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ANALYSIS OF SET-UP PARAMETERS IN HEAD AND NECK PATIENTS RECEIVING RADIOTHERAPY AT CHARLOTTE MAXEKE JOHANNESBURG ACADEMIC HOSPITAL: A REVIEW OF CURRENT CLINICAL PRACTICE

by

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Professor DG van der Merwe

2012

DECLARATION

I declare that "Analysis of set-up parameters in head and neck patients receiving radiotherapy at Charlotte Maxeke Johannesburg Academic Hospital: A review of current clinical practice" thesis is my own work and that all sources that I have used or quoted have been indicated and acknowledged by means of complete references.



21/8/12

BP Van Wyk

Date

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OVERVIEW

AIM: This studied aimed at analysing the set-up error (margin) of head and neck cases, treated in a vacuum formed acrylic shell with an in-house immobilisation system.

METHODS AND MATERIALS: Two population groups were studied, namely virtual simulated and intensity modulated radiotherapy (IMRT) cases. All cases were treated with the in-house immobilization system, which located centrally, but not longitudinally, to the treatment couch. Verification of the couch position, other than the isocentric angle, was not activated. The virtual simulated cases consisted of two lateral fields with a matched anterior neck field. The borders of these fields were chosen by the radiation oncologist. The IMRT cases were planned by a medical physicist and consisted of 6-9 fields of 3-4 intensity levels each. Digitally reconstructed radiographs (DRRs) of the 2 lateral fields and the anterior neck field for the virtual simulated cases, and the 2 lateral and anterior composite fields at the same isocentre for the IMRT cases, were printed and represented the ideal patient position. On the first day of treatment, megavoltage verification films were taken of the treated or positioning fields respectively. These verification films were compared to the DRRs and approved by a radiation oncologist. The absolute bed position in the vertical (Y), lateral (X) and longitudinal (Z) directions at the time of film approval, was used as the reference or ideal position. The absolute readings of the couch position that were captured daily over the course of treatment were then compared to the initial couch position to give an indication of the systematic and random errors. One linear accelerator was used in this study and weekly mechanical quality control (QC) was performed on it.

RESULTS: The total number of daily fractions (F) studied in this thesis was 5644 and 600 for virtual simulated and IMRT cases respectively. The systematic error of this population was 4.7 and 4.4 mm for the virtual simulated and IMRT cases respectively. This compares well with published results using a similar immobilisation system. The random error of this population was 7 mm and 6.1 mm for the virtual simulated and IMRT cases respectively.

This is three times larger than the results reported in the literature (using a similar immobilization device).

CONCLUSION: Offline monitoring of couch position provides insight into setup margins and this can contribute to realistic institutional planning target volumes. Better results were obtained in the IMRT cases and this could be due to the requirement for weekly verification imaging. Lack of radiation therapist vigilance and insufficient training were most likely responsible for the individual cases with systematic variations of larger than 3 cm. The data confirm that the immobilisation system can be located to a fixed position on the tabletop; this will allow online verification of absolute bed position for treatment and further decrease the chance of incorrect setup.

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ABBREVIATIONS

A

AAPM.....American Association of Medical Physicists

C

cm……centimeter

CMJAH.....Charlotte Maxeke Johannesburg Academic Hospital

CRT…….Conformal Radiotherapy

CT……Computed Tomography

CTV…….Clinical Tumour Volume

D

DRR .....Digitally Reconstructed Radiographs

2D……...Two dimensional

3D.....Three dimensional

E

ENT.....ear, nose and throat

EPID.....Electronic Portal Imaging Device

G

Gy.....Gray

GTV……Gross Tumour Volume

I

ICRU……..International Commission of Radiation Units and measurements

IGRT…….. Image Guided Radiotherapy

IMRT……..Intensity Modulated Radiotherapy

ITV.....Internal Tumour Volume

K

kV.....Kilovoltage

L

LANTIS…….”Local Area Network Treatment Information System”™

LINAC……Linear accelerator

M

MLC.....Multi-Leaf Collimators

mm…….millimeter

MRI……Magnetic Resonance Imaging

MU…….Monitor Unit

MV…….Megavoltage

P

PTV.....Planning Tumour Volume

Q

Q.C…….Quality Control

Q.A…….Quality Assurance

R

RVS.....Record and Verify System

T

TV .....Television.

1. INTRODUCTION

1.1 HEAD AND NECK CANCERS: A REVIEW

Head and neck cancers are among the most challenging cancers to manage and treat, with 60% of cases presenting at locally advanced stages and loco-regional recurrence constituting the predominant recurrence pattern [12]. In the National Cancer Registry of South Africa it was reported that head and neck cancer formed approximately 4% of all cancer cases treated in the year 1998 and 1999 [13]. At Charlotte Maxeke Johannesburg Academic Hospital (CMJAH) 10% of the patients treated with radiation oncology present with head and neck cancer according to the registrations on the local electronic patient information system (LANTIS^{TM}).

All patients with head and neck tumours usually undergo a full ear, nose and throat (ENT) examination, to define the local extent of the tumour. A chest x-ray is also conducted to exclude lung decease, which is the most common site of distant metastasis. Other sites of distant metastasis for head and neck tumours include the mediastinal lymph nodes, liver, brain and bones. Tumours may also spread along the nerves, such as high-grade parotid tumours, which are known to involve the facial nerve and cause paralysis.

The “standard” treatment for head and neck tumours could either be surgery (with preoperative or postoperative radiotherapy) and chemotherapy. The advances made in surgical reconstruction of the head and neck region has led to more patients being treated with a combination of primary surgery and postoperative radiation, rather than primary radiation with surgery for salvage. The “general” consensus is to include the entire operative bed for radiotherapy treatment and to start as soon as the surgical wound has healed, usually three to four weeks after surgery. A combination of chemotherapy and radiotherapy may also be used for inoperable and unresectable tumours (stage three and four).

Radiotherapy is a standard non-surgical treatment for locally advanced head and neck cancers. Radiotherapy therefore plays an important role in the management of head and neck cancer patients. The decision to irradiate postoperative tumours will depend on the presence of perineural invasion, lymph node involvement, pattern of spread, etc. Patients who had neck dissections may receive post-operative irradiation if there was an incomplete excision, nodal involvement at more than one level, or extra-capsular spread. The aim of radiotherapy is to deliver a radiation dose to a well-defined target volume whilst sparing the surrounding normal tissue, thereby achieving an optimal therapeutic ratio with the minimal level of morbidity. Patients can either be treated with a linear accelerator (LINAC) or a Cobalt teletherapy unit, based on the target volume in question. A cobalt unit may be preferable for patients with superficial lesions, because part of the volume is immediately adjacent to the skin; and a linear accelerator may be preferred for deeper seated tumours. "Standard" radical (curative intent) fractionation to the primary tumour and/or lymphadenopathy is 1.8 - 2 gray (Gy) per fraction. Both the tumour and the associated lymphadenopathy are included in the treated volume but the variability of the body contour in the head and neck region poses a challenge to dose uniformity.

A shrinking field technique is often used, whereby the clinical target volume (CTV) is sterilised and the known gross disease (GTV) is then further "boosted" to the final dose as prescribed by the radiation oncologist. Tolerance of the spinal cord is critical to the treatment technique. Several radiation side effects are known to the head and neck area which may include loss of appetite, sore mouth, skin reactions, weight loss, acute laryngeal oedema (larynx cases), etc. In some cases re-planning during treatment may be necessary. Vigilance is needed by the radiation oncology team to ensure that the best possible quality in the daily treatment delivery is maintained in spite of the changes in the target volumes and the challenges posed by the side effects experienced by the patient.

1.2 HEAD AND NECK IMMOBILISATION, POSITIONING AND REFERENCING

Head and neck immobilisation, positioning and referencing is critical to achieve the goal of radiation therapy, by fixing the relationship between the radiation beam and target. External

markers are usually applied on the immobilisation device during simulation or data acquisition procedures to reproduce the alignment of the target to the beam [42].

1.2.1 HEAD AND NECK IMMOBILISATION

Precise target coverage according to radiation treatment planning depends on the reproducibility of the patient position on a day-to-day basis throughout the course of treatment. Depending on the intent, target position or the precision required for beam delivery, patients may or may not require an external immobilisation device for their treatment. For instance, cases of the central nervous system require rigid immobilisation whereas cases for total body irradiation may not. Prior to an immobilisation device being made, it is essential that the physician, physicist, mould room technologist and therapist agree on the optimal patient position for treatment planning. Immobilisation devices have two fundamental roles: to immobilise the patient during treatment and to provide a reliable means of reproducing the patient position from simulation (or computed tomography (CT)) to treatment, and from one treatment to another. Moreover, a well-constructed immobilisation system may reduce the daily positioning time of the patient and make the patient feel more secure and less anxious. The construction of an effective immobilisation device requires a thorough understanding of the extent of the target anatomically, and the device should extend beyond the treatment volume. It is also important for an immobilisation device to be rigid and durable enough to a course of radiotherapy treatment. There are two classifications of immobilisation devices, namely simple and complex. Simple immobilisation devices restrict "some" patient movement and therefore patient movements will not be entirely deterred. Some examples of such immobilisation are masking tape, large rubber bands or a bite block. Complex immobilisation devices restrict the patient's movement entirely, and ensure reproducibility in positioning. These devices are usually made of plaster, plastic and Styrofoam. Both these immobilisation techniques require the patient's voluntary co-operation.

Complex immobilisation devices are very important for the treatment of head and neck cancers. The basic immobilisation device used for head and neck treatments is the head rest, shaped to fit snugly under the patient's head and neck area, allowing the patient to lie

comfortably on the treatment couch. The head rests also locate to a base plate positioned on the treatment couch. The combination of the head rest and mask prevent movement from that position on the couch during a treatment session.

At CMJAH in South Africa all the patients with head and neck cancers, who are treated with curative intent (radical) have individualised Perspex shells (masks) to prevent movement during treatment. The mask and head rest is secured to a base plate. The head and neck base plate clips onto a removable body board. The entire system was developed locally. The superior underside of the head and neck base plate fits into the centre spine of the couch. The table top inserts are therefore removed and this increases clearance around the head and neck area during treatment, which is important for the treatment of lateral posterior neck electron fields without removing the mask or intensity modulated radiotherapy (IMRT) fields with multiple beam ports. Clearance between the patient and the treatment head is therefore improved and treatment using an electron applicator that extents to the patient is expedited, for instance. There are "lips" at the shoulder level that fit around the sides of the table top to centre and secure the entire system. Adjustable hand grips are used to keep the patient's shoulders out of the field of treatment. Further reproducibility can also be achieved by using a body cast. Figure 1.1 shows the in-house manufactured head and neck immobilisation system.

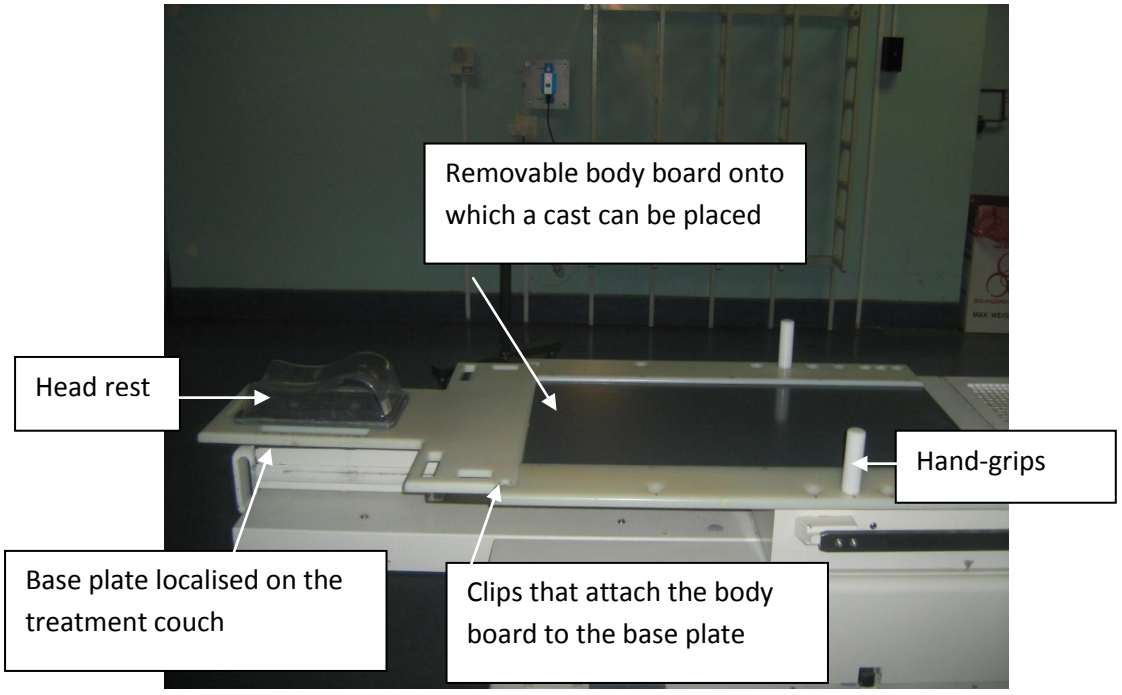


Figure 1.1: An in-house manufactured radical head and neck immobilisation system positioned on the linear accelerator.

1.2.2 HEAD AND NECK POSITIONING

The patient's positioning for head and neck treatment depends on the type of cancer being treated, the objectives regarding the tumour volume(s) and which tissue needs saving/or sparing. Literature has shown that one of the weakest links in radiotherapy treatment planning is patient positioning [15]. If the patient is not correctly positioned neither the most sophisticated plan nor the quality of the immobilisation device would be effective. In fact sometimes it is not possible to produce an acceptable treatment plan.

Incorrect patient positioning could lead to geometrical tumour misses (of 10% or greater) and unnecessary irradiation of normal tissue leading to unacceptable morbidity [15]. However in many situations the patient's precise position may be difficult to maintain, e.g. nervous or restless patient. Positioning aids (different from an immobilisation system) can be used to place the patient in a particular treatment position, e.g. a chin support device for improved prone positioning as shown in Figure 1.2.



Figure 1.2: An example of a chin positioning device (courtesy of CIVCO).

These devices are generally easy to use, widely available and may be used for more then one patient (thus cost-effective and convenient). It is important to understand that these positioning aids will not prevent patient movement (as immobilisation devices do), during treatment. That is why the patient must be cooperative and fully understand the importance of not moving during positioning or treatment.

1.2.3 HEAD AND NECK REFERENCING

Supine, prone and decubitus (open neck) positions are most frequently used to deliver radiation to the head and neck area. The patient's head and chin positions (which can be extended, neutral or flexed) are also very important to either include subclinical disease or to spare critical organs (like the eyes). The patient's reference position (very first position), along with the positioning aids and anatomical measurements should always be documented accurately to ensure reproducible treatment during the course of radiotherapy.
Three-directional lasers (in the transverse, coronal and sagittal planes) are usually used to aid radiotherapy staff in positioning patients daily and the intersection of the lasers is known as the reference point. The reference point usually marks the isocentre or is related to the treatment isocentre position by a fixed translation when the patient is in the reference position. The translation is achieved using the lateral, longitudinal and vertical couch movements. Sometimes column rotation and couch isocentric movements are also used to reach the treatment isocentre position. Additional descriptive topographic anatomical information can be used to confirm reference markings.

1.3 HEAD AND NECK TREATMENT TECHNIQUE

The field arrangement for head and neck cancer treatments are traditionally parallel opposed lateral photon fields. The patient imaging information used to localise the fields relative to the target volumes and organs at risk can either be defined in two or three dimensions. At CMJAH only three dimensional imaging techniques are currently being applied for radical head and neck treatments. Two different planning techniques are being applied.

The first technique comprises of a field arrangement of parallel opposed lateral and offcord fields with a matched anterior supraclavicular neck field. It is a technique with two isocentres (to include the primary tumour volume and the neck volume) and then lateral electron fields are used to boost the posterior neck region for nodes. The electron fields are treated concurrently with the off-cord photon fields. CT-scanning is utilised for multiple transverse slices over the region of interest and multi-leaf collimators (MLC) are used to conform the fields to the PTV (conformal radiotherapy). Software called virtual simulation is utilised;

which "provides the user with an accurate reproduction of anatomical features from the viewpoint of the treatment source" [10]. The virtual simulation system can display both internal anatomy and beam geometries in 3D, which aid in the planning of patients. Virtual simulation can in addition, overcome the geometric constraints experienced with a conventional simulator in which the image intensifier limits all combinations of gantry and couch rotation. The treatment field size (for each treatment unit) and the treatment isocenter, along with any beam modifier can be established at the virtual simulation workstation, without the presence of the patient. This assists staff to work at their own pace and fits in well with the protocol of a busy radiotherapy department.

