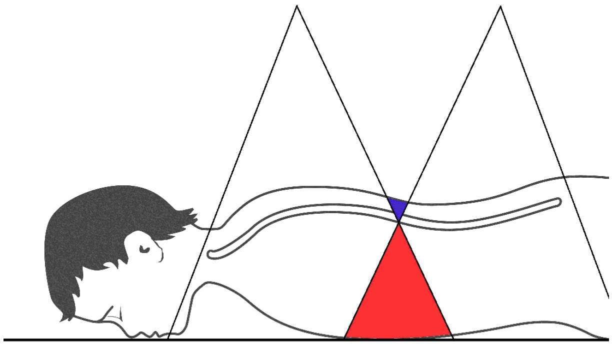

Figure 1.13: Sketch showing two adjacent fields not geometrically matched. The underdosage region (where none of the fields contribute) is highlighted in blue. The overdosage region (where both fields contribute) is painted in red.

To achieve a uniform dose distribution across the junction adjacent fields have to be geometrically matched to one another in such a way that their side planes coincide. This is a complex problem due to the divergence of the fields, especially when fields with oblique orientations are involved. The solution to this problem requires the precise matching of field side planes, also called geometrical field matching. One possibility to match adjacent fields consists in using the 3D views offered by modern TPSs. These can show the side planes from selected fields and, hence, they permit to visually assess different configurations until an acceptable matching is achieved. However, this procedure is time consuming. The knowledge of the exact analytical solution to this problem would, therefore, be highly useful in clinical practice.

IMRT may not require the use of fields with different gantry angles in adjacent parts of the treatment volume and, thus, these techniques can avoid field matching in some occasions. However, adjacent fields are widely used in clinical practice, in approximately between 10% and 15% of all radiation therapy treatments.

1.4.1 Geometrical field matching

In the following sections some examples are given where field matching is used. These examples include breast treatments with a supraclavicular field, craniospinal irradiation and head and neck treatments with a lower anterior field (P Mayles and Rosenwald 2007; Bentel 2009).

1.4.1.1 Breast treatments

For the treatment of breast cancer two tangential fields are typically used to treat the breast or chest wall. A separate anterior field is necessary when the supraclavicular (SC) region is also to be treated. The SC field is usually considered to be 'fixed', and tangential fields are matched to it by using collimator and couch rotations and selecting the appropriate field size. In Fig. 1.14 a sketch is given showing a case with two tangential fields and an anterior SC field.

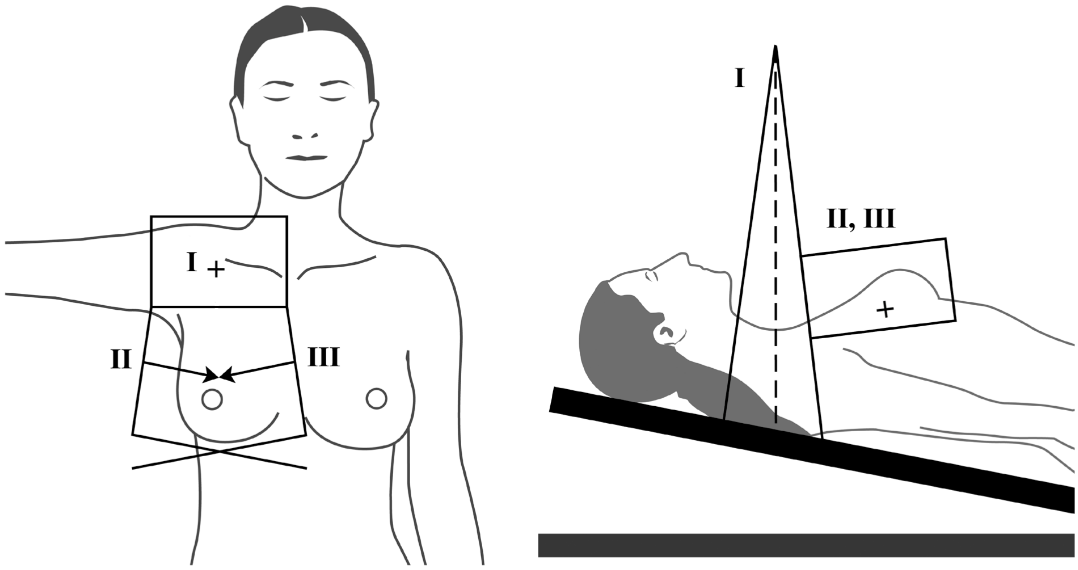

Figure 1.14: Sketch with a lateral and an anterior view of a breast treatment with a SC field. The anterior SC field (I) and the two tangential fields (II and III) are illustrated.

