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Linas, Kudrevičius. Influence of Patient Immobilization Devices on Treatment Dose Planning. *Master's* Final Degree Project / supervisor Prof. dr. Diana Adlienė; Faculty of Mathematics and Natural Sciences, Kaunas University of Technology.

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SUMMARY

Radiotherapy is one of the available cancer treatment methods commonly used in Lithuanian. During radiotherapy treatment procedure patients are immobilized using specially designed devices that help delivery of the prescribed radiation dose exactly to the tumour. Immobilization devices are made from carbon fibre because of its outstanding mechanical properties and transparency to radiation. Due to this fact the influence of immobilization devices is ignored when planning the dose for the treatment. In this work X-ray attenuation caused by the presence of immobilization devices has been investigated with the aim to evaluate possible impact of attenuation on the absorbed dose. Ionization chamber was used for dose measurements and the results were compared with those obtained from calculations performed by treatment planning system.

It was found that the deviations between measured dose with immobilization equipment (treatment couch) and without do not exceeded acceptable 2% level for 15 MeV. In the case of 6 MeV photon beam, this 2% level was exceeded at gantry angles of 115^0 – 145^0 and 215^0 – 245^0. Immobilization devices (treatment couch with combiboard) exceeded acceptable 2% level for both 6 and 16 MeV photon beams at gantry angles of 120^0 – 240^0. This caused reduction of delivered doses as compared to the planned doses by 2.4%.

It should be noted that immobilization devices have are characterized by low Hounsfield units values and require manual contouring, also they are not always fully scanned using computed tomography. It was shown that correction coefficient for posterior side (130^0 – 230^0) photon beams could be applied during lung and oesophageal cancer treatment planning. It was estimated that the usage of 6% correction for 6 MeV and 4% for 15 MeV photon beams may reduce the total delivered dose difference in radiotherapy plan up to 0.2% and make almost identical PTV coverage with 95% isodose.

Kudrevičius Linas. Pacientų imobilizacijos priemonių įtaka planuojant apšvitos dozes. *Magistro* baigiamasis projektas / vadovas Prof. dr. Diana Adlienė; Kauno technologijos universitetas, Matematikos ir gamtos mokslų fakultetas.

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Reikšminiai žodžiai: *spindulinė terapija*, *imobilizacijos priemonės*, *fotonų sugertis, plaučių vėžys, stemplės vėžys, spindulinio gydymo planavimo optimizavimas.*

Kaunas, 2018. 54 puslapiai.

SANTRAUKA

Spindulinė terapija yra vienas iš galimų vėžio gydymo būdų, kuris plačiai taikomas Lietuvoje. Gydymo metu pacientai su specialiomis priemonėmis yra įmobilizuojami tam, kad nepajudėtų ir navikas gautų paskirtą radiacijos apšvitą. Šiuolaikinės imobilizacijos priemonės gaminamos iš anglies pluošto, kuris pasižymi geromis mechaninėmis savybėmis ir radiacijos pralaidumu. Būtent dėl to planuojant gydymo apšvitą nėra atsižvelgiama, kad fotonų spinduliai praeina pro imobilizacijos priemones ir yra dalinai sugeriami. Šiame darbe buvo ištirta, kokią rentgeno fotonų dalį sugeria imobilizacijos priemonės ir kokią tai įtaką turi sugertajai dozei. Sugertis buvo išmatuota su cilindrine jonizacine kamera ir rezultatai buvo palyginti su gautais naudojant gydymo planavimo sistema.

Buvo nustatyta, kad skirtumas tarp išmatuotos dozės su gydymo stalu ir be, neviršija maksimaliai leistinos 2% paklaidos esant 15 MeV energijos fotonams, o naudojant 6 MeV energijos fotonus, esant $115^0 – 145^0$ ir $215^0 – 245^0$ kampams, sugertis yra didesnė negu 2%. Kai naudojamas stalas su krūtinės imobilizacijos priemone 6 MeV ir 15 MeV fotonų spinduliai viršija šią paklaidos ribą esant $130^0 – 230^0$ gantrio kampams. Dėl to gydymo metu visa sugertoji dozė sumažėja iki 2,4% palyginus su suplanuota doze.

Imobilizacijos priemonės turi žemas haunsfieldo vienetų vertes ir todėl nėra automatiškai apibrėžiami ir ne visada yra pilnai nuskenuojami naudojant kompiuterinį tomografą. Buvo nustatyta, kad planuojant stemplės ir plaučių naviko gydymą galima naudoti pataisos koeficientą užpakalinės pusėms ($130^0 – 230^0$) laukams. Naudojant 6% pataisos koeficientą 6 MeV, o 4% – 15 MeV rentgeno fotonų spindulių monitoriaus vienetams, gydymo plane suplanuotos dozės skirtumas sumažėja iki 0,2% ir 95% izodozė sutampa.