The other technique that is currently practised for head and neck cases at CMJAH is an IMRT technique. This is an advanced form of conformal radiotherapy (CRT) whereby the fields are not only geometrically shaped but the intensity within the shaped fields is also varied. This enables treatment with a simultaneous integrated boost technique. A non-uniform fluence is delivered to the patient from each position of the gantry to optimize the composite dose distribution. This is especially useful when the target volume has a concavity in its volume and/or closely juxtaposes organs-at-risk. Intensity modulation allows dose escalation of targets surrounded by sensitive structures, e.g. nasopharynx – in this case, the parallel opposed technique described above would limit the total dose possible. At the time of this study CMJAH was using what is known as forward planning for IMRT cases. With this technique the medical physicist tries a variety of beam configurations until a suitable match is found to the dose prescription for each target volume. A typical IMRT case would include instead, a field arrangement of 6 – 9 gantry angles providing 3 – 4 levels of intensity each. A matched anterior neck field is then also used to treat the supraclavicular neck nodes.

For both the virtual simulation and IMRT the reference isocentre position is recorded and the treatment isocentre position is documented using reference images from digitally reconstructed radiographs (DRRs), in which the anatomical structures can be seen. For the virtual simulated technique, DRRs are produced for each of the treatment fields whereas orthogonal images are produced at the treatment isocentre position for the IMRT technique.

1.4 TREATMENT VERIFICATION AND RECORDING AT CMJAH

Verification (megavoltage portal imaging) on the treatment provides a final "check" of patient positioning and set-up just before treatment of a radiotherapy case commences. For virtual simulation cases, the verification also proves that the target volume is covered by the treatment beams as per the treatment plan, normal tissue is shielded according to the plan and that the MLC field shape is correctly downloaded. For the IMRT cases the individual beam segments are checked offline and therefore the anterior, right and left lateral positioning portal images are used to verify correct set-up of the patient.

Currently, the setup of head and neck patients is furthermore electronically verified by using beam and field specific parameters and the bed isocentric rotation angle. The information is obtained from a local area network system connected between the planning and treatment units. The lateral, longitudinal and vertical transformations of the patients from their reference position on the couch table top are currently provided in descriptive text format. This system aids the therapists during set-up of the patient. The actual absolute couch positions used for the patient treatment are however captured by the system and they are available as part of the electronic treatment record. The latter are however not activated in the software to influence or restrict the set-up.

The possibility exists to extend verification to all other bed positions measured in terms of absolute parameters (lateral, longitudinal, vertical and column position) and in addition, to initiate full automatic couch control of the patient's set-up into the future. Prior to activating full bed control, it is necessary however to accurately predict the location of each head and neck patient as a function of the bed and machine isocentre coordinates. The best possible longitudinal location at which to fix the head and neck base plate to the centre spine should therefore be established first.

In addition, the set-up margin achievable with the current head and neck clinical practice is also unknown. Offline monitoring of couch positions can also provide insight into the random and systematic errors that are currently being achieved at the institution.

1.5 AIM OF THE STUDY

This study aims to collect and analyse the recorded daily setup parameters of the bed as they are incidentally captured on the integrated record and verify system in its current operational mode. This will be done on some radical head and neck patients treated from 2008 to 2010. Most of these patients have anterior neck fields that are set-up using fixed couch longitudinal movement (more than one treatment isocentre). It is hoped that the ideal absolute position of the patient on the bed relative to the isocentre of the treatment machine, for a course of head and neck radiotherapy at CMJAH, can be established. Knowledge of the set-up margin achievable will also assist in defining the tolerance assigned to couch parameters on the electronic verify and record system such that setup is restricted accordingly.

1.6 LIMITATIONS OF THE STUDY

There are two limitations to this study. The first is that only one treatment site is being considered, namely head and neck treatments and of these cases only IMRT and virtual simulation cases will be studied. The second limitation is that the research is conducted in one South African hospital (CMJAH) using a locally produced immobilisation system. Therefore, it is apparent that the results may not be universally applicable.

These two limitations however are warranted, since a head and neck setup margin has not been established at CMJAH using the in-house manufactured immobilisation systems, and this is good practice especially when new techniques, like IMRT, are introduced.

1.7 METHODOLOGY

Between 2008 and 2010 a series of 110 radical patients treated on a LINAC with an integrated record and verify system, were identified. Only the patients that completed their cycle of Radiotherapy were included.

Using the electronic treatment record, which captures the patient's lateral, longitudinal and vertical positions, the absolute bed position used for each of these patients was obtained. This data was used to establish the systematic and random error for these cases.

1.8 SUMMARY

The management of head and neck tumours requires an integrated interdisciplinary collaboration among the surgical, radiation, medical, and dental teams.

Parameters such as the type of immobilisation device and the expertise of radiotherapy staff in positioning and referencing patients are likely to influence the overall accuracy achievable during the course of head and neck treatments.

The research studied the electronic data files of 110 patients in the hope of establishing a setup margin for the head and cases at the institution. A predictable absolute couch position that determines setup to isocentre can be introduced for all radical head and neck patients treated at CMJAH. In addition, the position of the base plate along the centre spine used to permanently fix the local head and neck system on the table top, was established

2. LITERATURE REVIEW

2.1 INTRODUCTION

During a course of radiotherapy the task of accurately aligning a target volume with the radiation beam (s) on a daily basis has many components. There are usually four volumes included in the radiation treatment fields. Firstly there is the gross tumor volume (GTV). This is the clinically evident volume (visible on CT and magnetic resonance imaging (MRI)) for instance. Secondly there is the clinical target volume (CTV), which contains the GTV and a margin. This contains all the tissue at immediate risk for containing a microscopic population of tumour cells. Thirdly there is the internal target volume (ITV), which accounts for involuntary movement such as breathing or swallowing, for instance. Often this can be determined using image guided radiotherapy (IGRT) to establish a more precise "movement" margin. Fourthly there is the planning target volume, which contains all the volumes previously described plus a margin to account for daily geometric and technical set-up uncertainties. This set-up margin defines the volume that this study aims to establish at CMJAH.

All these volume definitions have been adopted and published as part of the International Commission on Radiation Units and Measurements (ICRU) [14, 17]. The PTV has to account for internal organ motion, beam geometry and treatment set-up uncertainties to ensure adequate coverage of the CTV. The extent to which the margin of these two volumes can be reduced is influenced by the use of rigid immobilization and accurate positioning. A schematic diagram of the volumes is illustrated in Figure 2.1. In this figure one can see that the PTV encompasses the beam geometry or field size. This will include the CTV and GTV (with margins).

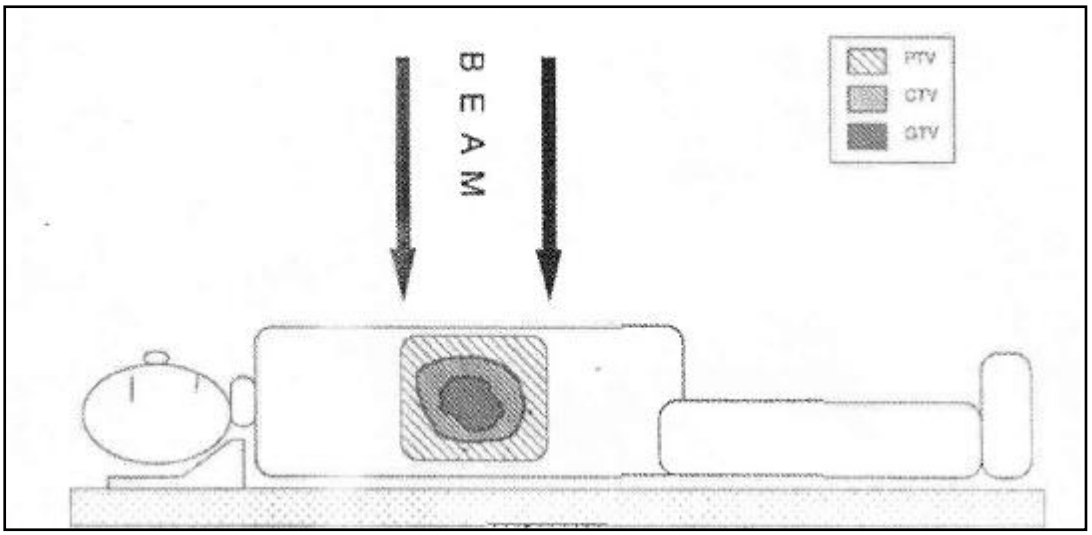


Figure 2.1: ICRU volumes of interest in the patient.

There are a number of issues that need to be considered when treating a head and neck case:

The PTV might not be rigidly fixed within the patient (because of breathing, swallowing and patient position), and therefore might move relative to other normal tissue.
The PTV might change shape and/or size during a course of radiotherapy, because of the effect of radiation on the tumour. To determine the PTV, one must make an assessment of the magnitude of each type of error likely to be encountered during treatment of the patient.

2.2 SET-UP MARGIN FOR HEAD AND NECK PATIENTS

A set-up margin needs to be determined for every institution treating head and neck patients [6]. This set-up margin will depend highly on the immobilization technique that the institution uses as well as the accuracy with which the radiotherapists set-up the patient.

Typically there are three categories of immobilisation devices used for head and neck treatment:

- A thermoplastic shell, which requires immersion in a warm water bath before being moulded and positioned on the patients head and neck.

- A vacuum formed Perspex shell, custom made from a plaster of Paris impression of the patients head and neck (this is the technique used in this study).

- A stereotactic frame, for localisations requiring a precision of the order of 1mm.

An interesting comparison of the first two immobilisation techniques by Bentel et al, show an average reproducibility using an Orfit^{TM} thermoplastic mask of 5-10mm, compared to 3-4mm for the Perspex shell [16]. The Orfit^{TM} technique is dependent on the stretching of the material and how many times the shells are being re-used. The reproducibility of the Perspex shell on the other hand is dependent on the fit, the "length" of patient's hair and the number of fixations used on the headboard. The theoretical superiority of the Perspex shells and the availability of the vacuum former justified the use of this immobilisation technique at CMJAH.

2.3 COMPUTER CONTROLLED RADIOTHERAPY

Computer controlled radiotherapy were introduced as a safety measure in radiotherapy treatments [18]. It was found that these systems improved patient safety and reduced treatment errors when used properly [18-20].

2.3.1 RECORD AND VERIFY SYSTEMS (RVS) – ONE WAY OF VERIFYING TREATMENT SET-UP IN RADIOTHERAPY

The position of the treatment couch (using its binary classifier) can be used as a surrogate for patient position. The patient's very first treatment couch position can be compared to the planned treatment isocentre position. In so doing, a set-up error for each patient can be established from the couch co-ordinates.

When an immobilisation device is indexed to the table, it attaches rigidly in the same place for each fraction of radiotherapy treatment. Theoretically this improves the coupling between the digital position readout of the couch and the patient's placement with respect to the

isocenter. This requires couch indexing software and is easier to implement in departments where all imaging and treatment couches are the same. The couches at CMJAH are not uniformly indexed, meaning immobilization devises can only locate laterally and vertically on all the tabletops.

Podmaniczky et al. suggested that locatable immobilization devises would improve the ability to detect mistakes in setup [22]. A statistical analysis of recorded studies was used, and the RVS was utilised to collect data on patient setup. Analysis included the variations that existed in the axes of the treatment machine. Patton et al. [29] compiled a review of errors and determined that indexed immobilisation along with couch position tolerance (limits) was an important part of achieving correct patient setup. His study also recognized the interplay between couch tolerance limits and usability by therapists to detect incorrect patient positioning. Klein et al [31] suggested different tolerance limits based on indexed immobilization systems and the treatment technique or diseased site.

All these studies analyzed patient set-up using the couch as a surrogate. Other techniques of analyzing patient set-up are described in Section 2.3.4. Therefore the importance of every institution in determining its set-up margin is again stressed, since there are different techniques by which the set-up margin can be determined, affecting results obtained.

2.3.2 OTHER METHODS OF VERIFYING CORRECT PATIENT POSITIONING IN RADIOTHERAPY

The first technique of patient verification position was described in section 2.3.1. The sections below will look at other means of patient positioning verification.

2.3.2.1 X-RAY IMAGING

The accuracy of dose delivery is limited by uncertainties in target localization at the time of treatment delivery [33-36]. Megavoltage imaging is one of the methods used to correct for patient positioning errors in radiotherapy, and to account for target localization. Online and offline strategies are used for correcting patient position errors. Offline strategies refer to

images of the patient's anatomy taken in the treatment delivery room from which a set-up analysis is only done after treatment has been given. This strategy is not as popular anymore and less practiced universally [33]. On-line strategies refer to IGRT techniques in which images of the patient's anatomy are taken in the treatment delivery room and compared to the reference image (discussed in chapter one) prior to treatment. Adjustments in patient position are made prior to treatment, if necessary.

Megavoltage imaging can be performed using an emulsion-type film placed in the radiation beam beyond the patient. These films can be used in two ways depending on the sensitivity to radiation or film speed. For localization a "fast film" (requiring only a few cGy) is placed in each beam [33]. This is the technique used in this thesis. For verification a "slow film" is placed in each beam for the duration of treatment [33]. This however results in a poor quality film, because of patient and/or involuntary organ motion.

These localization films do not require intensifying screens such as the ones used in diagnostic radiology [41]. A single thin layer of copper and/or aluminum is used in front of the film to provide electronic buildup and increase film efficiency. Single or double exposures may be taken with this film. In single exposure, the film is irradiated with the treatment field alone. This technique is well suited to areas where the anatomical features can be seen clearly inside the treatment field. In the double exposure technique the film is irradiated with the treatment field first. The collimators are then opened wider (usually 5 - 10cm beyond the field size of the treated field), and a second exposure is taken. The resulting image not only shows the treated field but also the surrounding anatomy. The latter technique cannot be used for clinical imaging during treatment.

2.3.2.2 ELECTRONIC PORTAL IMAGING DEVICES (EPID'S)

Another form of imaging used in radiotherapy is electronic portal imaging. This consists of a suitable radiation detector mainly fluoroscopic, ionization and amorphous silicon [41]. This is usually attached to the LINAC, and capable of transferring detector information to a computer. The computer will then process the information and convert it into an image.

The fluoroscopic imaging detectors work on the same principle as a simulator image intensifier system [41]. It consists of a metal plate and phosphor screen, a 45° mirror and a television (TV) camera. The metal plate converts incident x-rays to electrons and the fluorescent screen converts these electrons to light photons. The mirror deflects the light to the TV camera, and the TV camera producers an image. Only a few MU are required to produce an image.

Ionization chamber detectors consists of two metal plates (±1mm apart), with each plate divided into 256 electrodes. Ionization is measured when a voltage is applied [41]. A 2D ionization map is created and converted into a grayscale image. The maximum image size is usually smaller than that of a conventional fluoroscopic system.

The amorphous silicon detector consists of a large rectangular matrix of amorphous silicon photodiodes. It also consists of a fluorescent screen like the fluoroscopic system. Images are obtained through the electron-hole pairs produced by the light photons emitted in the response to the radiation fluence. These systems produce images with greater resolution and contrast than the other two systems discussed previously [41].

2.3.2.3 IGRT

Image guided radiotherapy is another technique of verifying patient set-up [18]. This however has a very broad definition in that it may refer to imaging prior to treatment, or imaging during the course of radiotherapy treatment. For image verifications prior to treatment, film, an kV x-ray unit, an EPID, a CT or MV cone beam CT connected to the linear accelerator may be used to obtain images that are used to analyze set-up before treatment. For imaging during a course of radiotherapy treatment, weekly CT images can also be taken to analyze set-up errors. Both methods have advantages. “Real-time” imaging gives a reflection of the patient’s position at that particular moment. The necessary corrections can therefore be made at the next fraction of treatment. Alternatively a mean shift can be determined from a series of pre-treatment images. With regard to “phase-imaging” (also known as adaptive imaging), weekly verifications of the treatment volume can be taken. This is usually in the form of multiple CT-images, from this any changes in the volume

(shrinkage/growth) can be discovered, and the necessary corrections made. This may involve re-planning.

2.4 ERRORS THAT MAY OCCUR DURING HEAD AND NECK TREATMENTS

The term “error” used in this thesis refers to an incorrect process in the setup of the patient - implying that the patient is in the wrong (non-desired) treatment position. This term is further described as a “setup error”, which is the systematic and random geometric displacement of a target from its planned position. Correct setups would be those that used the correct information and in which all setup instructions were followed correctly.