1.4.1.2 Craniospinal irradiation

Patients with leukaemia and medulloblastoma are usually treated with a craniospinal (CSI) irradiation, that is, in the prone position with a posterior spinal field adjacent to two parallel-opposed lateral cranial fields (with gantry angles 270^o and 90^o). In CSI the spinal cord is included in the junction zone. Underdosage increases the risk of recurrence, while in the case of overdosage complications such as spinal cord damage and paralysis may occur. Therefore it is crucial to achieve a correct match. In CSI the two lateral fields need collimator and couch rotations in order to be matched to the posterior field. In adult patients the region to be treated with the posterior field is usually larger than the maximum field length, which is 40 cm at the isocenter plane. In consequence, an additional posterior field is needed, which needs to be matched to the other posterior field as well.

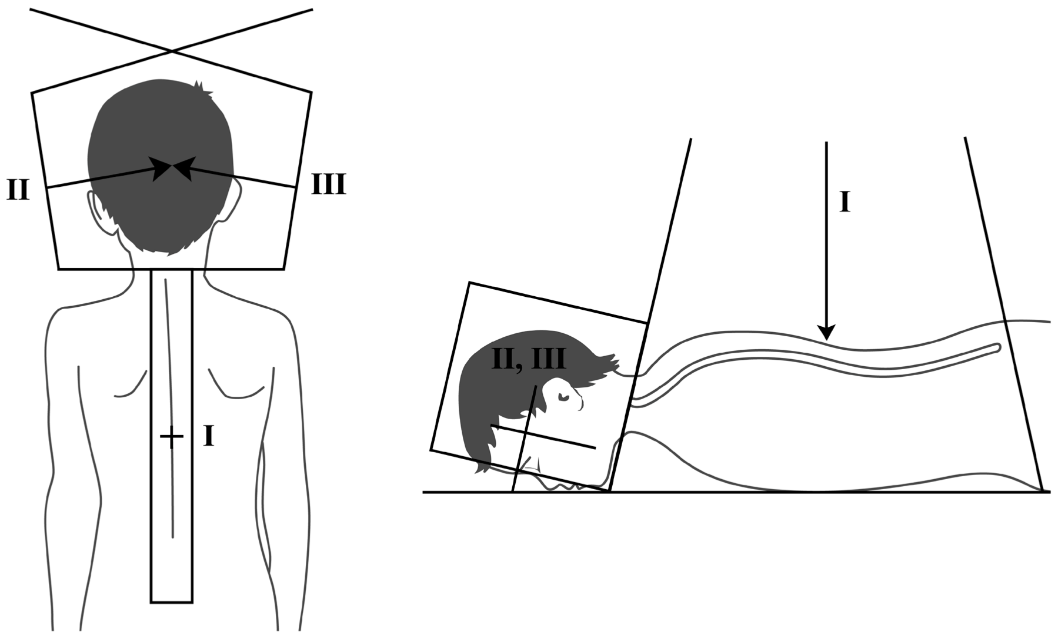

Figure 1.15: Sketch with a lateral and a posterior view of a CSI treatment with a posterior spinal field (I) adjacent to two parallel-opposed lateral cranial fields (II, III).

In Fig. 1.15 the three-field technique after the matching has been performed is outlined. The patient can also be treated in the supine position; in this case, considerations regarding field-matching are similar.

1.4.1.3 Head and neck treatments

In head and neck treatments it is common to use orthogonal fields, such as two opposed lateral fields, and an anterior SC field. In this case the considerations regarding field matching are equivalent to those of the CSI case described above. Nevertheless, in head and neck treatments there are many situations where the involved fields are oblique, which increases the complexity of field matching.

1.4.2 Single-isocenter half-beam techniques

Modern medical linacs incorporate asymmetric jaws, which can move independently from each other (see section 1.2.3). With asymmetric jaws the divergence of a field side plane can be eliminated by moving the corresponding asymmetric jaw to the central axis of the field, which is called the 'zero position' of the jaw. Thus, a half-beam is produced, which can be combined with other half-beams with different gantry angles. An opposite half-beam can be generated, for instance, by opening the jaw at the zero position and setting the opposite jaw from the same pair to zero. Thus, the matching of non-divergent half-beams can be readily achieved (Datta *et al* 1979; Chiang *et al* 1979; Podgorsak *et al* 1984; Rosenow *et al* 1990).