LIST OF ACRONYMS AND ABBREVIATIONS

3D CRT – Three-dimensional conformal radiation therapy

AAA – Anisotropic analytical algorithm

CBCT – Cone beam computed tomography

CT – Computed tomography

CTV – Clinical target volume

DICOM – Digital Imaging and Communications in Medicine

EBT – Electron beam therapy

GTV – Gross tumour volume

HN – Head and neck

HU – Hounsfield units

IGRT – Image-guided radiation therapy

IMRT – Intensity modulated radiotherapy

Linac – Linear accelerator

MRI – Magnetic resonance imaging

MU – Monitor unit

PBC – Pencil-beam convolution

PDD – Percentage depth dose

PMAA – Polymethyl methacrylate

PTV – Planning target volume

RT – Radiotherapy

SAD – Source axis distance

SRS – Stereotactic radiosurgery

SSD – Source to surface distance

TPS – Treatment planning system

VMAT – Volumetric modulated arc therapy

WET – Water equivalent thickness

INTRODUCTION

In Lithuanian every year many patients are diagnosed with new or secondary (metastasis) cancer. Radiotherapy (RT) is one of the possible method for cancer treatment besides surgery and chemotherapy. RT can be external using linear accelerator (linac) or internal (brachytherapy) where radionuclides are placed into patient body temporally or permanent (seeds). External radiotherapy goal is to deliver radiation dose to the tumour target within 3% - 5% accuracy while avoiding critical organs and structures. Now this is achievable with treatment planning system (TPS). In TPS plan is created on the patient 3D reconstructed images from computed tomography (CT) or magnetic resonance imaging (MRI) scanning. Immobilization devices are using for patient comfort and to achieve the same patient position during scanning (planning) and radiotherapy treatment process. During treatment planning tumour location, critical organs are contoured and treatment parameters like beam angles, particles energy, field weight and others are selected, defined and optimized. Treatment planning system assumes that everything in the patient 3D reconstructed image also will be during the treatment. Couch top and immobilization devices usually are deleted or not defined as structures in scans and TPS does not consider existence of immobilization devices for calculations of dose distribution, as patient would be in empty space. It is doing because CT, MRI couch tops, and patient immobilization devices are made from believable transparent to radiation carbon fibre and can be different during scanning and radiotherapy treatment procedure. In this situation real dose distribution during treatment is different compared to the dose distribution prescribed in treatment planning system. It is because radiation is attenuated by couch top and immobilization devices at posterior beam angles (100^0 to 260^0). This dose perturbation should be investigated individually in each radiotherapy department because of different possible combinations of couch and immobilization devices. Research was done in Hospital of Lithuanian University of Health Sciences Kauno Klinikos.

The aim of this research was evaluation of factors influencing treatment dose planning in the presence of patient immobilization devices. To achieve this purpose, **these tasks were raised**:

- Assessment of patient dose planning problems when using patient immobilization devices.
- In vitro measurements of beam attenuation caused by applied patient immobilization devices.
- Calculations of X-ray attenuation caused by immobilization devices using algorithm of treatment planning system.
- Retrospective investigation of dose treatment plans, evaluation of the X-ray attenuation caused by patient immobilization devices and its influence on total dose delivery to patient.

1 BASIC OF EXTERNAL RADIOTHERAPY

External radiotherapy is one of many possible methods for cancer treatment. This treatment method is based on radiation caused DNA damage to cancer cell. DNA damage can be direct causing double or single strand breaks or indirect producing free radicals that causes DNA damage and kills cancer cells. Radiotherapy treatment can be performed with cobalt 60 gamma radiations machines, medical photons, electrons, linear accelerators (linac) or protons accelerators. One of the most common radical treatment course is 25 fractions with 2 Gy per fraction (50 Gy total) irradiation using x-ray photons. Palliative treatment course are shorter and have higher dose per fraction. Palliative bone pain treatment course is 5 fractions with 4 Gy each and lung, central nervous system have 10 fractions 3 Gy each. ėAt first, cancer is diagnosed, and its site, stage and extent are clinically evaluated. After this oncologist decides if radical or palliation treatment is required and discuss treatment options with the patient. If RT treatment is prescribed, at first patient 3D images acquired. During scanning patient is immobilized and scanned in CT or MRI with specific protocol for desired location imaging and from these scans patient 3D image is reconstructed. In the next step oncologist contours: tumour location and critical organs that need to be spared, (for example spinal cord, eyes, hearth, lungs, kidneys) in patient 3D reconstructed image and prescribes treatment course: dose per fraction and number of fractions. There are different target volumes defined in ICRU report 50 [1]. Gross tumour volume (GTV) is location of malignant tumour. It may consist of primary tumour, metastatic lymphadenopathy and metastases. Where tumour cell density is highest and thus GTV must get all the prescribed dose. It can be a whole organ or part of it. Clinical target volume (CTV) is GTV plus volume that have probability of subclinical tumour cells. It should be treated the same way as gross volume. Planning target volume (PTV) is CTV plus margin. This margin is added to evaluate uncertainties, varieties of organ movement, shape, patient positioning and external radiotherapy is planned to the PTV to assure prescribed radiation dose to the CTV. There are different treatment planning systems by each vendor, for example: Eclipse™ by Varian medical systems, Monaco® and XiO® by Elekta, Pinnacle[3] by Philips and others. With this information treatment is planned in TPS by required technique such as 3D CRT (three-dimensional conformal radiation therapy), IGRT (Image-guided radiation therapy), IMRT (Intensity modulated radiotherapy), VMAT (Volumetric