2.4.1 RANDOM ERRORS

The random error is the deviation that occurs between different fractions (meaning the inter-fractional differences arising from comparisons between each treatment session). The treatment population’s random error will be studied during this thesis. This is the mean of the individual random errors over a course of treatment [39]. Random errors occur at the treatment delivery stage, and the one investigated during this study is the patient set-up random error. These are the varying, unpredictable changes arising from changes in the patient’s position, treatment equipment or set-up methodology between fractions. Other random errors (not studied during this thesis) include the change in target position and shape between fractions. Another is the intrafraction error, which describes changes in the patient’s position and internal anatomy during the treatment session itself. Random errors are also influenced by the immobilsation system, patient compliance and departmental protocols.

2.4.2 SYSTEMATIC ERRORS

The systematic error is the deviation between the simulated or planned patient position and the average patient position. This is the deviation that occurs in the same direction and is of a similar magnitude for each fraction throughout the treatment course. In this study the population systematic error will also be studied. This is the spread of individual mean errors

for the group of patients. Systematic errors may occur at localization, planning or treatment delivery. Systematic errors during treatment delivery will be looked at in this study. Possible causes for this error includes changes in the patient's position, shape or size (weight loss, hair loss, etc.). Other systematic errors not studied during this thesis include target delineation, position and shape errors. Another quite frequent systematic error (also not studied during this thesis) is the phantom transfer error [39]. This occurs when transferring image data from its initial location through the treatment planning system to the linear accelerator. This "end to end" testing of the treatment planning system has been performed and validated at CMJAH.

Figure 2.2 demonstrates the difference between a large random error and a large systematic error. This figure shows a small systematic error for Patient 1. However there is a large random spread (error) present when compared to Patient 2. Patient 1 consequently has an overall treatment accuracy that is closer to that which is intended.

Figure 2.3 demonstrates the fact that set-up errors are linked to CTV-PTV geometric margins. This figure shows how random errors lead to a "blurring" of the dose distribution as well as how systematic errors lead to an unknown shift in the dose distribution. During the treatment of head and neck cases both errors occur.

The random and systematic errors in this thesis are calculated according to the method employed by Hurkmans et al. [6]. This method is similar to the one used by Hong et al, however, it has been adjusted to account for small sample sizes [7]. Equations 2.1 and 2.2 show how the random and systematic errors were calculated.

In all equations, N is the total number of patients, F_i is the number of fractions for patient i, and F is the total number of fractions for all patients. The measurement of the translation of patient i during fraction f along one of the principal axes is denoted by σ_i; m_i is the individual systematic error, M being the mean translation deviation:

$$\sigma_{random} = \sqrt{\frac{N}{F-N}\sum_{i=1}^{N}(F_i - 1)\sigma_i^2} \qquad 2.1$$

$$\sigma_{systematic} = \sqrt{\frac{N}{F(N-1)}\sum_{i=1}^{N} F_i(m_i - M)^2}$$

2.2

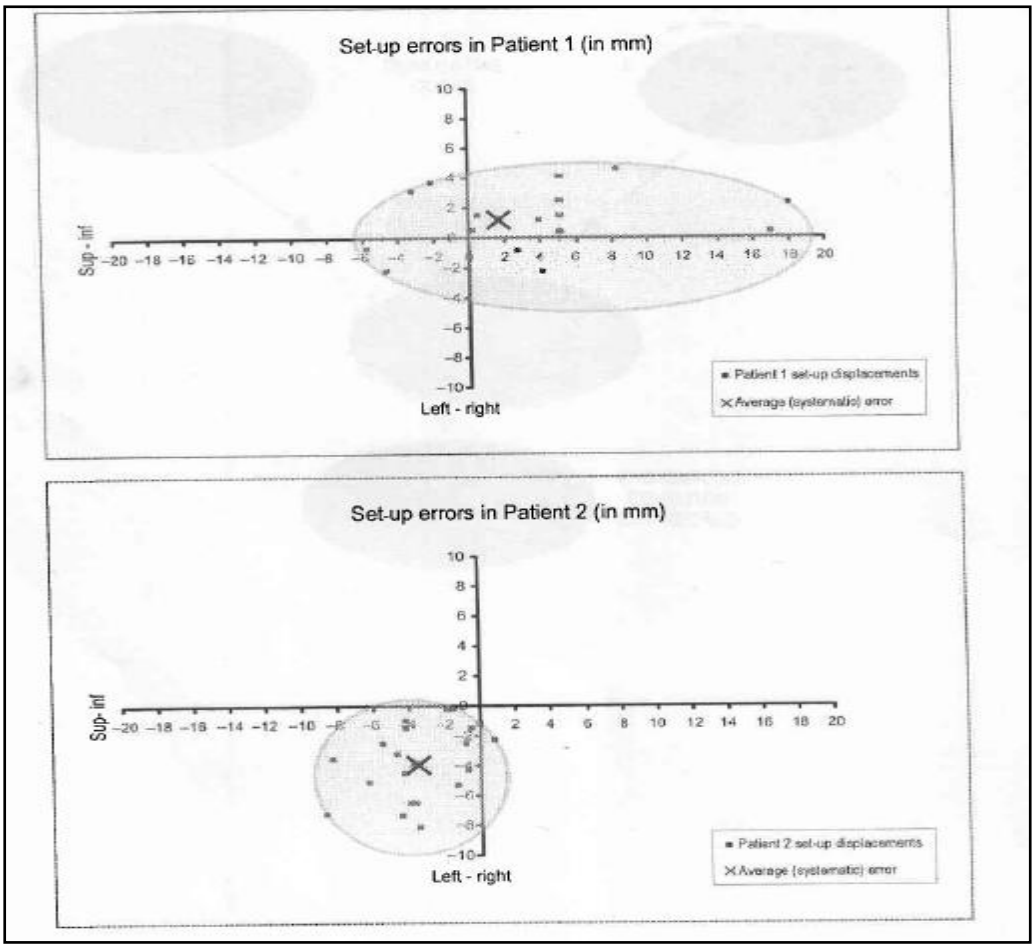


Figure 2.2: Difference between a large systematic and a large random error.

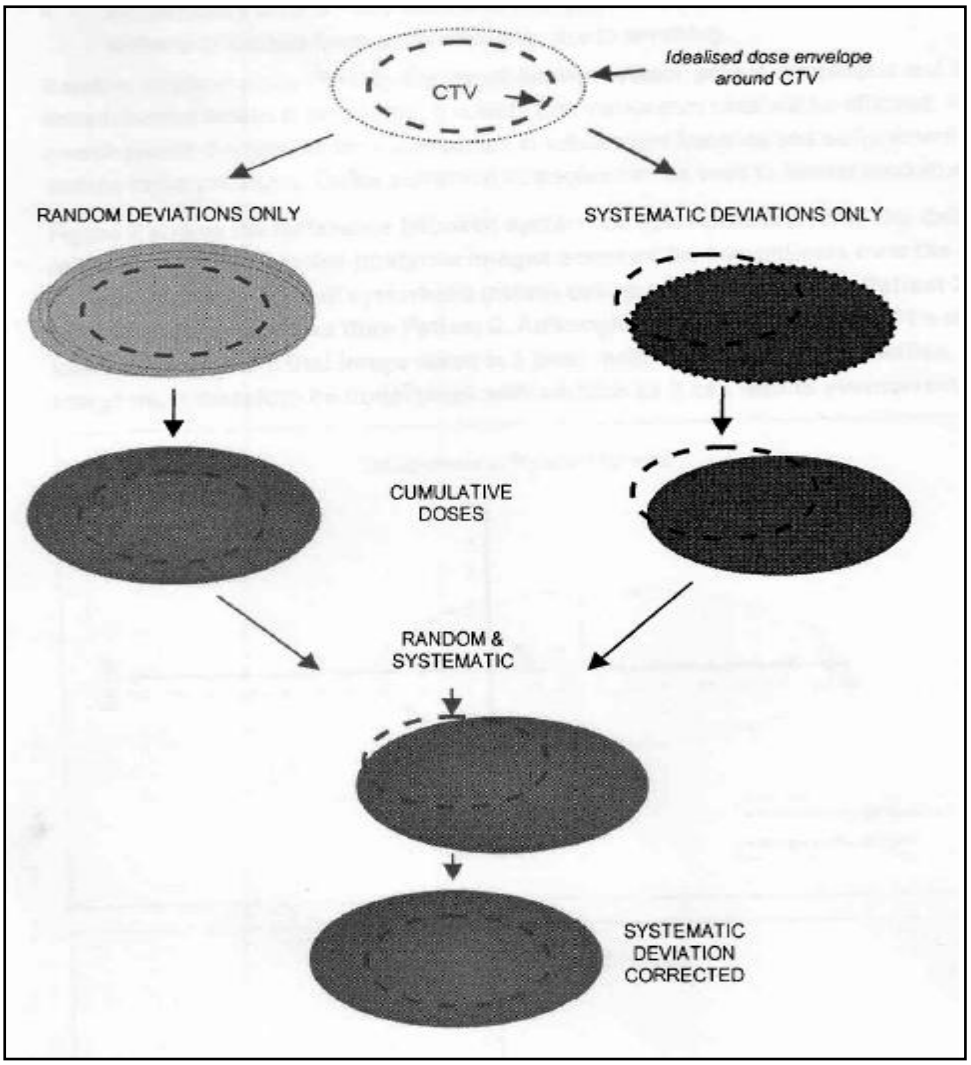


Figure 2.3: Demonstration of how systematic and random errors are linked to the volumes. mentioned in Section 2.2.

2.5 TYPICAL RANDOM AND SYSTEMATIC ERRORS IN THE LITERATURE

With standard head and neck radiotherapy immobilisation techniques (conventional Perspex shell and three point laser alignment), a setup variation of 2 – 5 millimeters has been suggested in various studies [5-7]. A patient set-up error is the difference between the actual and intended position of the part of the patient that is irradiated, with respect to the treatment beam(s) during treatment. A similar study by Hurkmans et al. [6] showed systematic errors of 4.6 mm and random errors of 2.0 mm [6]. By using dental casts for immobilisation, a setup accuracy of 2 mm (one dimensional) standard deviations for both types of errors is

achievable. A recent study by Hong et al. [5] using a high precision optically-guided patient localisation system reported a 3 mm absolute average daily setup error in any one of the three dimensions, with a composite vector setup error of 6.97 mm in 3D space. There are a number of sources that cause systematic and random errors, namely:

- Mechanical shortcomings (e.g. laser alignment) – systematic error
- Patient skin marking movements – systematic error
- Immobilisation (e.g. patient mobility during treatment) – systematic error
- The accuracy with which the Radiotherapists are able to position the patient using the set-up marks and instructions. This ability is usually influenced by experience such as previous training and concentration, as well as time available to position the patient – random error
- Physical and mental state of the patient (e.g. a restless patient) – random error.

At CMJAH patients are setup according to their planned lateral, longitudinal and vertical positions (ascertained from the reference images) and verified on the LINAC using film before starting the first treatment. Patients for IMRT are subject to an additional weekly verification at CMJAH. Tighter treatment margins are used. The prescription request for two isocentres (an additional anterior neck field) could theoretically imply that there is a higher risk of dose inhomogeneity across the target particularly if systematic errors are present.

Methodologically, a similar study was done at CMJAH, and completed in January 2011 in which the setup accuracy of a positioning device for supine pelvic radiotherapy was studied [42]. This was done for two groups of patients, those who were treated with a positioning device and those who had none. All patients had pre-treatment verification films and the treatment couch position was recorded. The daily couch positions were then analysed and a systematic and random error obtained. Data were divided into the X (medio-lateral), Y (antero-posterior), and Z (supero-inferior) planes. The results of this study showed that both the random and systematic error were less for the immobilised patients. The systematic errors were greater in the X and Z planes. One third of the immobilised patients had more than 2 cm variation in setup margin.

2.6 SUMMARY

This chapter reviewed the ICRU acronyms and definition, and there are basically four acronyms of importance in radiotherapy treatments, namely the GTV, CTV, ITV and PTV.

Different set-up errors in the literature were also looked at. These set-up errors range from 2 mm through to 10 mm for head and neck cases and are dependent on the immobilisation and techniques used to analyse them. The different analysis techniques looked at in this chapter were computer controlled (used in this thesis), x-ray imaging, EPIDs, and IGRT.

Random and systematic errors were defined and the difference between the two was schematically shown in a diagram. The formula used in this thesis was also given as well as some of the source for random and systematic errors.

3. METHODOLOGY

3.1 INTRODUCTION

In this chapter the research methodology will be discussed, as well as a look at the type of cases that would be studied.

Questionnaires did not form part of this research design. Since patients treatment data were collected retrospectively no input was required from the patient or the treatment team (oncologist, radiotherapist or physicist). Ethics was applied for, and approved for this study. The clearance number was M10616.

This study focuses on RVS data captured into the electronic patient's file from the position of the treatment couch. The difference in the daily digital position of the couch over a course of treatment (which is the patient's placement with respect to the isocenter) will be compared. From this a software interlock may be established to provide a level of automatic oversight to the patient setup. Tolerance limits can be applied to the baseline position of the treatment couch, which will allow treatment to continue only if the couch position is within the preset tolerance limits.

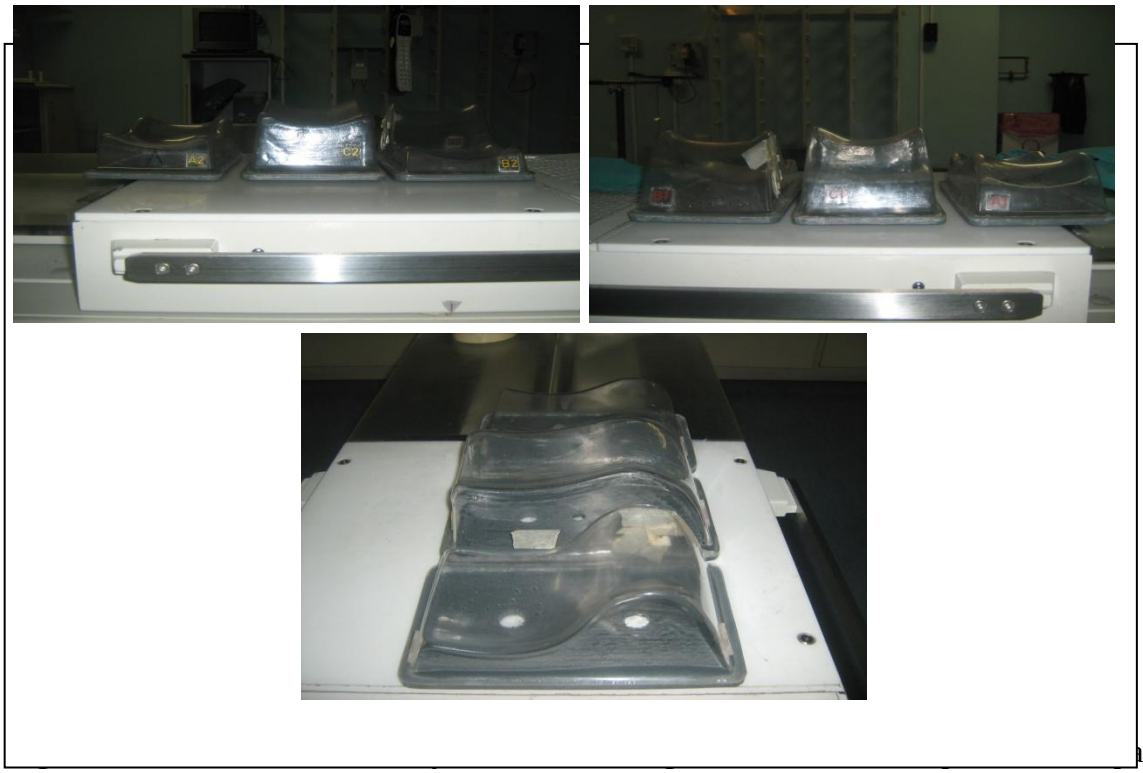
3.2 POPULATION TO BE STUDIED

There are two main categories of sampling; random (probability) and non-random (non-probability) sampling. Random sampling usually works best for any form of statistical analysis [40]. Under this category every sample unit has an equal chance of being selected [40]. With non-random sampling the researcher looks at particular features of the sample.

At the time of this research CMJAH had four large clinics to treat different cancer sites, namely head and neck, gastro-intestinal, gynaecology, and breast. A decision was undertaken to only look at the set-up margin/error for head and neck cases, and only for virtual simulation and IMRT cases. The reason for this decision was that all virtual simulation and

IMRT cases are for radical intent and a large degree of accuracy is aimed for. Determination of a set-up margin would hopefully confirm that the patients indeed received more accurate radiotherapy. Imposition of more rigorous RVS parameters to ensure a tighter treatment margin would ensure less room for error during patient set-up.