In the single-isocenter half-beam (SIHB) technique only one isocenter is used and the treatment is delivered by combining multiple half fields with different orientations. SIHB is probably the technique most widely used because of its simplicity. It is important to note that a disadvantage inherent to it is that the doses at the junction are very sensitive to the calibration of the zero jaw position and, therefore, important dose inhomogeneities can appear due to imperfect calibration of the jaws (Saw *et al* 2000; Rosenthal *et al* 1998). The most recent recommendation from the American Association of Physicists in Medicine (AAPM) establishes a tolerance of 1 mm for the zero position of asymmetric jaws (Klein *et al* 2009). However, deviations within this tolerance still have a substantial impact on the dose distribution across the junction of abutting fields. Indeed, misalignments within the ± 1 mm tolerance produce inhomogeneities of up to 25-35% of the prescribed dose (Lee 1997; Saw and Hussey 2000; Fabrizio *et al* 2000; Abdel-Hakim *et al* 2002; Abdel-Hakim *et al* 2003). These misalignments originate a systematic error throughout the entire course of the treatment and can yield under or overdose in the PTV. This makes it necessary to look for better methods to calibrate the jaw positioning (Clews and Greer 2009).

Another major limitation associated with this technique stems from the fact that only half of the field is available and, frequently, a larger field is needed. This implies that full-fields with divergence in all directions are unavoidable.

Chapter 2

Results

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2.1 Summary of contributions

The results of this thesis are divided into two groups: the geometrical problem of field matching and optimization of field matching in single-isocenter half-beam techniques.

In the first group the geometrical problem of matching the edges of adjacent fields is addressed. A general analytical solution to this problem is presented that calculates all the parameters needed to achieve an exact match. Additionally, practical implications are derived from the general solution for specific situations.

In the second group, issues regarding the single-isocenter half-beam (SIHB) technique are investigated. First, the effect of the field set-up in SIHB techniques is analyzed. Second, a new method to calibrate the zero jaw position is proposed that improves the dose homogeneity at the junction of half-beams.

These results have been reported in the following four papers:

Geometrical Field Matching

1. V Hernández, M Arenas, F Pons and J Sempau (2009). A general analytical solution to the geometrical problem of field matching in radiotherapy. *Med. Phys., 36*, 4191-4196. DOI: 10.1118/1.3183498.

   Impact Factor = 2.704, 1st quartile

2. V. Hernández, M. Arenas, F. Pons and J. Sempau (2011). Clinical applications of geometrical field matching in radiotherapy based on a new analytical solution. *Med. Dos., 36*, 160-165. DOI: 10.1016/j.meddos.2010.02.008.

   Impact Factor = 1.000, 3rd quartile

Single-isocenter half-beam techniques

3. V. Hernández and J. Sempau (2011). The influence of the field setup on the dosimetry of abutted fields in single-isocenter half-beam techniques. *Med. Phys., 38*, 1468-1472. DOI: 10.1118/1.3557882.

   Impact Factor = 2.830, 1st quartile

4. V. Hernández, J. Sempau, R. Abella, M. López, M. Pérez, M. Artigues and M. Arenas (2013). A method for accurate zero calibration of asymmetric jaws in single-isocenter half-beam techniques. *Med. Phys., 40*, 021706-1-021706-6. DOI: 10.1118/1.4773314.

   Impact Factor = 2.830, 1st quartile

The four papers listed above are included in the next sections. The results of this thesis have also been presented in the following scientific conferences:

- V.Hernández, M.Arenas, C.B.Carrascosa, LL.Anglada and M.Artigues. Optimización de la unión de campos tangenciales y supraclavicular en la irradiación de neoplasias de mama. XIV Congreso Nacional de Física Médica, SEFM, Vigo (Spain), June 17-20, 2003. Poster.

- V.Hernández, M.López, M.Pérez, R.Abella, M.Artigues and J.Sempau. Calibration of asymmetric jaws for single-isocenter half-beam techniques. European Society For Therapeutic Radiology and Oncology Congress ESTRO29, Barcelona (Spain), September 12-16, 2010. Poster.