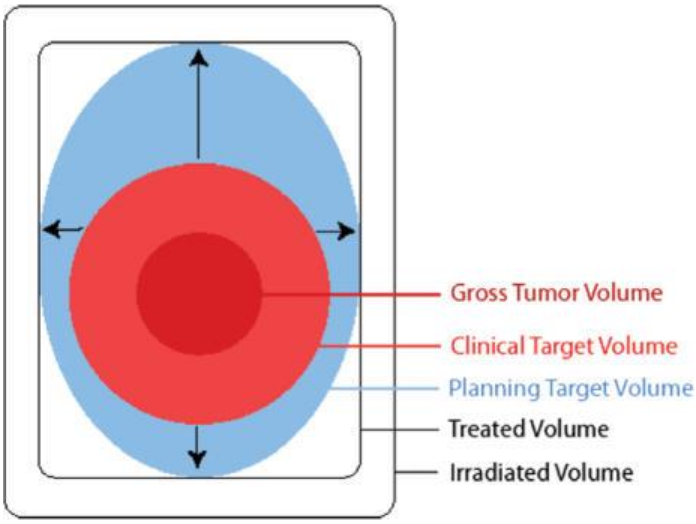

Fig. 1.1 Schematic illustration of the different volumes as defined in ICRU Report 50 [1]

modulated arc therapy), stereotactic radiotherapy or electron beam therapy (EBT) depending on the tumour location, clinical situation. Radiotherapy treatment with medical linear accelerator and planning with treatment planning system have various changeable parameters. Photon beams, they are configurated during linac installation most common are 6 and 15 MeV but some departments uses 10 and 18 MeV or others energies. Linear accelerator gantry can rotate around the isocentre which is in the patient, thus changing radiation beam angle, see Fig. 1.2. In gantry head there is collimator that also can rotate around isocentre to better adjust radiation field size to PTV. Collimator have main jaws and multileaf collimator that shapes radiation field for to PTV. During treatment patient is laying down on the table (couch) that usually have four degrees of freedom. Couch can rotate around isocentre, move vertically, laterally and longitudinally. Newest design treatment couches have two additional degrees of freedom: couch roll and pitch.

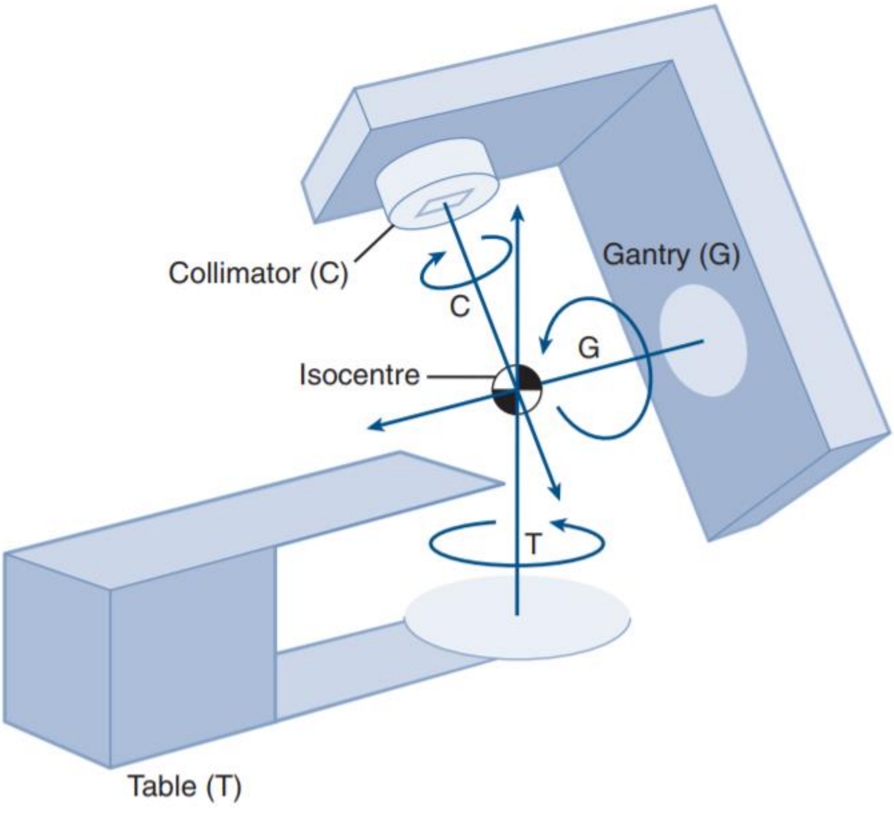

Fig. 1.2 Schematic illustration of medical linear accelerator layout and rotation axis around isocentre [2]

Also radiation intensity (field weight) and if needed treatment aids like bolus, shielding blocks or wedges can be adjusted. During planning all these treatment parameters are chosen to deliver prescribed radiation dose to the PTV and minimize radiation dose to the healthy, critical organs. In the last step patient is treated over next weeks, depending on number of fractions in the treatment course. During entire treatment course patient must be in the same position as in 3D scans and this repositioning is achieved with the help of the fiducial markers, patient positioning lasers and image-guided radiation therapy (IGRT) and immobilization devices. Before starting treatment if it is possible patient position is verified with the help of portals or cone beam computed tomography (CBCT). Verification is completed by comparing two new x-rays scans (usually at 0 and 90 or 270 angles depending on tumour location) with existing scans from CT. It is very important during treatment process to immobilize and suspend patient movement, so tumour and all organs would be in the same position as in TPS. This means patient arms, head rotation should be always in the same position. This allows to achieve that prescribed radiation dose would be the same during every treatment session as in it was planned in TPS.