In this study 50% of the 100 virtual simulation cases had carcinoma of the larynx, 30% had cancer of the oral cavity and 20% were "other cases" which consisted of cancer of the oropharynx, pyriform fossa, etc. All larynx cases were treated with the patient's head in extension to avoid the eyes during treatment, and to include the entire larynx in the field. For the rest of the cases, the neck was in a neutral position. The position of the head in all these cases may have influence set-up, and this formed a sub-analysis. At the time of the study CMJAH had 6 different locally-manufactured rigid headrest shapes, which could be used to influence head and neck position. The system comprises of 3 devices, which can be positioned on either side. Three different views of the head-rests are shown in Figure 3.1.



atients head in 6 different shapes.

Ten IMRT cases were also investigated. All the patients were positioned with their neck in extension.

Initially two hundred and thirty virtual simulation and twenty IMRT cases were proposed to be studied. However there was no statistically significant difference between samples one to thirty and samples thirty to sixty and therefore sampling was discontinued after 110 cases. At the time, only 10 of these were IMRT cases that had completed treated.

3.2.1 TREATMENT COUCH USED IN THE STUDY

Errors in the patient setup may be present when portal imaging is not used [18]. In these situations the RVS software interlocks on the couch position may be the only means of determining patient setup. Given that RVSs are installed and in use in many radiation therapy clinics, careful analysis of their use seems warranted [18-21]. The Siemens ZXT^{TM} treatment table used in this study is fully remote controlled from outside the treatment room but this is not activated at CMJAH. It also has an LED display for isocentric and column rotation as well as lateral, longitudinal and vertical positioning [37]. Readouts are in IEC convention and a free-float capability exists for simultaneous lateral and longitudinal motion. It is a fully-motorized table. The versatile tabletop design allows headboard attachment at either end of the table. The dimensions of the ZXT^{TM} treatment table are described in Table 3.1, and a schematic presentation is shown in Figure 3.2. The digital read-out display is shown in Figure 3.3.

Table 3.1: Features and specifications of the ZXT treatment table

FEATURE	**SPECIFICATION**
Tabletop length (with headboard)	245 cm
Tabletop width without accessory rails	50 cm with accessory rails: 60.2 cm
Tennis racquet opening	43 cm wide x 76 cm long
Maximum field size from the posterior with table at highest position	57 cm wide x 57 cm long
Tabletop deflection	≤5 mm
Accessory rail length	109 cm height: 25 mm thickness: 10 mm

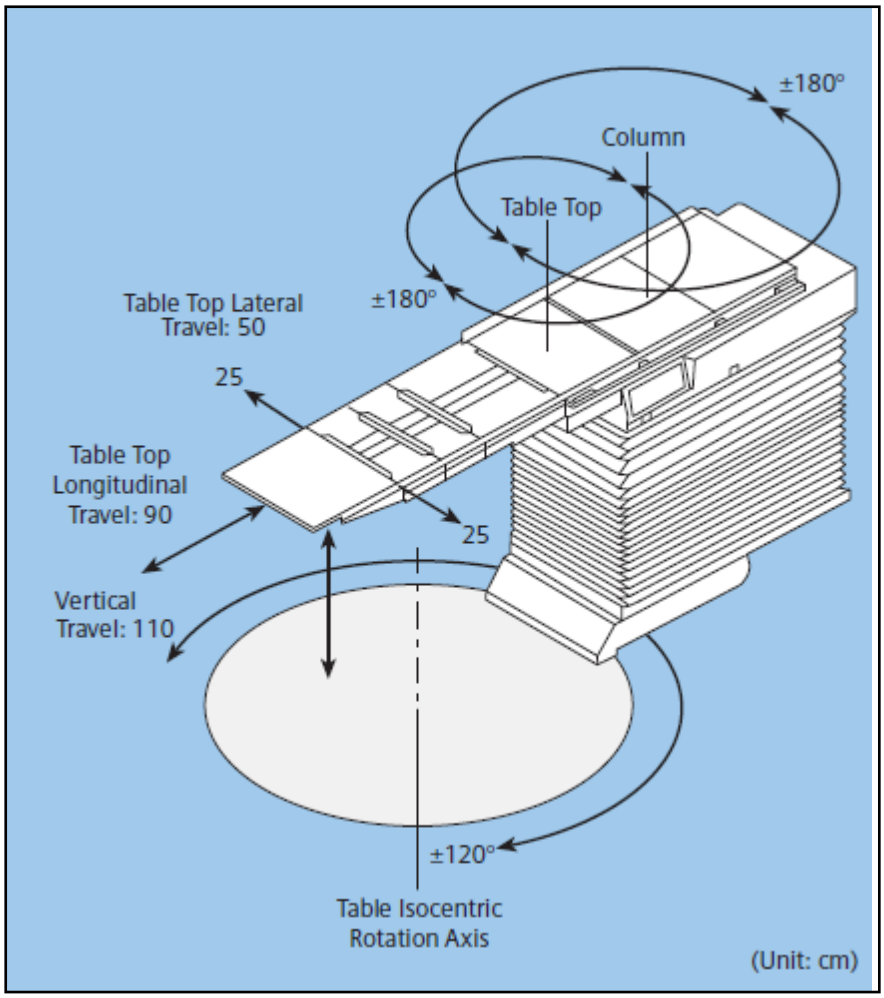


Figure 3.2: Schematic diagram of the ZXT™ treatment table.



Figure 3.3: The digital reading as displayed on the couch control panel. Each value can be zeroed in order to assist setup, but the absolute values are captured and stored by the LANTIS™ for each treatment.

3.2.2 QUALITY ASSURANCE PERFORMED ON THE COUCH

There may be inaccuracies in the radiation treatment of patients resulting from other mechanical and dosimetric sources of uncertainty on the LINAC [38]. Mechanical sources include errors in the field edge position, the optical indicator, the isocenter location, positioning lasers and MLC position. The tolerance allowed for each of these parameters was ±2 mm at the time of the study. The weekly quality control (QC) followed at CMJAH is given in Figure 3.4. This assured the integrity of the data captured for this study.

		ADDITIONAL QA CHECKS:	
Localising lasers:			Check on calibration phantom
Place a piece of linear graph paper on the wooden/perspex couch insert and centre to cross-hair			
Light field:	Symmetric fields	**10 cm x 10 cm**	_____
		20 cm x 20 cm	
	Offset fields	**X1 = -5.0 cm**	
		X2 = 5.0 cm	_____
		Y1 = -5.0 cm	
		Y2 = 5.0 cm	
	Couch movements	**Lateral +/- 5cm**	
		Longit +/- 20 cm	
		Vertical +/- 10 cm	
	Isocentric rotations	**Collimator 90**	
		Couch 270	
		Gantry +/- 20	
	Backpointer		
Facility interlock:			**Rad on/off lights:**
Approved/Not Approved For Treatment:			
Physicist:			Radiographer:
Time: _____			Time: _____

Figure 3.4: The documentation for the weekly mechanical QC performed at CMJAH on all treatment couches.

3.2.3 METHODOLOGY OF THE VIRTUAL SIMULATED CASES

The virtual simulation workflow is demonstrated in Figure 3.5.

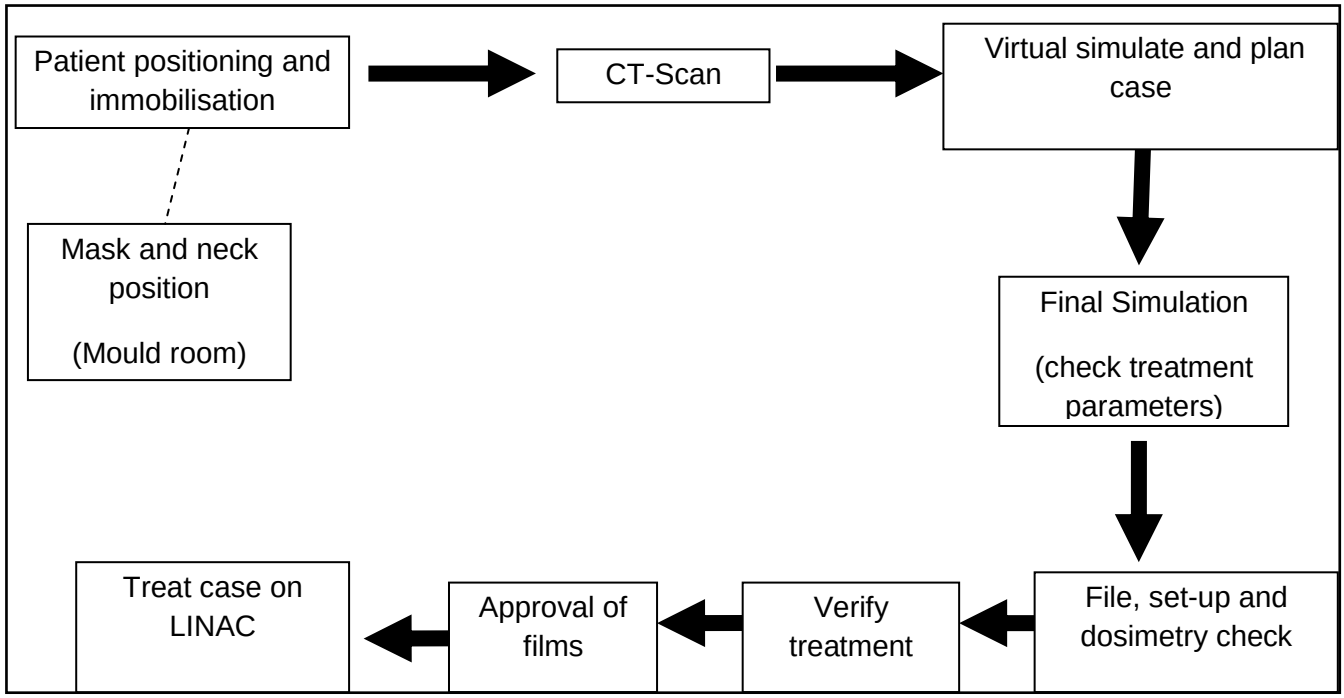


Figure 3.5: Virtual simulated treatment path.

All patients vacuum tight acrylic mask were made in the mould room. Plaster of paris mould was made of the patients on the first visit according to the decision of the new planning conference (the suitable neck position for the patient). Vacuum formed shells were then manufactured using the positive impressions. At the second visit, the Perspex mask was fitted and straps attached compatible with the system.

Patients were then CT-scanned. Three millimeter slice-spacing were chosen for all head and neck cases, from the patient's vertex to clavicles. This was done to include the tumour, any micro-scopic disease and surrounding anatomy so that reasonable digitally reconstructed radiographs (DRRs) could be obtained from the CT series. The treatment beam projections were also clearly marked on the DRRs.

The virtual simulation treatment plans consisted of two lateral fields usually with a matched anterior neck field. This is demonstrated in Figure 3.6. All fields were 6 MV photon beams. The lateral and anterior neck field borders were localised and approved by the radiation

oncologist. The Y_2-jaw for the anterior neck field is closed off superiorly resulting in a non-divergent field matched to the lateral fields. T1 and T2 larynx that did not have an anterior neck treatment field were also included in this study. Posterior neck electron fields also formed part of the patient's treatment. The electron fields were not analysed in this study.

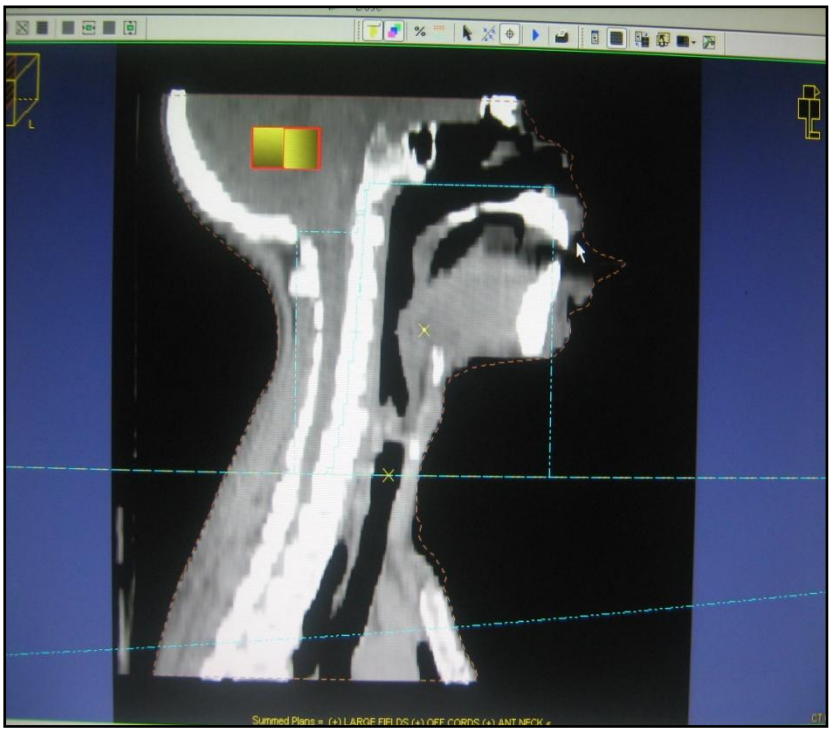


Figure 3.6: Field positioning arrangement, with a matched lateral and anterior neck field. The depth of the anterior neck field is set to 3 cm on the axial level at the inferior border.

Final simulation consisted of verifying all treatment parameters of the planned patient treatment. These check included all movements in the longitudinal (Z), vertical (Y) and lateral (X) directions from the reference point. This reference point was chosen as the zero slice on the CT for all patients. All of this is done to ensure the correct patient treatment position.

At the time of the study, CMJAH had a QA radiotherapist tasked to further check treatment plans, prescription, final simulation movements, etc. Thus ensuring that no obvious mistakes were made before the actual treatment of the patient. This QA procedure formed part of the management of all the patients in this study.

A verification film of the patient's planned treatment fields was taken on the LINAC prior to the first treatment. These films would then be compared with the reference DRRs in order to confirm the planned treatment for the patient. The films are approved offline by the radiation oncologist. The patients then continue on this treatment course.

The couch position at the time of the approved verification films was recorded and taken as the "pure sample" (or ideal position). The couch position was given by the lateral (X), vertical (Y) and longitudinal (Z) directions on the LANTIS^{TM}, the RVS used. Figure 3.7 shows a screenshot of the couch co-ordinates from the LANTIS^{TM}. This ideal position on the couch was then compared to the daily thirty-three or thirty-five (depending on the prescription) couch positions from each treatment session in all planes (X, Y and Z).

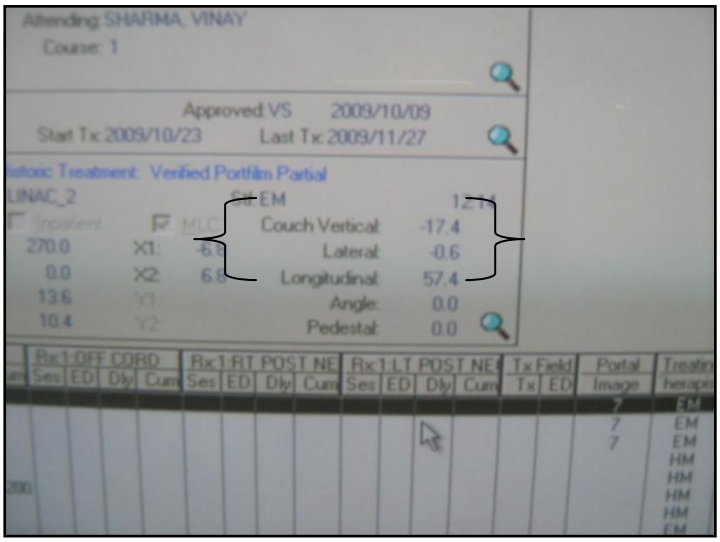


Figure 3.7: Demonstration of the readings taken off LANTIS.

The longitudinal (Z) position was expected to vary from day to day owing to the placement of the base plate on the table top. This is shown in Figure 3.8. True random set-up errors in this direction were therefore not feasible. However the difference in the Z-positions between the lateral fields and anterior neck field was relevant to this study and the difference in the Z-position data were used for this purpose.