- V.Hernández, M.López, M.Pérez, R.Abella, M.Artigues and J.Sempau. Calibración del posicionamiento de las mandíbulas asimétricas para técnicas de hemicampos con isocentro único. II Congreso Conjunto de las Sociedades Españolas de Física Médica y Protección Radiológica, SEFM y SEPR, Sevilla, May 10-13, 2011. Poster.

- V.Hernández and M.López. Use of dynamic field matching to reduce uncertainties in the match region and increase robustness of treatment plans. ESTRO 31 Conference and World Congress of Brachytherapy, Barcelona, May 10-13, 2012. Poster.

- V.Hernández, J.Sempau, R.Abella, M.López, M.Pérez, M.González and M.Artigues. Método para la calibración de las mandíbulas asimétricas en técnicas de hemicampos y efectos en la práctica clínica. III Congreso Conjunto de las Sociedades Españolas de Física Médica y Protección Radiológica, SEFM y SEPR, Cáceres, June 18-21, 2013. Oral presentation.

- V.Hernández and M.López. Uso de uniones de campo dinámicas para reducir incertidumbres y obtener tratamientos más robustos. III Congreso Conjunto de las Sociedades Españolas de Física Médica y Protección Radiológica, SEFM y SEPR, Cáceres, June 18-21, 2013. Poster.

2.2 Paper I

A general analytical solution to the geometrical problem of field matching in radiotherapy.

V Hernández, M Arenas, F Pons and J Sempau (2009). A general analytical solution to the geometrical problem of field matching in radiotherapy. *Med. Phys.*, *36*, 4191-4196. DOI: 10.1118/1.3183498.

Attention¡¡

Pages 30 to 36 of the thesis are available at the editor's web

http://scitation.aip.org/content/aapm/journal/medphys/36/9/10.1118/1.3183498

2.3 Paper II

Clinical applications of geometrical field matching in radiotherapy based on a new analytical solution.

V. Hernández, M. Arenas, F. Pons and J. Sempau (2011). Clinical applications of geometrical field matching in radiotherapy based on a new analytical solution. *Med. Dos.*, *36*, 160-165. DOI: 10.1016/j.meddos.2010.02.008.

Attention¡¡

Pages 36 to 44 of the thesis are available at the editor's web

http://www.sciencedirect.com/science/article/pii/S0958394710000257

2.4 Paper III

The influence of the field setup on the dosimetry of abutted fields in single-isocenter half-beam techniques.

V. Hernández and J. Sempau (2011). The influence of the field setup on the dosimetry of abutted fields in single-isocenter half-beam techniques. *Med. Phys.*, *38*, 1468-1472. DOI: 10.1118/1.3557882.

Attention¡¡

Pages 46 to 50 of the thesis are available at the editor's web

http://scitation.aip.org/content/aapm/journal/medphys/38/3/10.1118/1.3557882

2.5 Paper IV

A method for accurate zero calibration of asymmetric jaws in single-isocenter half-beam techniques.

V. Hernández, J. Sempau, R. Abella, M. López, M. Pérez, M. Artigues and M. Arenas (2013). A method for accurate zero calibration of asymmetric jaws in single-isocenter half-beam techniques. *Med. Phys.*, *40*, 021706-1-021706-6. DOI: 10.1118/1.4773314.

Attention¡¡

Pages 52 to 56 of the thesis are available at the editor's web

http://scitation.aip.org/content/aapm/journal/medphys/40/2/10.1118/1.4773314

Chapter 3

Conclusions

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Conclusions

This thesis provides tools to improve field matching in radiation therapy, thus allowing the use of more accurate and safer treatments in clinical practice. The main conclusions are classified in two groups: geometrical field matching and single-isocenter half-beam techniques (SIHB).

3.1 Geometrical field matching

- A general analytical solution to the geometrical problem of field matching has been obtained. The solution provides an exact match for the two situations encountered in clinical practice: fixed field sizes and fixed positions for each isocenter. For the first time equations have been derived for the calculation of either the field size or the isocenter coordinates of the fields. These equations (coded in Fortran in the Appendices) provide not only parallelism but also coincidence between the side planes of adjacent fields.

- These results can be easily implemented in modern treatment planning systems, since these systems already manage all the variables involved in the calculations. Thus, the calculations needed for field matching can be automated in the clinical practice.