1.1 RESEARCH OF IMMOBILIZATION DEVICES INFLUENCE TO DOSE DURING TREATMENT

Dose delivery in radiotherapy always must be accurate within couple of percentage, depending on used technology and standards. During RT treatment radiation beams from posterior field are attenuated by couch and immobilization devices. This dose lost was ignored because it depends on couple of parameters like gantry angle, radiation energy, used couch and immobilization devices. Now couch tops, immobilization boards are thin, made from carbon fibre without metal parts and are considering to be transparent to radiation. Another reason why they used to be ignored because in some cases larger field of view CT images would be required to introduce all immobilization devices, thus reducing CT resolution. These two are main reasons why immobilization devices used to be and in some departments are still ignored during treatment planning. Some radiotherapy departments have small correction factor for posterior side radiation fields MU (monitor units). Monitor units is linear accelerator output measurement unit. Approximately 100 MU is equal to 1 Gray (Gy). With increasing technology precision, dose accuracy and modern treatment planning systems, there was more published articles about evaluation and investigation of dose perturbation by immobilization devices [3]. It is investigated and published that attenuation by patient support and immobilization devices ranging from 0.1 – 11 % depending on beam energy, beam angle, detector used during measurements and immobilization device itself, while couch tops with metal rails have attenuation up to 17% [1, p. 6-8]. Now it is recommended, if possible to incorporate couch tops and immobilization boards into TPS by AAPM (American Association of Physicists in Medicine) task group 176 report. With various new radiotherapy technique like: intensity modulated radiotherapy (IMRT), volumetric modulated arc therapy (VMAT), stereotactic radiosurgery (SRS) and different immobilization devices, vendors and overall combinations it is important to investigate and evaluate dose perturbation and if needed dosimetric corrections during exact treatment situation and setup combination in each radiotherapy department individually.

1.2 IMMOBILIZATION DEVICES PROPERTIES

In this paragraph will be summarized most common and widely used patient immobilization devices that are used during radiotherapy treatment. It is important to familiarize with common immobilization devices types, materials.

Couch tops or in other literature called table tops are an essential component for patient positioning and treatment. During RT patient is laying down on the couch. Like with most devices there are different models from different vendors like for example Qfix, Varian, MEDTEC Inc. and others, see Fig. 1.2.1.

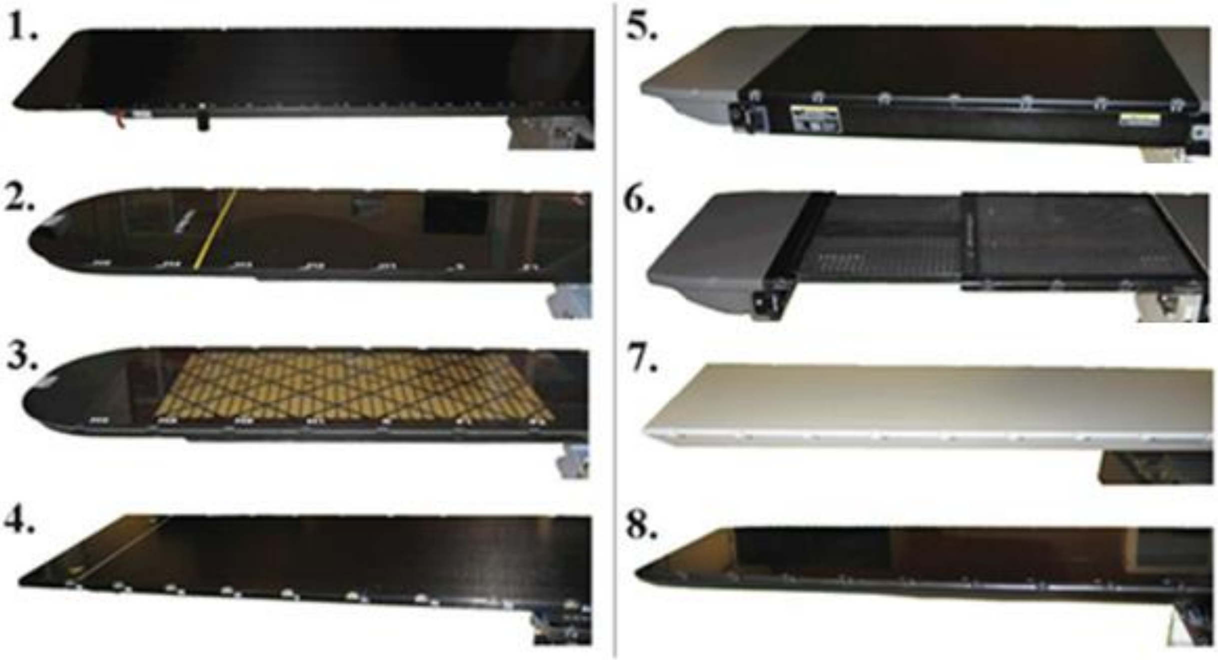

Fig. 1.2.1 1) BrainLAB imaging couch top, 2) Qfix kVue Standard, 3) Qfix kVue DoseMax, 4) MEDTEC model MT-IL 3303, 5) universal sandwich panel, 6) Varian grid insert, 7) DIGNITY AirPlate, 8) Varian Exact IGRT couchtop [4]