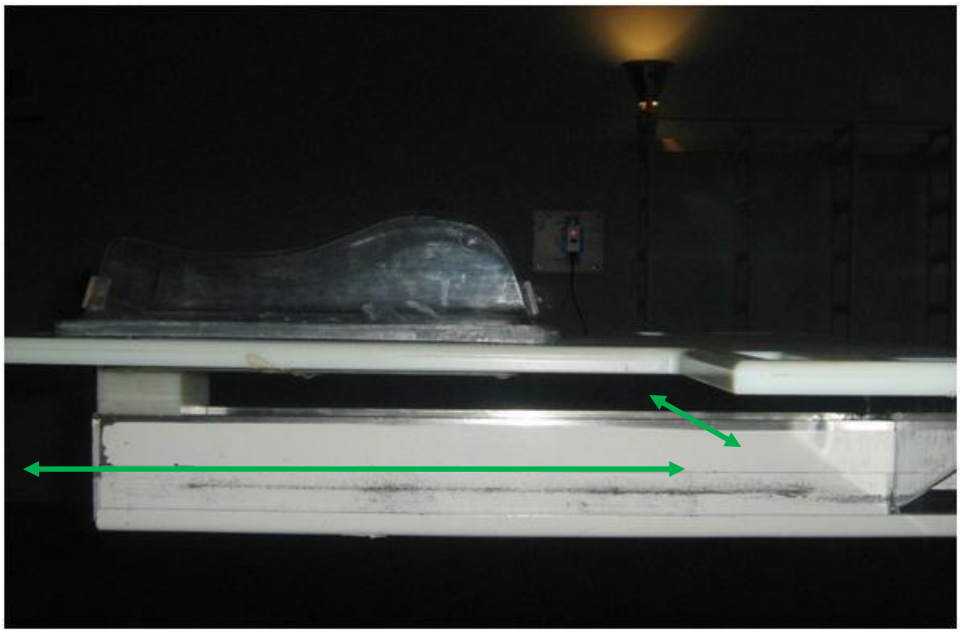


Figure 3.8: Immobilisation device on the treatment couch with "clearance" to treat post neck fields.

A further sub-analysis was done on the virtual simulation cases to consider variations between patients undergoing similar treatment to establish if there was an identifiable trend in set-up errors with disease site.

Only one LINAC was used for the virtual simulation cases studied in this thesis.

3.2.4 METHODOLOGY OF THE IMRT CASES

At the time of this research CMJAH was using a forward-IMRT technique for planning radical nasopharyngeal head and neck cancer cases. All these cases followed the workflow shown in Figure 3.9. The patients' neck position was extended to separate organs at risk (such as the brain, spine, eyes, etc.) from the target volumes. The treatment plan usually consisted of 6-9 treatment field directions, which were segmented to produce 3 – 4 intensity levels each. An offline dry test run was done on all cases to ensure accurate MLC download and no collision of the couch and gantry.

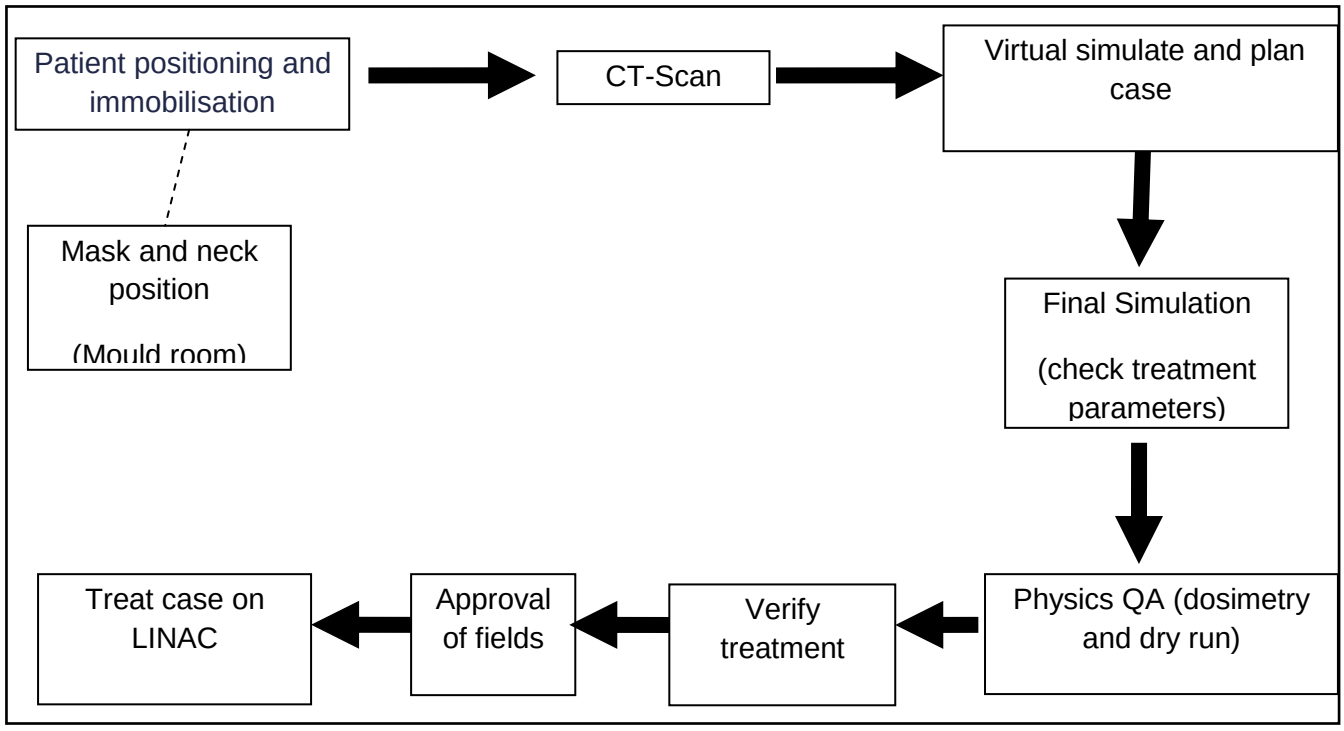


Figure 3.9: CMJAH IMRT treatment path.

Since IMRT allows one to plan the cancer treatments with multiple, highly-conformed small fields from different beam directions, accurate reproducible treatment requires precise daily patient setup for a long course of RT. The initial verification and film approval procedure was the same as for virtual simulated patients. However, as an additional measure, CMJAH requires all these patients to have a weekly positional check. This positional check consists of weekly films of the patient's set-up, using orthogonal anterior and lateral open fields. These films were compared to the DRRs of the same open fields produced at the same treatment isocentre position. This additional weekly verification also formed part of the analysis of this thesis. This verification procedure is described in AAPM 40 [38]. At CMJAH, the radiation therapists visually check the films and continue with treatment. The medical physicist and radiation oncologist then review and approve these films after treatment, offline. Each week at least one lateral and the anterior field verification would be taken after/or before the patients treatment.

Again, the couch position of the initial approved set of orthogonal verification films was again taken as the "pure sample" (or ideal position). The couch positions recorded were for the lateral (X), vertical (Y) and longitudinal (Z) directions. This ideal position on the couch was then statistically analysed and compared to the daily thirty-five couch positions in all

three planes (X, Y and Z). The same difficulty applies to the longitudinal (Z) position. Similarly therefore, the matched couch position between the intensity modulated fields and anterior neck field were also analysed. An example of an IMRT planned patient's fields are shown in Figure 3.10. The anterior neck field match was achieved in the same manner as for the virtual simulation patients.

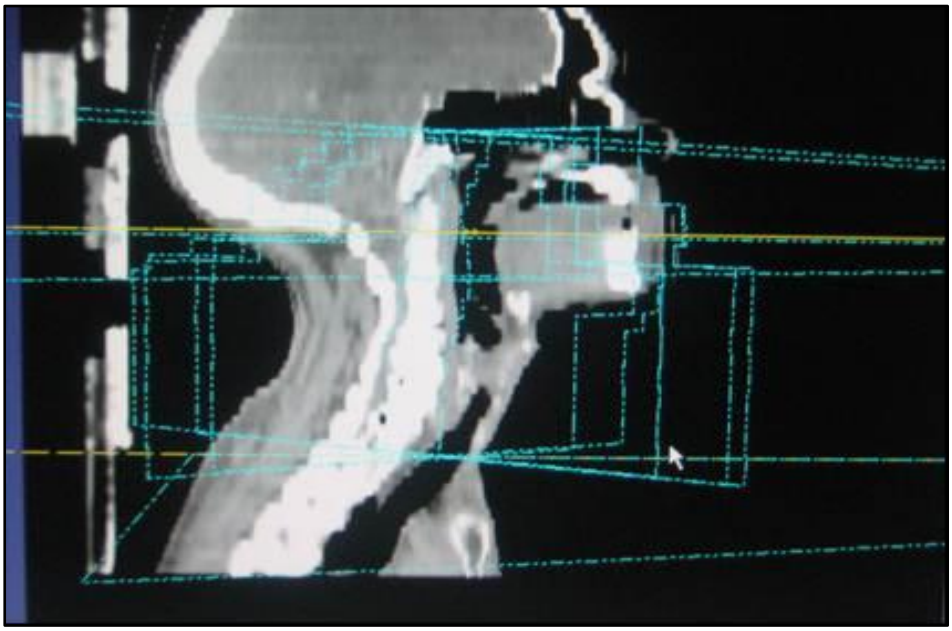


Figure 3.10: IMRT treatment plan.

The data read off LANTIS^{TM} in the three different couch positions (X, Y, and Z) were analysed in the same manner as the virtual simulation cases.

Altogether ten IMRT cases were studied including the weekly verifications of these cases

3.3 SUMMARY

Two treatment techniques, namely virtual simulation and IMRT were analysed. All together 110 cases were studied, a 100 being virtual simulation and 10 of the cases being IMRT. The workflow of these cases as well as a schematic diagram of the treated fields was also given in this chapter.

The daily couch position (X, Y and Z) was captured for analysis. A sub-analysis including the variation of the couch position for the weekly verifications of the IMRT cases, was also done.

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

The total number of patients studied (N) in this thesis was 110; 100 were virtual simulated and 10 were IMRT cases. The total number of daily fractions (F) for these cases were 5644 and 600 respectively. The virtual simulated cases had 3321 daily fractions for the lateral fields and 2323 fractions for the anterior neck fields. The IMRT cases had 350 daily fractions for the intensity modulated fields and 250 daily fractions for the anterior neck fields.

Figure 4.1 demonstrates the virtual simulations cases studied. All together the number of virtual simulated larynx, oral cavity and "other" cases were 50, 30 and 20 patients respectively.

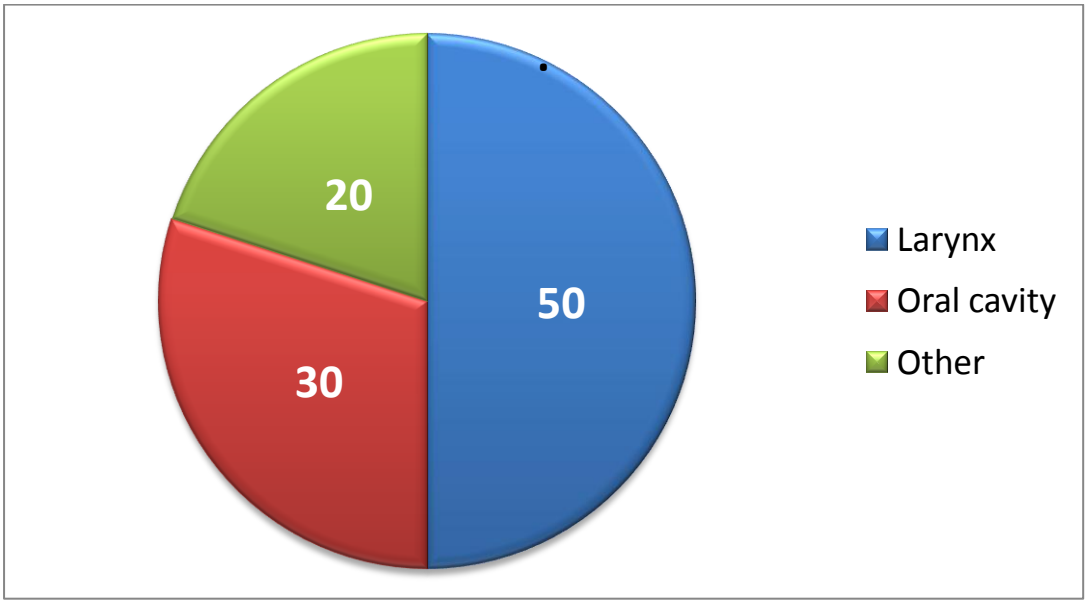


Figure 4.1: The number of virtual simulated cases studied.

4.2 RESULTS OF THE VIRTUAL SIMULATED CASES

Figures 4.2 - 4.7 represent the individual variations of a single virtual simulation case for the lateral and anterior neck field.

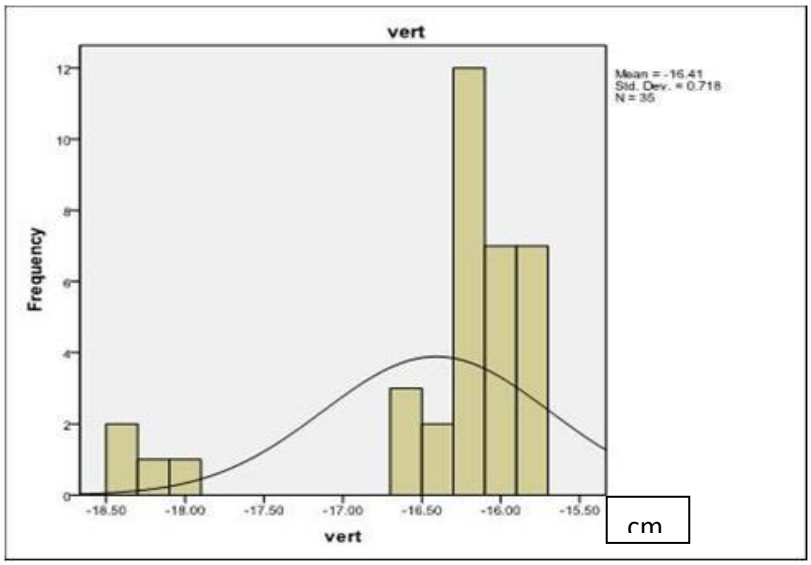


Figure 4.2: Variation of the lateral neck fields in the vertical (Y) direction.

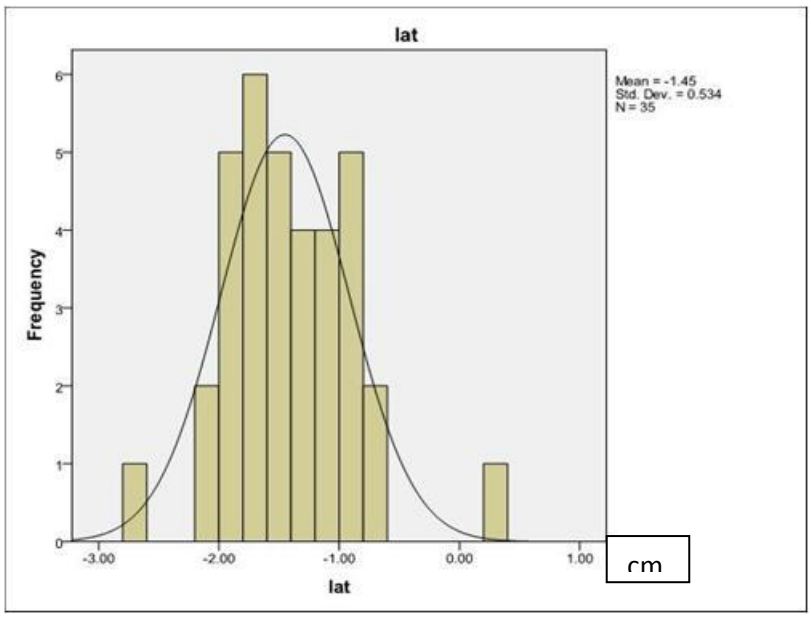


Figure 4.3: Variation of the lateral neck fields in the lateral (X) direction.

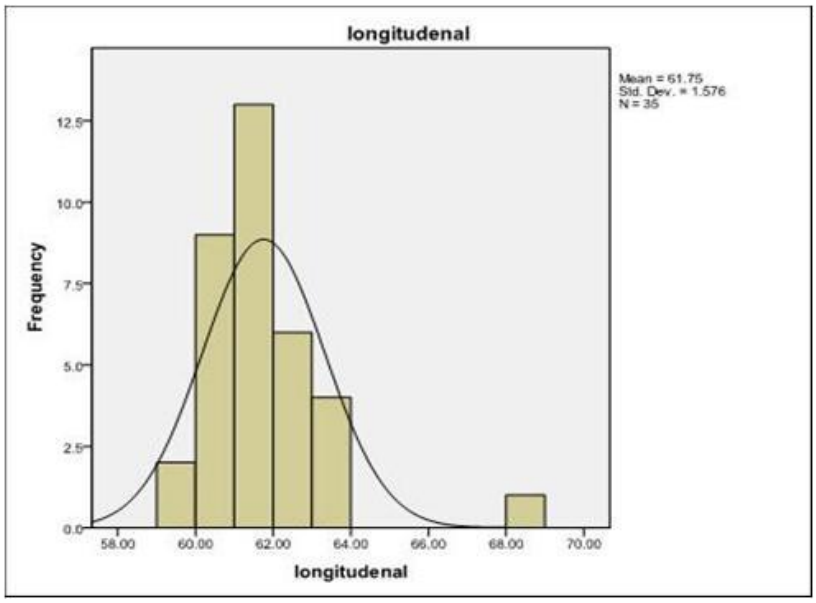


Figure 4.4: Variation of the lateral neck fields in the longitudinal (Z) direction.