- Implications of using fixed SSD (source-to-surface distance) or isocentric techniques can be evaluated with these general expressions. Practical considerations regarding specific techniques such as breast with supraclavicular field, craniospinal irradiation and head and neck treatments have been addressed. This formalism is a useful tool to analyze and compare different techniques where matching of adjacent fields is necessary. In particular:

1. Commonly used expressions for the simple case of matching an anterior/posterior field and a lateral field are not exact. However, they are a good approximation to the rotation angles obtained in our work (equations 10,11 in Paper II), with differences $<0.2°$. In consequence, these expressions can still be used, but they should be complemented with the calculation of the field size or the isocenter coordinates.
2. In breast cancer with tangential fields and a separate anterior supraclavicular (SC) field the use of a half field for the SC area is highly recommended, since it offers significant advantages over the full field.

3.2 Single-isocenter half-beam techniques

- An effect of the field set-up on the dosimetry at the junction of half fields in SIHB techniques is observed, with differences in the junction dose around 18% depending on the relative position of the fields involved. This effect results from the fact that the gantry does not behave as a perfect mechanical device and slight gantry deflections due to gravity introduce inaccuracies at the junction.

- Having a uniform dose distribution for two fields at gantry 0° does not guarantee a uniform distribution at other gantry angles. Methods aiming to assess or to optimize the dose homogeneity at the junction should take this fact into account.

- A new method for calibrating the zero position of asymmetric jaws that provides higher accuracy at the central axis has been developed. The presented procedure can be applied in modern medical linacs, although it is not currently possible to introduce a potentiometer shift in the system. We therefore recommend that the manufacturer allows the introduction of such a shift, which would greatly facilitate the new procedure.

- The new calibration method reduces the dose deviation at the junction for gantry angle 0° from a maximum of $\pm 40\%$ to a maximum of $\pm 8\%$. In typical field set-ups (combining fields with different gantry angles) the dose deviation is reduced from a maximum of $\pm 30\%$ to a maximum of $\pm 15\%$. Thus, our method improves dose homogeneity at the junction of half-beams, allowing a more accurate and safer use of SIHB techniques.