Generally, are two different designs: support bar tables and homogenous tables. Support bar tables consist of a tennis racket or thin carbon fibre insert with solid adjustable support rails underneath. Oldest designs had support rails made from solid steel and they “were associated with substantial radiation attenuation” [5], now they are made from carbon fibre as well. Homogenous tables are made from carbon fibre in sandwich design: two 1.8 – 4.5 mm thick carbon plates with 45 – 47 mm think of polymeric foam or resin-impregnated paper honeycomb material in between [3] without support rails. Carbon fibre is choice for radiotherapy because of great mechanical strength, low density and radiotransparent.

Patient immobilization boards are using during torso, breast and lungs radiotherapy treatments. There are different designs from various vendors, like Varian, Qfix, MacroMedics®, and others. Some designs are made for various tumours treatment in torso location and called combiboard. While others immobilization boards are designed for specific area treatment for example: head and neck, lung and breast location. Breastboards are designed for torso area treatment - usually breast and lungs cancer patients, see Fig. 1.2.2.

Fig. 1.2.2 Breastboard - Qfix Quest™ in the left [6] and MacroMedics® Breastboard LX™ in the right [7]

This design allows patient to be in supine position, while arms would rest over the head and will not be in radiation beams path during treatment. Breastboards usually have adjustable 5 – 25 degrees inclination with wedge to prevent from sliding. Commercial available breastboards are made from carbon fibre as a couch tops for the same physical properties. There is different design board for breast treatment - prone breast boards. It is made so that treated breast would hangs through a hole in the board. This breast position allows to reduce radiation dose to the lungs and heart during treatment.

For immobilization during pelvis and abdomen area tumour treatment, knee support with feet and head support are used. They can be combine with other immobilization devices depending on tumour location, other devices existence in department. For pelvic area there is alternative - belly boards, designed in similar way as a prone beast board. Belly hangs through specific cut hole in board. During immobilization belly is in prone position and this allows to minimize radiation doze to the small bowel.

Whole body can be immobilized using vacuutransm bags, cushions and polyurethane foam. Polyurethane foam (Alpha cradle by Smithers Medical Products or RediFoam by Civco Medical Solutions) is rigid immobilization device. First patient is lying down on the bag in the treatment position, then polyurethane is mixed with chemical compound in the bag and because of exothermic reaction expands to the patient form into rigid foam. Main disadvantages of this immobilization device is not ability to reuse for other patient treatment. Another type of whole body immobilization is vacuum bags filled with Styrofoam (polystyrene) balls. They are different size up to 230 x 120 cm and up to 120 litre fill capacity. Usually finishes are from nylon or urethane. While patient is lying on vacuum bag with vacuum pump air is evacuated from the bag and it fits patient posterior side and remains rigid. This formed bag is used for CT scanning and during entire RT treatment course. Main advantages over polyurethane cradles is reusability for other patient after completing treatment course.

Fig. 1.2.3 CIVCO Radiotherapy Vac-Lok™ 100 x 200 cm cushion for full body positioning [8]

There are quite different head holders and head immobilization devices depending on treatment location and technique. Head holders combined with wedges or bolsters are used for various tumours treatments not only in the head area but in thorax, abdominal depending on other immobilization devices used in department. Head holders come with different size and shape for patient comfort and can be made from carbon fibre, polymethyl methacrylate (PMAA) or polystyrene foam. For patients with brain, HN (head and neck) tumours usually thermoplastic mask or stereotactic frame are used. Thermoplastic masks are used together with head holders and are made for each patient individually by heating and moulding mask around patient profile and then after cooling it becomes rigid. These mask usually are 1.5 – 3.2 mm thick with ϕ 0.25 – 0.40 cm holes and from 20 up to 35 cm length. Longest mask extends to the should area for HN tumours treatment. Other vendors offer mask with holes for eyes, mouth, thus increasing patient comfort. Thermoplastic masks models distinguish by mechanical characteristics for example time required to heat, stretchiness, rigidity.

Fig. 1.2.3 Various thermoplastic masks models by MacroMedics® [9]

Stereotactic frames are used for precise radiotherapy or radiosurgery during small head tumours, functional disorders, arteriovenous malformations treatment. Radiosurgery have short treatment course with higher dose per fraction or even one 0.5 – 2 hours long treatment session. Traditional design stereotactic frame is screwed into patient skull during all treatment process. Other design stereotactic frame can be attached via bite block, dental mould.