The individual standard deviation for this specific patient's lateral fields were X=0.53 cm, Y=0.72 cm, Z=1.58 cm, showing a large variation (more then 1cm) in the Z direction, because of the placement of the base plate on the table. This graph in Figure 4.4 does not represent the match point of the individual patient but the actual variation in the Z-direction.

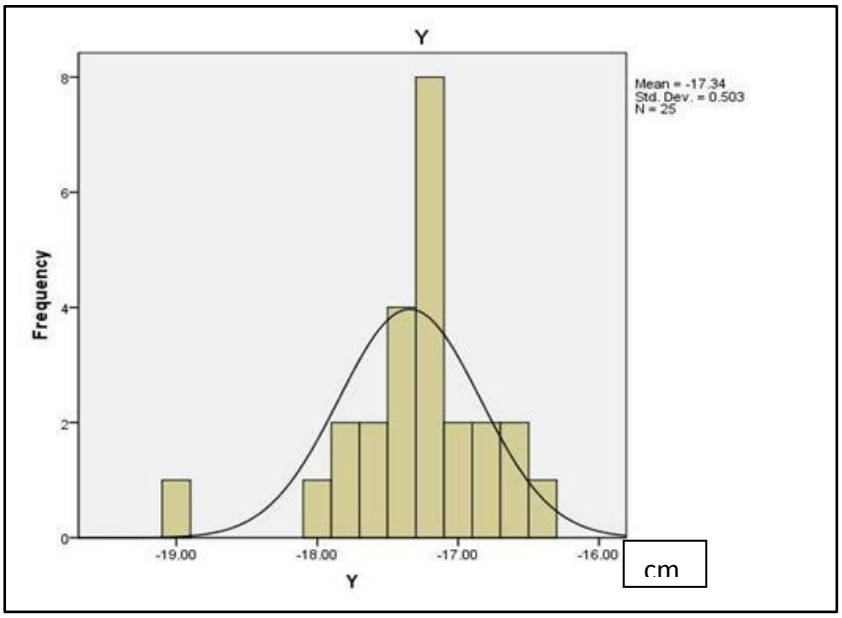


Figure 4.5: Variation of the anterior neck field in the vertical (Y) direction.

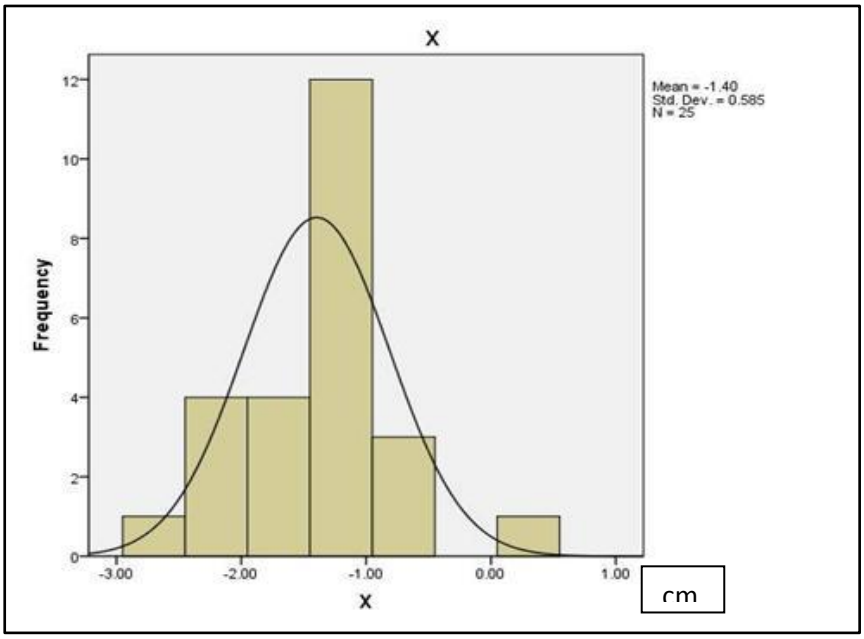


Figure 4.6: Variation of the anterior neck field in the lateral (X) direction.

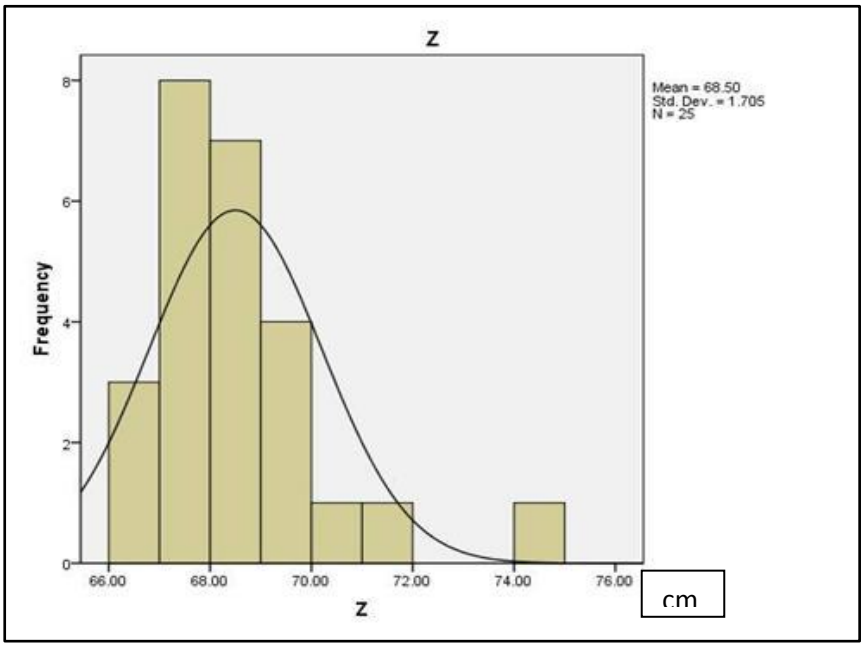


Figure 4.7: Variation of the anterior neck field in the longitudinal (Z) direction.

The individual standard deviation for this specific patient's anterior neck field was X=0.58cm, Y=0.50cm, Z=1.71cm, showing a large variation (more than 1cm) in the Z direction, for the same reason given above. This is the reason the match point for the patient's Z-direction was taken, as this would give a "true" indication of the set-up in the Z-direction.

4.2.1 INDIVIDUAL SYSTEMATIC SET-UP VARIATION (Mi)

The individual set-up variations for the lateral and anterior neck fields for each patient are shown in Figures 4.8 to 4.12 in each direction (X, Y and Z).

4.2.1.1 LATERAL FIELDS

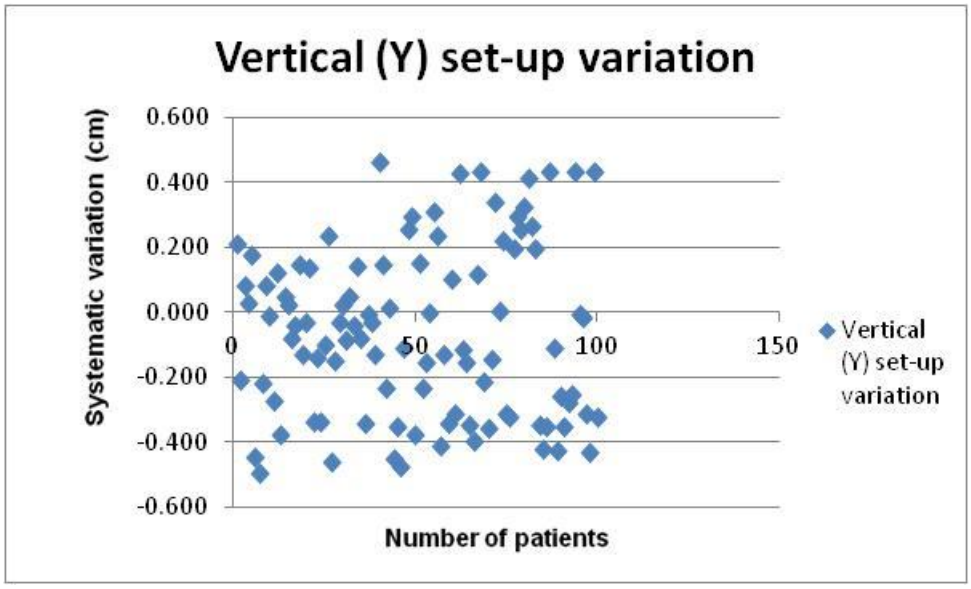


Figure 4.8: The individual patient systematic variation of the lateral fields in the Y-direction.

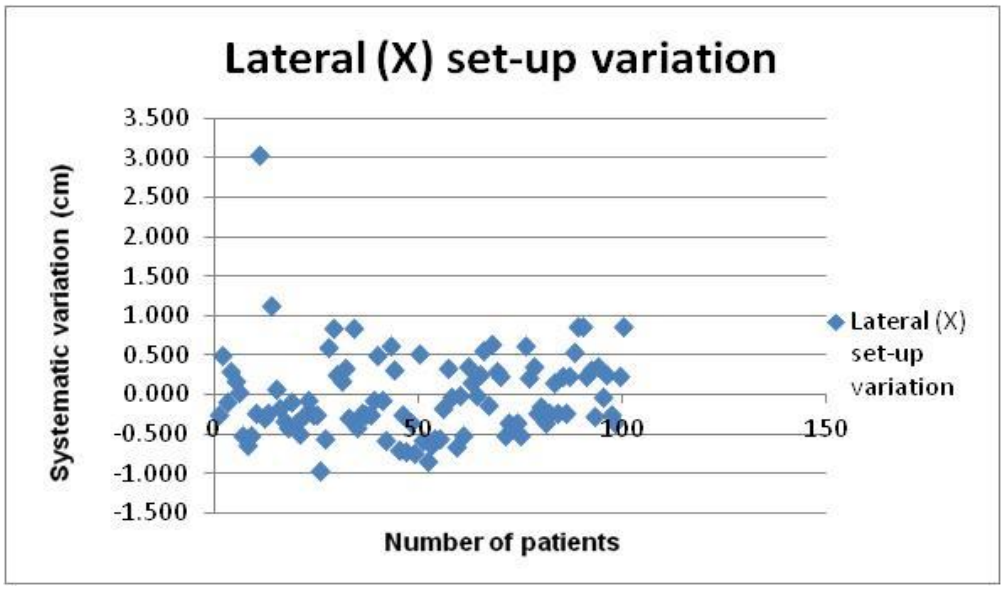


Figure 4.9: The individual patient systematic variation of the lateral fields in the X-direction.

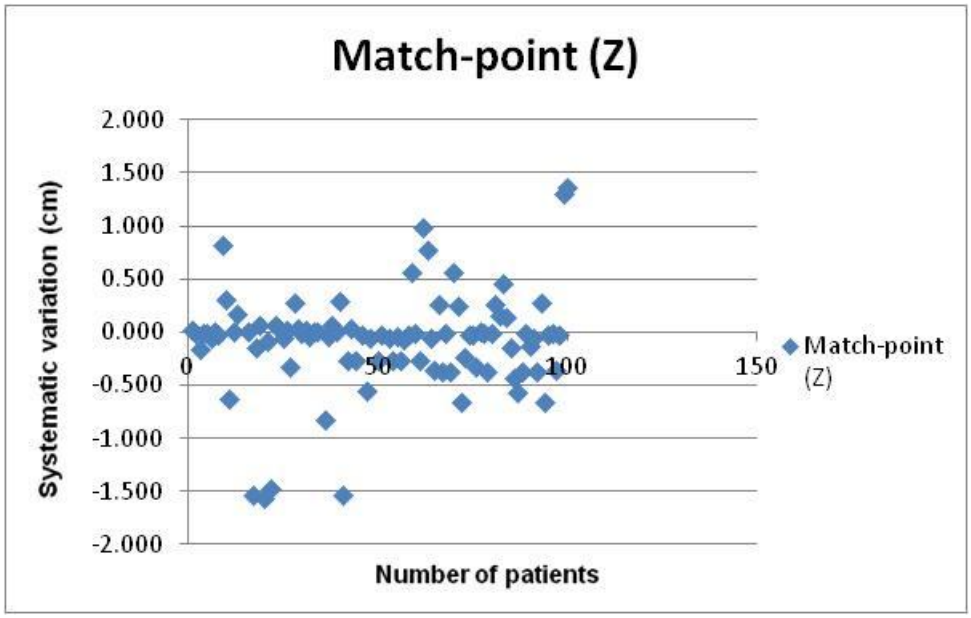


Figure 4.10: The individual patient systematic variation of the match point of the lateral and anterior neck fields in the Z-direction. A zero result implies that the patient's lateral fields were on average perfectly matched to the anterior neck field.

4.2.1.2 ANTERIOR NECK FIELDS

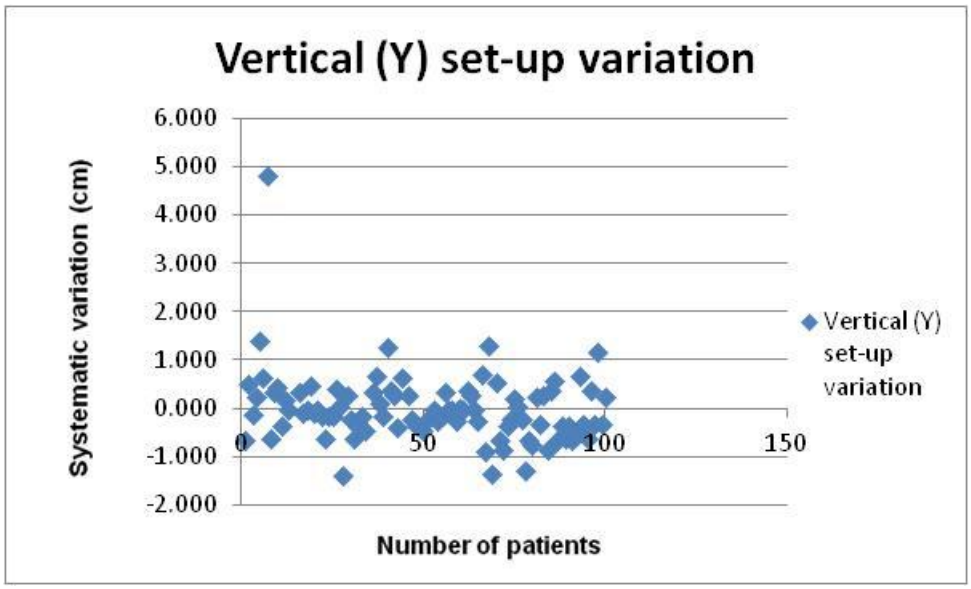


Figure 4.11: The individual patient systematic variation of the anterior neck fields in the Y-direction.

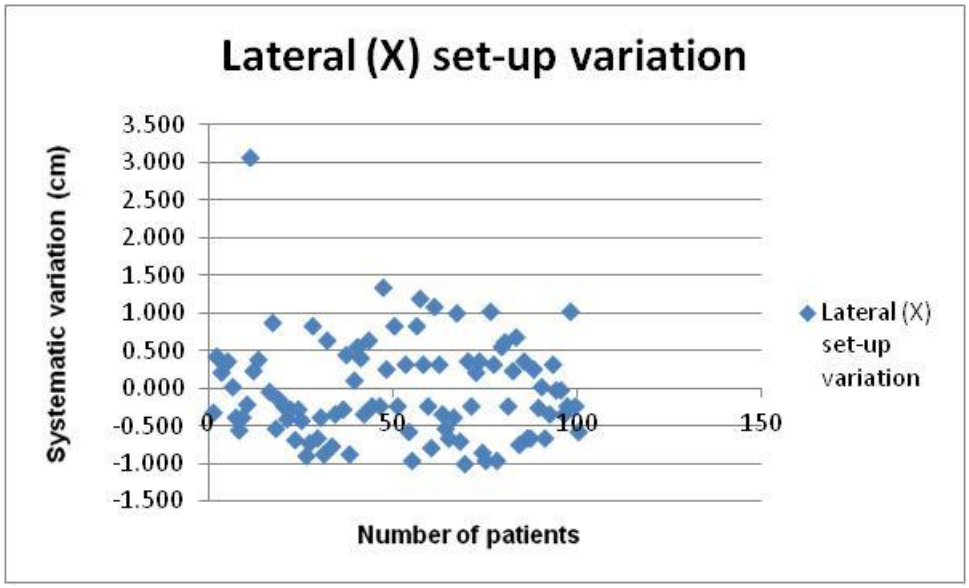


Figure 4.12: The individual patient systematic variation of the anterior neck fields in the X-direction.