Chapter 4

Appendices

4.1 Appendix A

The Fortran code for calculation of the parameters for geometrical field matching with the fixed isocenter positions is presented below.

```
!******************************************************************
!*     GEOMETRICAL FIELD MATCHING - FIXED ISOCENTER POSITIONS     *
!*                                                                *
!* Short description:                                             *
!*   Fortran code to compute the parameters that provide field    *
!*   matching for 2 abutted fields with fixed isocenter positions. *
!*                                                                *
!* The code is based on the method and nomenclature described     *
!* in the following paper:                                        *
!* V Hernandez, M Arenas, F Pons and J Sempau (2009). A general   *
!* analytical solution to the geometrical problem of field        *
!* matching in radiotherapy. Med.Phys., 36, 4191-4196.            *
!*                                                                *
!* No warranties, express or implied, that this software is free  *
!* of error or that it will meet your requirements for any        *
!* particular application, is made.                               *
!* No responsibility for any limitation of this code is accepted.  *
!*                                                                *
!* Victor Hernandez, email: vhernandezmasgrau@gmail.com           *
!* Hospital Sant Joan de Reus, Reus, Spain                        *
!******************************************************************

!******************************************************************
!*    MAIN                                                        *
!******************************************************************
   program main
   implicit none
   real*8 alpha1, alpha2, u, v, w, A, div
   real*8 g1,c1,t1,j1,g2,j2,c2,t2,t2sol1,t2sol2,cos1,cos2
   real*8 x1,y1,z1,x2,y2,z2,x,y,z,aux
   real*8, parameter :: pi = 3.141592653589793d0, SAD = 100.0d0
   real*8, parameter :: zero = 1.0d-10

   write(*,'(a)')''
   write(*,'(a)')'This is AFM version 2013-07-14'
   write(*,'(a)')''
   write(*,'(a)')'This code computes the parameters that provide '// &
                 'field matching for 2 abutted fields with fixed '// &
                 'isocenter positions.'
   write(*,'(a)')''
   write(*,'(a)')''
   write(*,'(a)')'Enter the gantry angle for field 1 (deg)'
   read (*,*) g1
   write(*,'(a)')'Enter the collimator angle for field 1 (deg)'
   read (*,*) c1
   write(*,'(a)')'Enter the couch angle for field 1 (deg)'
   read (*,*) t1
   write(*,'(a)')'Enter the position of the jaw to be matched '// &
                 'for field 1(cm)'
   read (*,*) j1
   write(*,'(a)')'Enter the x coordinate of the isocenter of field 1 (cm)'
   read (*,*) x1
   write(*,'(a)')'Enter the y coordinate of the isocenter of field 1 (cm)'
   read (*,*) y1
   write(*,'(a)')'Enter the z coordinate of the isocenter of field 1 (cm)'
   read (*,*) z1
   write(*,'(a)')''
   write(*,'(a)')'Enter the gantry angle for field 2 (deg)'
   read (*,*) g2
   write(*,'(a)')'Enter the x coordinate of the isocenter of field 2 (cm)'
   read (*,*) x2
   write(*,'(a)')'Enter the y coordinate of the isocenter of field 2 (cm)'
   read (*,*) y2
   write(*,'(a)')'Enter the z coordinate of the isocenter of field 2 (cm)'
   read (*,*) z2
   write(*,'(a)')''
```

```
   alpha1=atan(j1/SAD)
   x=x2-x1
   y=y2-y1
   z=z2-z1

!  Operations similar to the ones performed in the next 3 lines might be
!  needed if the coordinates introduced do not correspond to the reference
!  system described in the article (for instance,if the reference system
!  of a particular TPS is used).
   aux=y
   y=z
   z=-aux

!  Introduced angles are transformed to radians
   g1=g1*pi/180.0
   c1=c1*pi/180.0
   t1=t1*pi/180.0