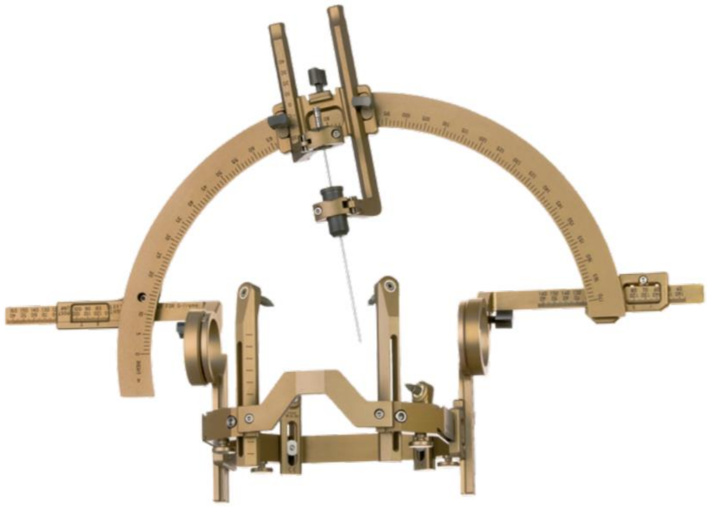

Fig. 1.2.4 Leksell stereotactic system® [10] [10]

1.3 IMMOBILIZATION DEVICES EFFECT FOR DOSE IN PROTON THERAPY

Proton therapy is one of the advanced radiotherapy technique that still becoming more popular and common. This method main advantage over traditional radiotherapy is proton ability to deliver most of the energy at specific depth, called Bragg peak. Percentage proton dose curve is show in Fig. 1.3.1.

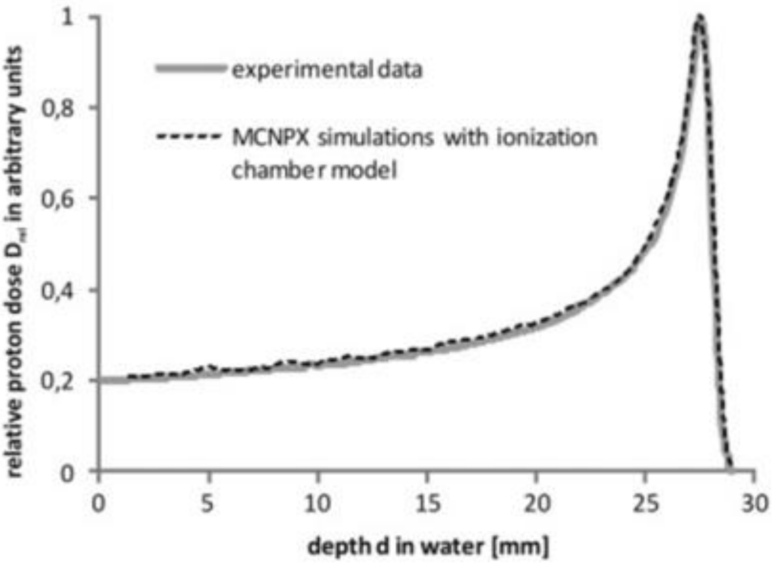

Fig. 1.3.1 The comparison of the relative proton dose curves: measured in a water phantom (solid line) and calculated (dashed line) by means of the modeled ionization chamber [11]

At first proton have build-up region with relative low energy deposition before rapidly increasing to maximum deposition region at Bragg peak and after it dropping to zero. This dosimetric characteristic allows to deliver maximum dose exactly at the targeted tumour location, thus sparing healthy tissues, skin. Example of proton therapy plan is show in Fig. 1.3.2 Because of this protons dosimetric characteristics in this treatment plan anterior side got less than 5 Gy, while craniospinal 23.4 Gy.

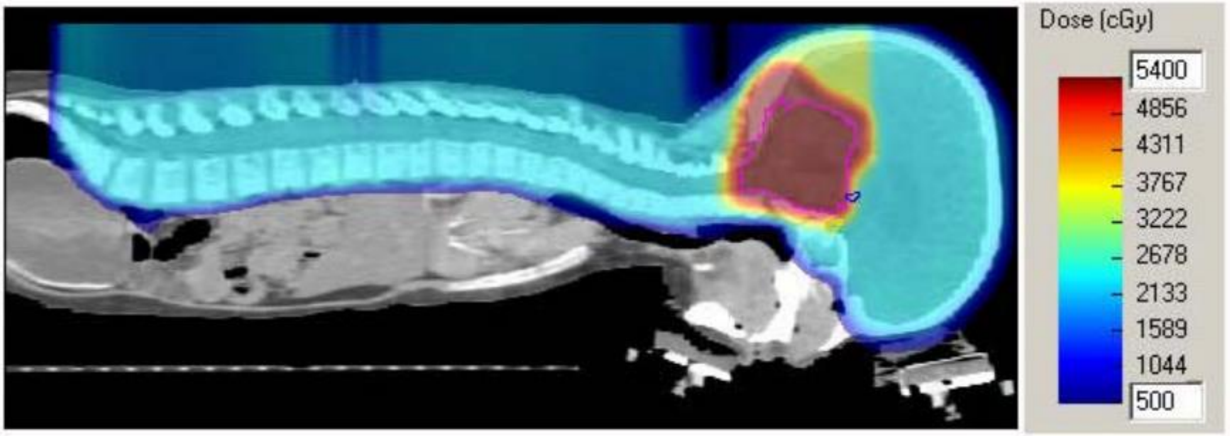

Fig. 1.3.2 Sagital colour-wash dose display for the treatment of meduloblastoma including the craniospinal irradiation to 23.4 as well as the posterior fossa boost to 54 cobalt gray equivalent [12]