The vertical (Y) individual set-up variation of the lateral fields seems to have the smallest variation, followed by the match point (Z) variation, with the lateral (X) having the largest variation. This is a "strange result" given that the system is centered. One of the reasons for this large variation in the X-direction could be due to the fact that CMJAH do not use the same thickness marker pen to mark the treatment position on the patient mask. The markers used are usually larger than the laser lines that can be seen on the mask. This can result in the radiotherapist aligning the lasers on the mask "where they see fit", resulting in a large variation systematically. The lateral fields' individual systematic variation was found to be as large as 0.49 cm, 3.03 cm and 1.5 cm in the Y, X and Z – directions respectively. The anterior neck field individual systematic variation was found to be as large as 4.81 cm and 3.07 cm in the Y and X directions respectively. These results are for patient number 7 and 11, on two different days of treatment. The mechanical Q.C results were looked at for these two days and it showed that the lasers were within 2mm for those days. So again this error could be due to the laser alignment to the mask markings. Another reason for these large errors could be the "rotation" of the upper body relative to the head.

4.2.2 OVERALL MEAN SET-UP VARIATION (M)

The population's mean set-up variation is given in Table 1.

Table 4.1: The mean set-up variation of the lateral and anterior neck fields

Fields	**Vertical (Y)**	**Lateral (X)**	**Match point (Z)**
Laterals	-0.091 cm	-0.021 cm	-0.109 cm
Anterior neck	0.205 cm	-0.015 cm	

The technique used at CMJAH is to set-up the vertical position at 97 cm SSD at the level of the inferior axial border.

4.2.3 RANDOM ERRORS

The random errors calculated from the standard deviation of set-up from the mean in each direction are given in Table 4.2

Table 4.2: Random error for the virtual simulation population studied.

Fields	**Vertical (Y)**	**Lateral (X)**	**Match point (Z)**
Laterals	± 0.77 cm	± 0.58 cm	± 0.74 cm
Anterior neck	± 1.79 cm	± 0.69 cm	

The population studied had a large overall random error (7.0 mm for the laterals and 12.4 mm for the anterior neck fields), when compared to a random error of 2 mm (for lateral fields) by Hurkmans et.al [6] (using a similar immobilization devices). The anterior neck variation was not given

The vertical random error for the anterior neck field is very large; the mechanical couch position was within mechanical tolerance during this period, which leads the investigator to question the comprehension of the set-up of the individual fields by the radiotherapists. This question could be a follow-up from this thesis in the future, comparing the set-up variations of the different radiotherapists at CMJAH, looking at years of experience in the field as well

as the vigilance of the radiotherapists in question, radiation therapist training and regular QA of the setup.

4.2.4 SYSTEMATIC ERROR

The systematic error calculated from the mean shifts in the standard deviation is given in Table 4.3

Table 4.3: Systematic error for the virtual simulation population studied.

Fields	**Vertical (Y)**	**Lateral (X)**	**Match point (Z)**
Laterals	± 0.21 cm	± 0.72 cm	± 0.53 cm
Anterior neck	± 0.88 cm	± 0.62 cm	

The population studied an overall systematic error of 4.7 mm for the laterals and 7.5 mm for the anterior neck fields. The lateral fields compare well to a systematic error of 4.6 mm reported by Hurkmans et.al. [6]. Again the systematic error for the anterior neck was not given for that study.

4.2.5 THE INFLUENCE OF THE HEAD POSITION (HEAD REST)

The head rest position did not influence the results of this population studied, since 65 cases (50 larynxes and 15 hypopharynx) of the population had the patient's head in extension. Therefore the population studied was biased towards the cases with the head in extension (65%), and no change in the systematic and random error of statistical significance was observed when compared to the other 35% of cases.

4.3 RESULTS OF THE IMRT CASES

Figures 4.13 - 4.18 represent the individual variations of a single IMRT case for the lateral and anterior neck field.

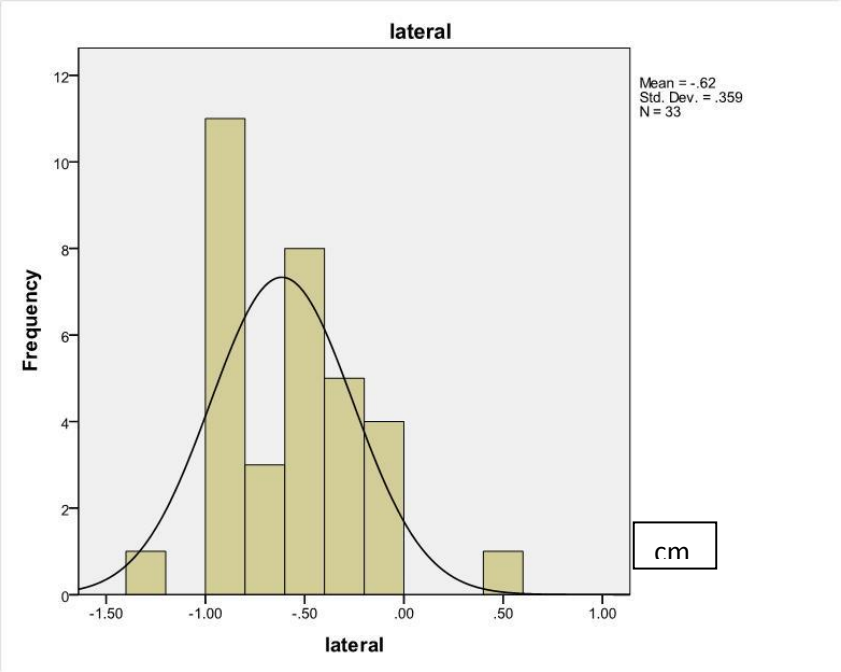


Figure 4.13: Variation of the IMRT fields in the lateral (X) direction.

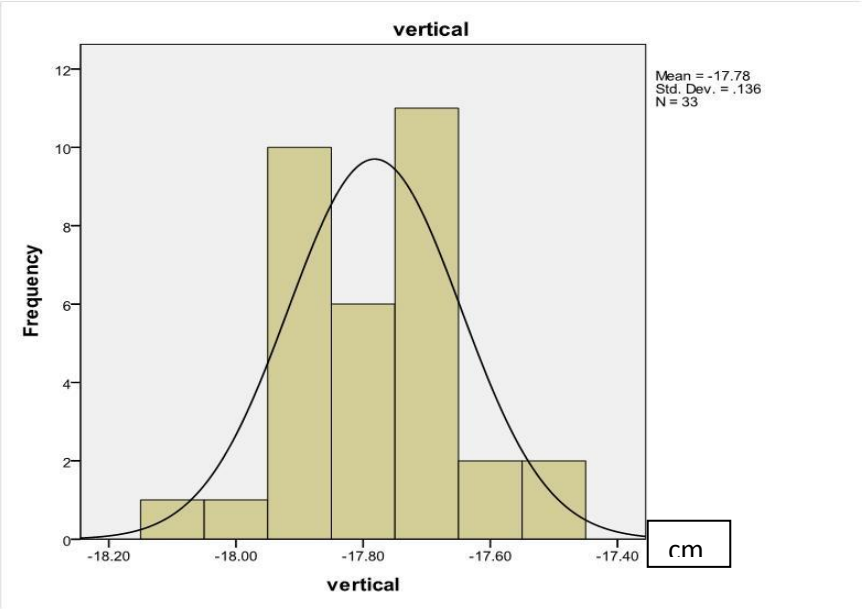


Figure 4.14: Variation of the IMRT fields in the vertical (Y) direction.

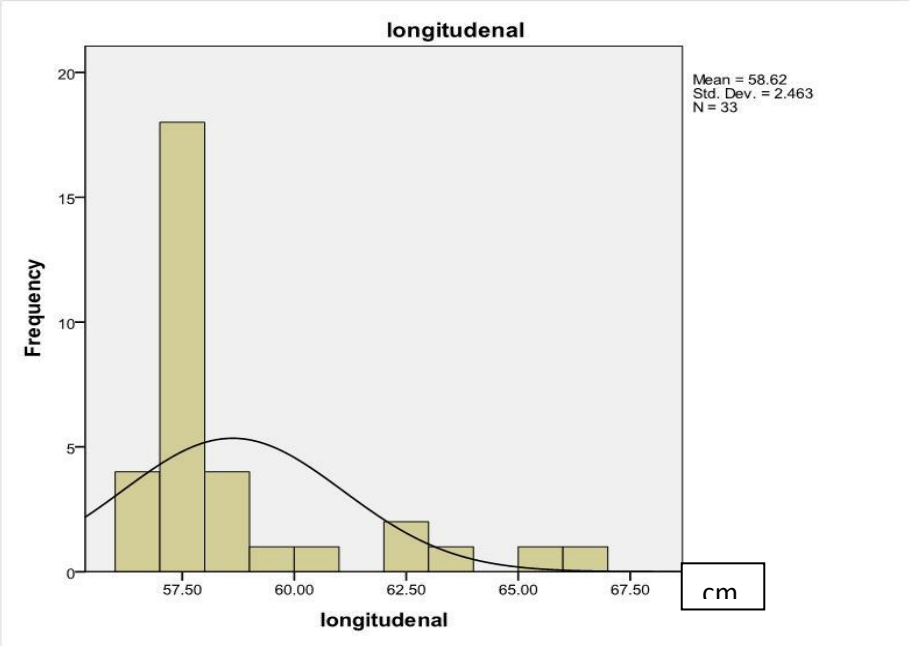


Figure 4.15: Variation of the IMRT fields in the longitudinal (Z) direction.

The individual standard deviation for this specific patient's IMRT fields were X=0.48cm, Y=0.53cm, Z=1.68cm, showing a large variation (more then 1cm) again in the Z direction, because of the placement of the base plate on the table.

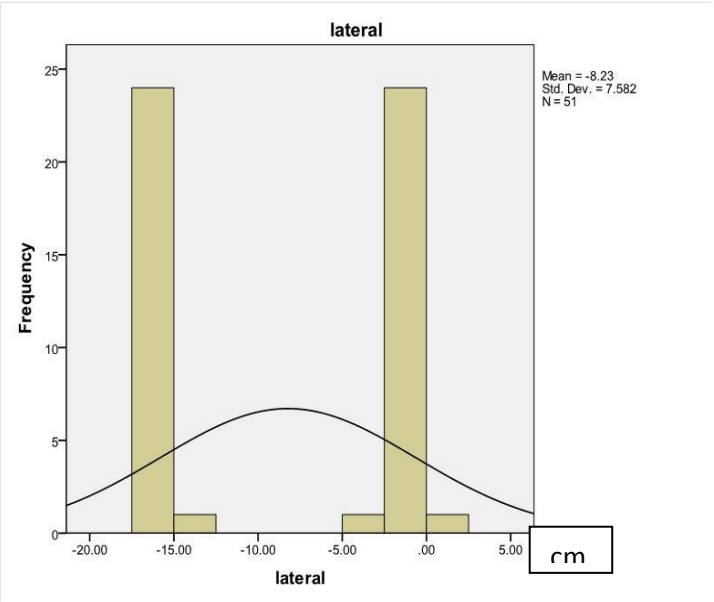


Figure 4.16: Variation of the anterior neck field in the lateral (X) direction.

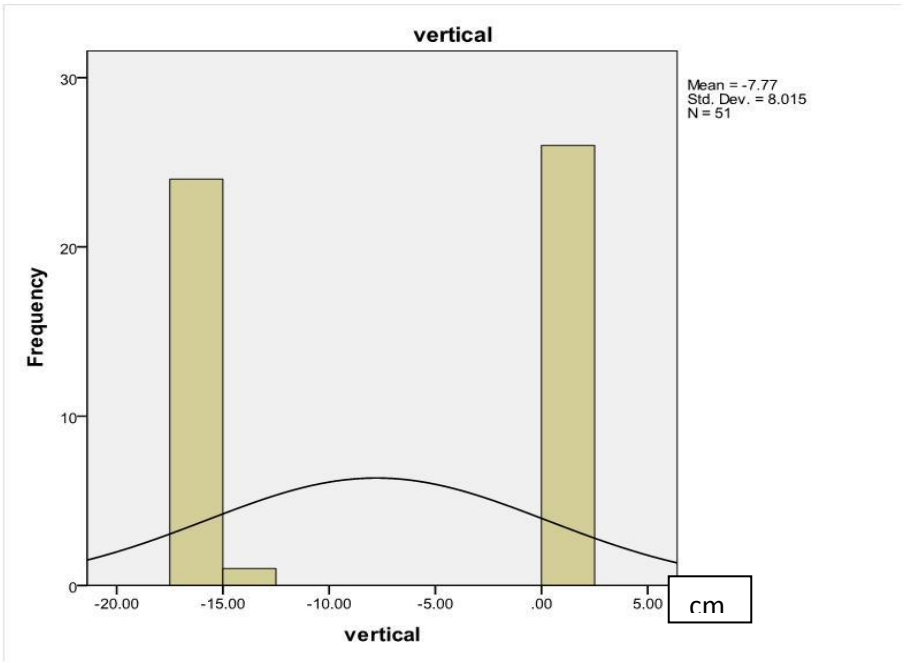


Figure 4.17: Variation of the anterior neck field in the vertical (Y) direction.

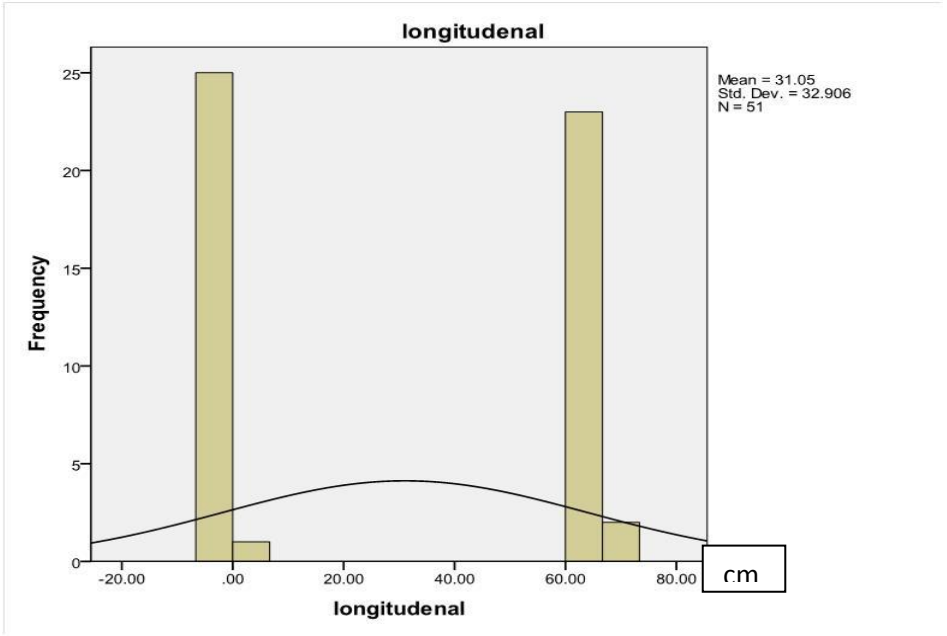


Figure 4.18: Variation of the anterior neck field in the longitudinal (Z) direction.

The individual standard deviation for this specific patient's anterior neck field was X=0.51cm, Y=0.47cm, Z=1.81cm, showing a large variation (more than 1cm) in the Z direction, for the same reason given above.

4.3.1 INDIVIDUAL SYSTEMATIC SET-UP VARIATION (m_i)

The individual set-up variations for the IMRT cases are shown in Figures 4.19 to 4.21 in each direction (X, Y and Z).

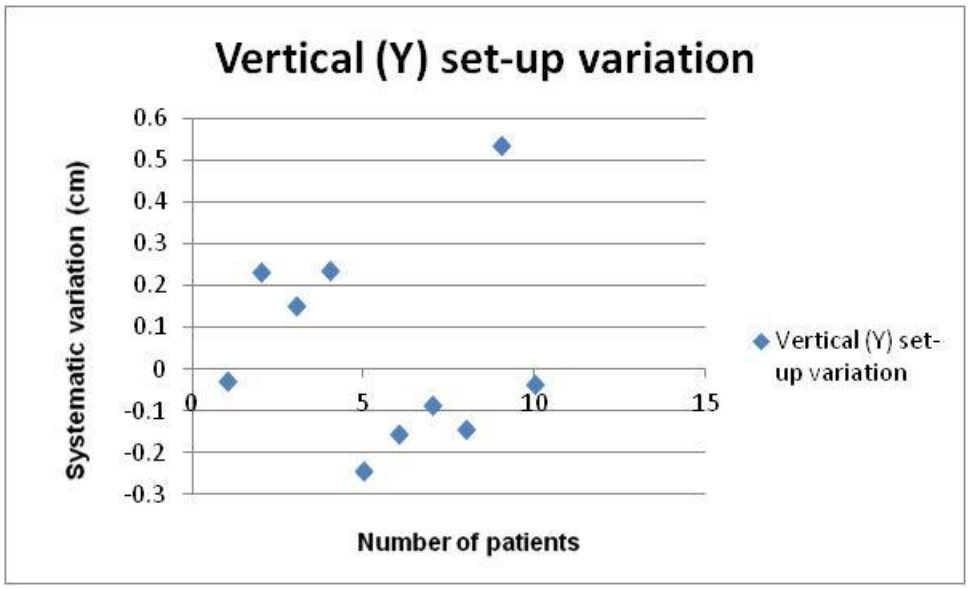


Figure 4.19: The individual patient systematic variation of the IMRT cases in the Y-direction.