   g2=g2*pi/180.0

!  The vector perpendicular to the side plane of field 1 (u,v,w) and the
!  parameter A are calculated
   u=cos(t1)*(-cos(g1)*sin(c1)*cos(alpha1)+sin(g1)*sin(alpha1))- &
     sin(t1)*cos(c1)*cos(alpha1)
   v=sin(t1)*(-cos(g1)*sin(c1)*cos(alpha1)+sin(g1)*sin(alpha1))+ &
     cos(t1)*cos(c1)*cos(alpha1)
   w=sin(g1)*sin(c1)*cos(alpha1)+cos(g1)*sin(alpha1)
   A=-u*x/SAD+u*cos(t1)*sin(g1)-v*y/SAD+v*sin(t1)*sin(g1)- &
     w*(z/SAD-cos(g1)+cos(g2))

!  Particular case when sin(g2)=0
   if (abs(sin(g2)).lt.zero) then  !zero defined as 1.0d-10
     write(*,'(a)') ''
     write(*,'(a)') 'Please set the field with gantry 0 or 180 '// &
                    'degrees as field 1 (the fixed field)'
     !Alternatively, as commented in the paper referenced above, in
     !this case t2 could be set to 0 and c2 computed with Eq.(11)
     write(*,'(a)') ' Press any key'
     read(*,*)
     stop
   endif

!  CALCULATION OF THE COUCH ANGLE FOR FIELD 2, t2
!  The term inside the square root is computed
   t2=A*A*v*v-(u*u+v*v)*(A*A-u*u*sin(g2)*sin(g2))
   if (t2.lt.0.0.and.t2.gt.-zero) t2=0.0d0 !to avoid rounding errors
   if (t2.lt.0.0) then
      write(*,'(a)') 'A solution does not exist'
      write(*,'(a)') 'Press any key'
      read(*,*)
      stop
   endif

!  To avoid a 'Division by 0' error
   if (abs(u*u+v*v).lt.zero) then
     write(*,'(a)') 'A solution does not exist'
     write(*,'(a)') 'Press any key'
     read(*,*)
     stop
   endif

!  The terms inside asin() are computed and the 2 solutions are obtained
   t2sol1=(A*v+sqrt(t2))/((u*u+v*v)*sin(g2))
   t2sol2=(A*v-sqrt(t2))/((u*u+v*v)*sin(g2))

!  To avoid "division by zero"
   if (abs(u).lt.zero) u=sign(zero,u)
   cos1=(A/sin(g2)-v*t2sol1)/u
   cos2=(A/sin(g2)-v*t2sol2)/u
```

```
!  The number of possible solutions depends on the values of the
!  trigonometric functions:
   if (abs(t2sol1).gt.1.0.and.abs(t2sol2).gt.1.0) then
      write(*,'(a)') 'A solution does not exist'
      write(*,'(a)') 'Press any key'
      read(*,*)
      stop
  endif
  if (abs(t2sol1).gt.1.0.and.abs(t2sol2).le.1.0) then
      t2=asin(t2sol2)
      if (cos2.lt.0.0) t2=pi-t2
  endif
  if (abs(t2sol1).le.1.0.and.abs(t2sol2).gt.1.0) then
      t2=asin(t2sol1)
      if (cos1.lt.0.0) t2=pi-t2
   endif
  if (abs(t2sol1).le.1.0.and.abs(t2sol2).le.1.0) then
!     Two (mathematically correct) solutions exist
!     Now the 'correct' solution is chosen (t2 in the 1st or 4th quadrant)
      if (cos1.gt.cos2) then
          t2=asin(t2sol1)
          if (cos1.lt.0.0) t2=pi-t2
      else
          t2=asin(t2sol2)
          if (cos2.lt.0.0) t2=pi-t2
      endif
  endif

!  CALCULATION OF THE FIELD APERTURE FOR FIELD 2, alpha2

   alpha2=sin(g2)*(u*cos(t2)+v*sin(t2))+w*cos(g2)
   if (abs(alpha2).gt.1.0) then
      write(*,'(a)') 'A solution does not exist for alpha2'
      write(*,'(a)') 'Press any key'
      read(*,*)
      stop
   else
      alpha2=-asin(alpha2)
   endif

!  CALCULATION OF THE COLIMATOR ANGLE FOR FIELD 2, c2

   c2=-cos(g2)*(u*cos(t2)+v*sin(t2))+w*sin(g2)
   !To avoid "division by zero":
     div=-u*sin(t2)+v*cos(t2)
     if (abs(div).lt.zero) div=sign(zero,div)
   c2=atan(c2/div)

!  PROGRAM OUTPUT

   write(*,'(a)') ''
   c2=c2*180.0/pi
   if (c2.lt.0.0) c2=c2+360.0
   write(*,'(a,f6.1,a)') 'Collimator rotation angle for field 2:',c2,' deg'
   t2=t2*180.0/pi
   if (t2.lt.0.0) t2=t2+360.0
   write(*,'(a,f6.1,a)') 'Couch rotation angle for field 2:     ',t2,' deg'
   j2=SAD*tan(alpha2)
   write(*,'(a,f6.1,a)') 'Position of the jaw for field 2:      ',j2,' cm'
   write(*,'(a)') ''
   write(*,'(a)') 'End of Program. Press any key'
   read(*,*)
   end program main

!>>>> End Of File >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

4.2 Appendix B

The Fortran code for calculation of the parameters for geometrical field matching with the fixed field sizes method is given below.