If the immobilization device or couch top is not defined in TPS during calculating and planning, it will add additional path length for protons to transverse during treatment, changing dose distribution. Difference between percentage depth dose with and without couch in posterior (180º) orientation is show in Fig. 1.3.3. This situation shifts radiation dose to the source and patient skin, decreasing maximum dose range and dose to the tumour. In this investigation couch reduce maximum dose deposition range by 0.96 cm [13]. This dose shift lowers radiation dose to the deeper tumour volume to about 20 % of prescribed.

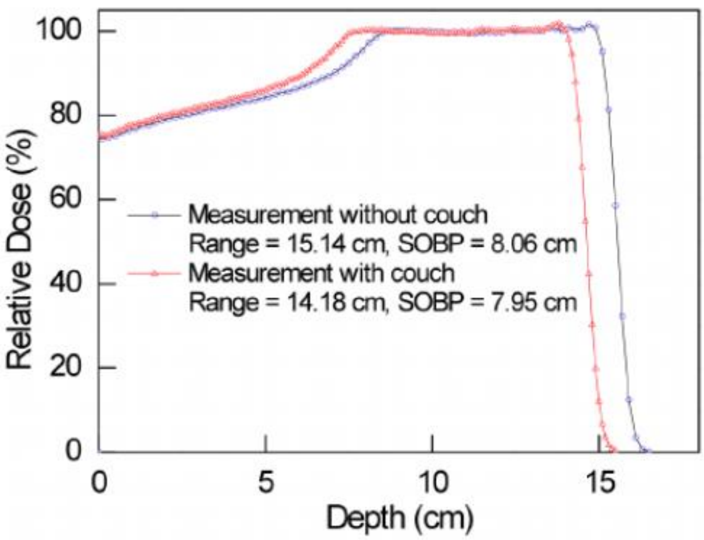

Fig. 1.3.3 Measured PDD curves and spread-out Bragg peak for proton therapy with and without couch [13]

This shift becomes more complicated in oblique posterior beams (180º± 89^0 gantry angles). In this situation not every proton have the same path length as in TPS and dose shifts becomes nonlinear, see Fig. 1.3.4. Protons that have couch top in their path will not reach maximum range as it was planned in TPS. This dose shift becomes more complicated in real treatment situations because of different gantry angles, radiation field size is using.

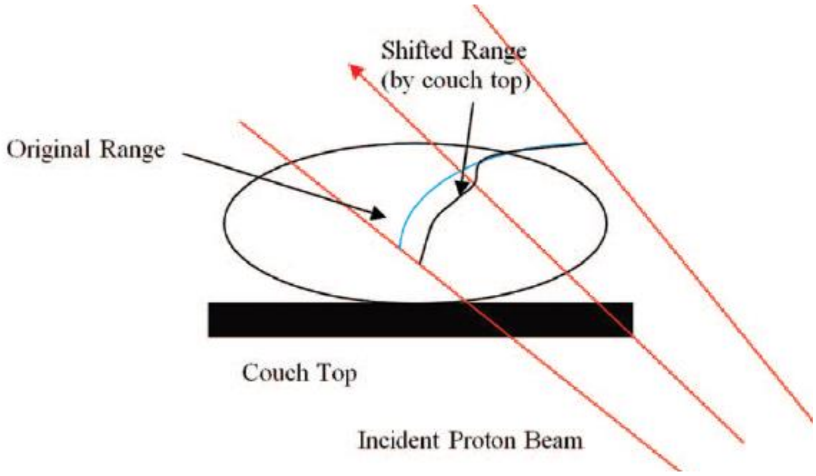

Fig. 1.3.4 Oblique posterior proton beam incident on couch and shifted range [3]

To evaluate immobilization devices effect in protons therapy more accurately, there are researches of water equivalent thickness (WET) of these devices. By F. Francesco [14] research using 128 MeV proton beam (proton range is about 120 mm) un-stretched CIVCO and Qfix thermoplastic masks have WET about 3.0 ± 0.1 mm, while stretched 0.5 and 0.8 respectably, difference because S-Mask have holes. Headrest by Qfix have similar WET as mask - 3.2 mm. The WET of kVue-Insert by Qfix is 5.4 ± 0.1 mm and WET of S-Overlay by CIVCO is 5.4 ± 0.2 mm, it shows less uniformity than others immobilization devices and both combine have 14.8 mm.