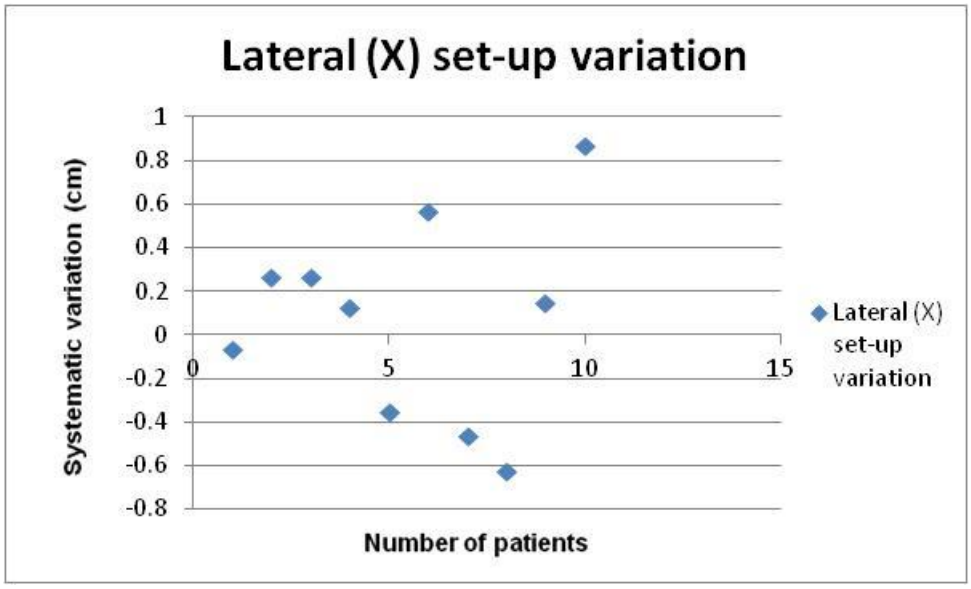


Figure 4.20: The individual patient systematic variation of the IMRT cases in the X-direction.

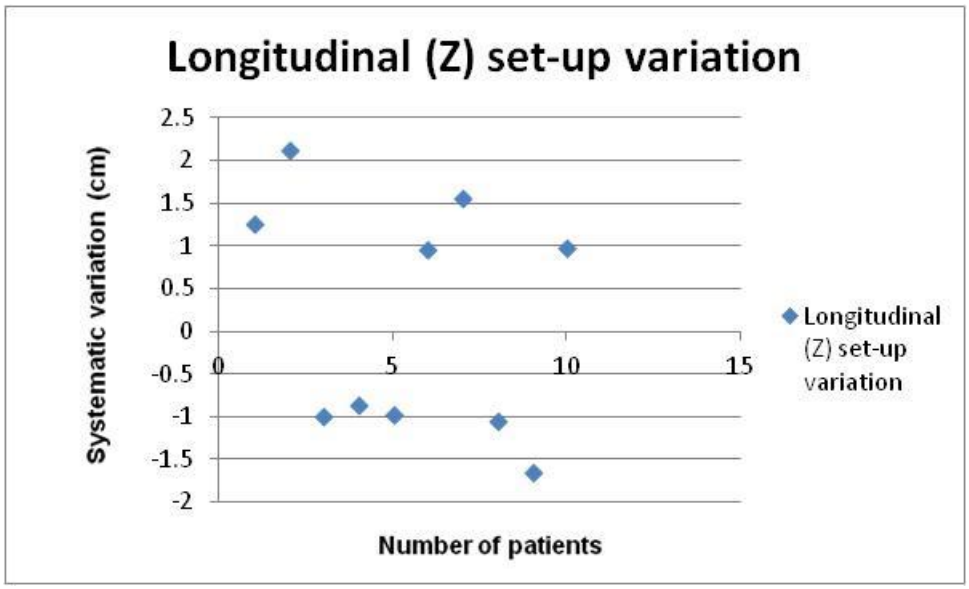


Figure 4.21: The individual patient systematic variation of the IMRT cases in the Z-direction.

The individual set-up variations for the IMRT cases anterior neck fields are shown in Figures 4.22 to 4.24 in each direction (X, Y and Z).

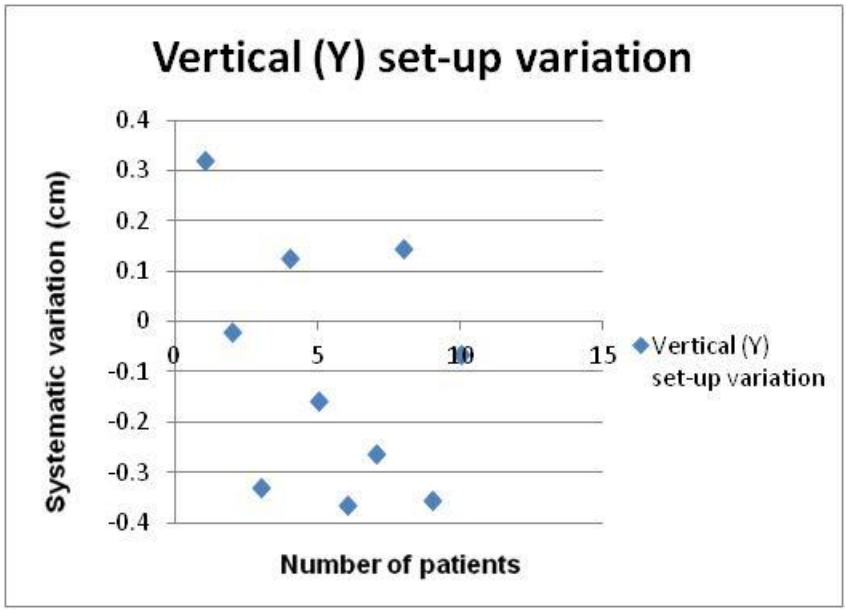


Figure 4.22: The individual patient systematic variation of the IMRT cases anterior neck field in the Y-direction.

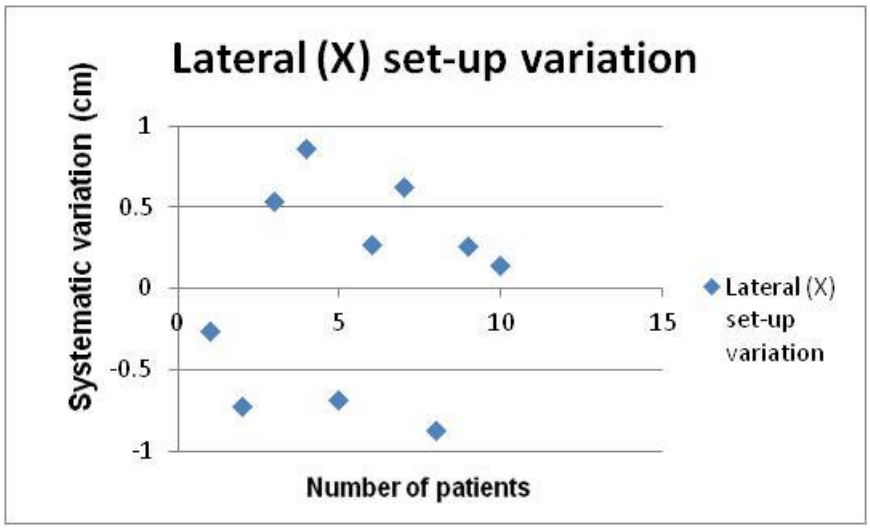


Figure 4.23: The individual patient systematic variation of the IMRT cases anterior neck fields in the X-direction.

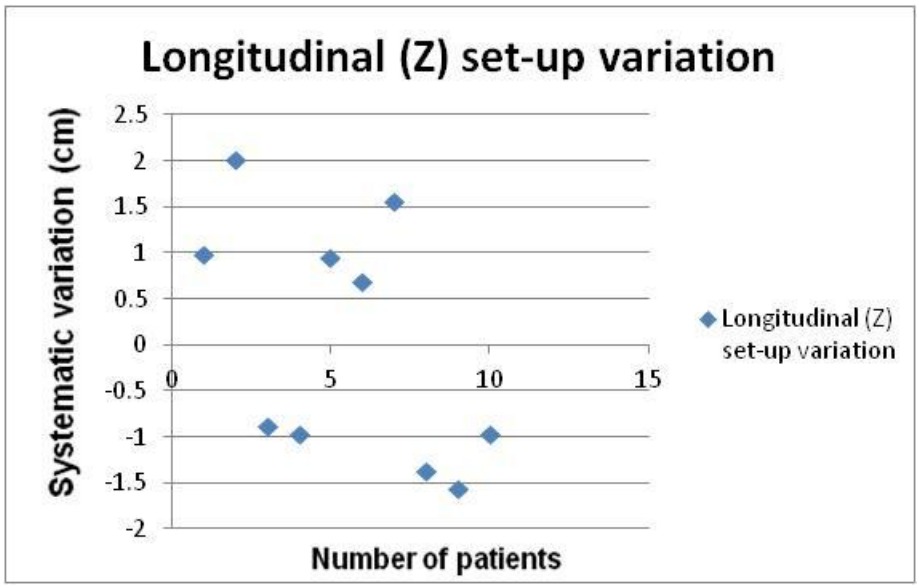


Figure 4.24: The individual patient systematic variation of the IMRT cases anterior neck fields in the Z-direction.

4.3.2 OVERALL MEAN SET-UP VARIATION (M)

The population's mean set-up variation is given in Table 4.4

Table 4.4: The lateral and anterior neck fields' mean set-up variation

Fields	Vertical (Y)	Lateral (X)	Longitudinal (Z)
IMRT	-0.087 cm	0.025 cm	-0.663 cm

There was a large variation in the longitudinal (Z) direction, and this was expected because of the arbitrary placement of the base plate on the table in the longitudinal direction.

4.3.3 RANDOM ERRORS

The random errors calculated from the standard deviation of set-up from the mean in each direction are given in Table 4.5.

Table 4.5: Random error for the IMRT cases

Fields	Vertical (Y)	Lateral (X)	Longitudinal (Z)
IMRT	± 0.69 cm	± 0.52 cm	± 1.89 cm

The IMRT results were similar to the virtual simulation results, excluding the longitudinal direction (again for the base plate reason) the random error for the IMRT set-up was 6.1 mm.

4.3.4 SYSTEMATIC ERROR

The systematic error calculated from the mean shifts in the standard deviation is given in Table 4.6 for the IMRT cases.

Table 4.6: Systematic error for the positioning of the planned fields in the IMRT cases

Fields	Vertical (Y)	Lateral (X)	Longitudinal (Z)
IMRT	± 0.20 cm	± 0.68 cm	± 1.10 cm

Once again excluding the longitudinal result (for reasons mentioned above) the IMRT cases had a good systematic error of 4.4 mm, which again is similar to the virtual simulated results.

4.3.5 WEEKLY VERIFICATION RANDOM AND SYSTEMATIC ERROR

The systematic and random errors for the weekly IMRT verifications are similar to the daily errors, and were found to be 4.3 mm and 5.9 mm respectively. However in investigating the weekly film verifications further, it was noted that the some patients did not have the chin positioned snugly in the mask (as demonstrated in Figure 4.25). For these cases the couch position was acceptable, which leads the investigator to suggest that there are limitations to the methodology of using the couch position alone. It is suggested that investigations of set up errors can indeed be complemented by studies of field positioning based on images of the patient. Vacuum formed Perspex shells are superior to other thermoplastic alternatives in that the snugness of fit can be visually inspected at the time of setup. However, the quality of a daily visual inspection of fit and the individual field projections relative to the patient, are difficult to measure and analyse. Couch position certainly cannot account for deficient chin or head position. The radiotherapists may also set up a patient (with the mask fitting) and with the correct couch position, but as soon as they leave the treatment room the patient may drop their chin or snuggle more "comfortably" in the head rest. This error may not be noticed when using the couch or pre-treatment images as a surrogate for the patient's set-up. On the other hand, verification films do not always indicate small differences in depth in an anterior neck field for instance, and then the vertical couch position is a better indicator for correct setup.

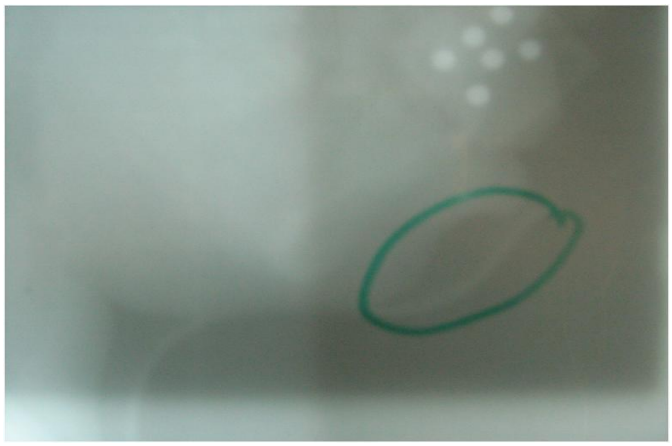


Figure 4.25: Demonstration of the patient chin position not fitting in the mask.

4.4 SUMMARY

The total number of daily fractions studied in this thesis was 5644 and 600 for virtual simulation and IMRT cases respectively.

The individual variations were given in this chapter for each patient and the random error for the virtual simulation population studied had a large overall random error of 7.0 mm for the laterals and 12.4 mm for the anterior neck fields, when compared to literature results of 2 mm. The IMRT random error was 6.1 mm; again this value was large compared to similar studies (given a 2 mm set-up margin). The systematic errors of this thesis compares well with published results of 4.6 mm, with this thesis obtaining a systematic error of 4.7 mm and 4.4 mm for virtual simulated and IMRT cases.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 RESEARCH OUTCOMES

The following was concluded or recommended from this thesis:

- The systematic error of this population was 4.7 mm and 4.4 mm for the virtual simulated and IMRT cases respectively. This compares well with published results using a similar immobilization system.

- The random error of this population was 7 mm and 6.1 mm for the virtual simulated and IMRT cases respectively. This is three times larger than the results reported in the literature (using a similar immobilization device).

- There were individual cases that had systematic deviations larger than 3 cm, the largest recorded value being 4.81cm. This leaves the investigator to recommend that the radiotherapists need to be more vigilant when setting up a head and neck case, especially the anterior neck field (in the vertical Y-direction). In addition procedures, training and regular QA of setups need to be improved.

- This thesis also leads to the question: "Does the set-up error differ when using different methodologies?" For the IMRT cases this question could be partly answered, from the imaging data of the 10 patients in which suboptimal chin or head positioning was observed. It is therefore recommended that a follow-up thesis is done at CMJAH in which setup errors obtained from different methodologies (such as imaging) are compared with these results. However offline monitoring of couch position provides insight into setup margins and this can contribute to realistic institutional planning target volumes.
- Pre-treatment approval of the weekly verifications, in which the medical physicist and radiation oncologist are present for the setup, may also improve setup errors. This could be concluded from the "better" results obtained in the IMRT cases which could be due to the requirement for weekly verification imaging.

- The investigator recommends more regular verification of the virtual simulated cases throughout the patient's course of treatment (commonly 33 – 35 fractions). This will aid radiotherapists in setting up the patient, by "checking" themselves more regularly and correcting their mistakes.

- The data confirm that the immobilisation system can be located to a fixed position on the tabletop; this will allow online verification of absolute bed position for treatment and further decrease the chance of incorrect setup.

- The absolute couch position (for this thesis) was estimated at -1.8 cm, -16.3 cm and +61.5 cm for the lateral (X), vertical (Y) and longitudinal (Z) directions respectively. The tolerance for introducing fully automated couch control should be 1cm (on either side) for both X and Y positions, and 2cm (on either side of the absolute position) for the Z direction.

- This study can definitely be a follow up study to analyse radiation therapist staff rotation as well as looking at their experience and manner in which they set-up patients, since the random error for this study was very large.

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