```
!****************************************************************
!*        GEOMETRICAL field MATCHING - FIXED FIELD SIZES        *
!*                                                              *
!* Short description:                                           *
!*   Fortran code to compute the parameters that provide field  *
!*   matching for 2 abutted fields with fixed field sizes.      *
!*                                                              *
!* The code is based on the method and nomenclature described   *
!* in the following paper:                                      *
!* V Hernandez, M Arenas, F Pons and J Sempau (2009). A general *
!* analytical solution to the geometrical problem of field      *
!* matching in radiotherapy. Med.Phys., 36, 4191-4196.          *
!*                                                              *
!* No warranties, express or implied, that this software is free *
!* of error or that it will meet your requirements for any      *
!* particular application, is made.                             *
!* No responsibility for any limitation of this code is accepted. *
!*                                                              *
!* Victor Hernandez, email: vhernandezmasgrau@gmail.com         *
!* Hospital Sant Joan de Reus, Reus, Spain                      *
!****************************************************************


!****************************************************************
!*    MAIN                                                      *
!****************************************************************
    program main
    implicit none
    real*8 alpha1, alpha2, u, v, w
    real*8 g1,c1,t1,j1,g2,j2,c2,t2
    real*8, parameter :: pi = 3.141592653589793d0, SAD = 100.0d0
    real*8, parameter :: zero = 1.0d-10

    write(*,'(a)') ''
    write(*,'(a)') 'This is AFM version 2013-07-14'
    write(*,'(a)') ''
    write(*,'(a)') 'This code computes the parameters that provide '// &
                   'field matching for 2 abutted fields with fixed '// &
                   'field sizes.'
    write(*,'(a)') ''
    write(*,'(a)') ''
    write(*,'(a)') 'Enter the gantry angle for field 1 (deg)'
    read (*,*) g1
    write(*,'(a)') 'Enter the collimator angle for field 1 (deg)'
    read (*,*) c1
    write(*,'(a)') 'Enter the couch angle for field 1 (deg)'
    read (*,*) t1
    write(*,'(a)') 'Enter the position of the jaw to be matched '// &
                   'for field 1 (cm)'
    read (*,*) j1
    write(*,'(a)') ''
    write(*,'(a)') 'Enter the gantry angle for field 2 (deg)'
    read (*,*) g2
    write(*,'(a)') 'Enter the position of the jaw to be matched '// &
                   'for field 2 (cm)'
    read (*,*) j2

    alpha1=atan(j1/SAD)
    alpha2=atan(j2/SAD)

!   Introduced angles are transformed to radians
    g1=g1*pi/180.0
    c1=c1*pi/180.0
    t1=t1*pi/180.0
    g2=g2*pi/180.0
```

```
!   The vector perpendicular to the side plane of field 1 is calculated
    u=cos(t1)*(-cos(g1)*sin(c1)*cos(alpha1)+sin(g1)*sin(alpha1))- &
      sin(t1)*cos(c1)*cos(alpha1)
    v=sin(t1)*(-cos(g1)*sin(c1)*cos(alpha1)+sin(g1)*sin(alpha1))+ &
      cos(t1)*cos(c1)*cos(alpha1)
    w=sin(g1)*sin(c1)*cos(alpha1)+cos(g1)*sin(alpha1)

!   Particular case when sin(g2)=0
    if (abs(sin(g2)).lt.zero) then
      write(*,'(a)') ''
      write(*,'(a)') 'Please set the field with gantry 0 or 180 '// &
           'degrees as field 1 (the fixed field)'
           !Alternatively, as commented in the paper referenced above, in
           !this case t2 could be set to 0 and c2 computed with Eq.(11)
      write(*,'(a)') ' Press any key'
      read(*,*)
      stop
    endif

!   CALCULATION OF THE COLLIMATOR ANGLE FOR field 2, c2
    c2=tan(alpha2)/tan(g2)+w/(cos(alpha2)*sin(g2))
    if (abs(c2).gt.1.0) then
      write(*,'(a)') 'A solution does not exist'
      write(*,'(a)') 'Press any key'
      read (*,*)
      stop
    else
      c2=asin(c2)
    endif

!   CALCULATION OF THE COUCH ANGLE FOR field 2, t2
    if (abs(u*u+v*v).lt.zero) then !To avoid a 'Division by 0' error
      write(*,'(a)') 'A solution does not exist'
      write(*,'(a)') 'Press any key'
      read(*,*)
      stop
    endif

!   To avoid a 'Division by 0' error
       if (abs(u*u+v*v).lt.zero) then
         write(*,'(a)') 'A solution does not exist'
         write(*,'(a)') 'Press any key'
         read(*,*)
         stop
    endif

    t2=(v*(sin(alpha2)+w*cos(g2))+u*cos(c2)*cos(alpha2)*sin(g2))/ &
       ((u*u+v*v)*sin(g2))
    if (abs(t2).gt.1.0) then
      write(*,'(a)') 'A solution does not exist'
      write(*,'(a)') 'Press any key'
      read (*,*)
      stop
    else
      t2=-asin(t2)
    endif

!   PROGRAM OUTPUT
    write(*,'(a)') ''
    c2=c2*180.0/pi
    if (c2.lt.0.0) c2=c2+360.0
    write(*,'(a,f6.1,a)') 'Collimator rotation angle for field 2:',c2,'
    deg'
    t2=t2*180.0/pi
    if (t2.lt.0.0) t2=t2+360.0
    write(*,'(a,f6.1,a)') 'Couch rotation angle for field 2:     ',t2,'
    deg'
    write(*,'(a)') ''
```

```
    write(*,'(a)') 'End of Program. Press any key'
    read (*,*)
    end program main

!>>>> End Of File >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

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[1]These bibliographic citations refer to the text in the Introduction section. References cited in each work of the present thesis are listed in the corresponding papers.