Category	Manufacturer	Type	WET
Thermoplastic mask	CIVCO Medical Solutions,Kalona, IA, USA	S-Mask (un-stretched)	3.1 ± 0.1 mm
		S-Mask (stretched)	0.5 ± 0.1 mm
	Qfix Systems,Avondale, PA, USA	Fibreplast (un-stretched)	3.0 ± 0.1 mm
		Fibreplast (stretched)	0.8 ± 0.1 mm
Treatment couch	CIVCO Medical Solutions,Kalona, IA, USA	S-Overlay	9.4 ± 0.2 mm
	Qfix Systems,Avondale, PA, USA	kVue-Insert	5.4 ± 0.1 mm
		CSI (kVue-Insert + S-Overlay)	14.8 mm
Headrest	Qfix Systems,Avondale, PA, USA	Moldcare	3.2 mm

Fig. 1.3.5 Multi-layer ionization chamber WET measurements of the immobilization devices with proton beam energy of 128 MeV [14]

This research agrees with report of AAPM Task group 176, that including immobilization devices in TPS as patient contour is sufficient in proton therapy.

1.4 IMMOBILIZATION DEVICES EFFECT FOR DOSE IN PHOTON THERAPY

Photons are one of the most used particles in radiotherapy for cancer treatment. Unlike protons, they do not have Bragg peak and have different percentage depth dose curve, see Fig. 1.4.1. This curve can be written as depth dose function of depth, field size and source to surface distance, see formula 1.1.

$$P(d,r,f) = 100\left(\frac{f+d_m}{f+d}\right)^2 \cdot e^{-\mu(d-d_m)}K_s \qquad (1.1)$$

There: *d* is depth, *r* is field size, *f* is source to surface distance, μ attenuation coefficient and K_s is scattering component.

This formula shows photon beams inverse square law, exponential attenuation and scattering component. Photons deposit most of their energy at lower depth compared to protons, for 10 x 10 cm radiation field size and 100 cm SSD (source to surface distance) 6 MeV photon beam deposits at 1.5 cm depth in water and 15 MeV photon beam at 2.9 cm, see Fig. 1.4.1. Because of lower depth of maximum dose, it is important to understand and evaluate immobilization devices effect for photon beams.

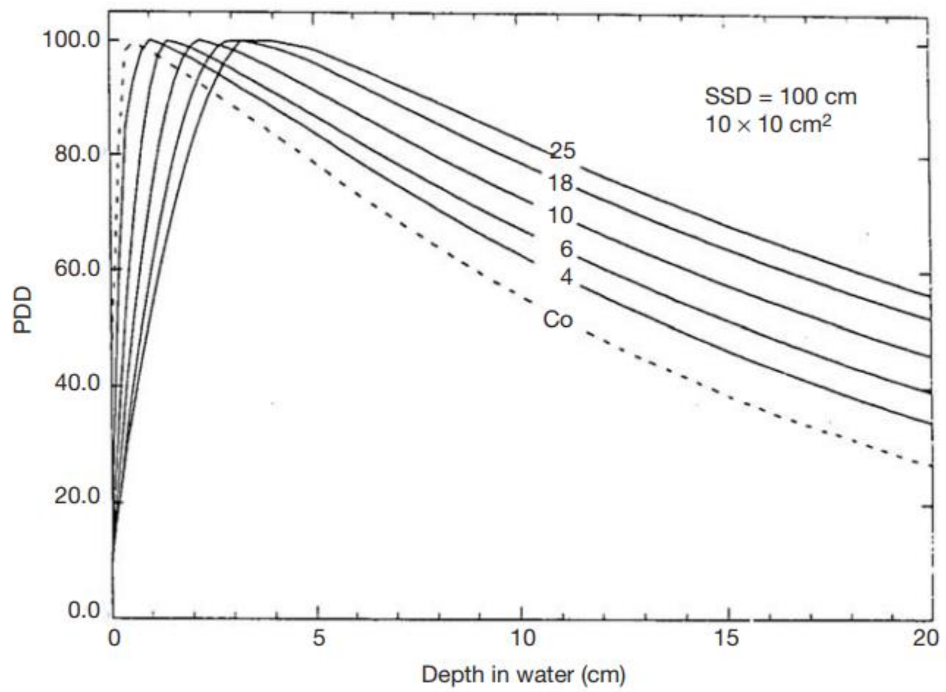

Fig. 1.4.1 PDD curves for ^{60}Co gamma rays and various megavoltage photon beams in water for a 10 × 10 cm radiation field size at 100 cm SSD [15]

Another difference between protons and photons dosimetric characteristics is that photons do not rapidly loose ability to deliver dose, see Fig. 1.4.1 and table 1. 6 MeV energy photon beams delivers 50% dose at depth of 15.6 cm in water, thus distance between $d_{50} – d_{max}$ is 14.1 cm, and d_{50} for 15 MeV photons beam is 20 cm, difference $d_{50} – d_{max}$ is 17.1 cm. Increasing photon beam energy increases depth of 100 % dose and distance between $d_{50} – d_{max}$.

Table 1. Depth of maximum dose and 50% dose for 10 x 10 cm field size photon beams of different energies in water [16]

Beam Energy (MV)	Depth of 100% Dose (cm)	Depth of 50% Dose (cm)	d_{50}-d_{max}
2	0.4	11.2	10.8
4	1	13.9	12.9
5	1.25	14.5	13.3
6	1.5	15.6	14.1
8	2	17.2	15.2
10	2.3	18	15.7
12	2.6	19	16.4
15	2.9	20	17.1
18	3.2	21	17.8
21	3.5	22	18.5
25	3.8	23	19.2
35	4.5	24.9	20.4
50	5.3	27.2	21.9

There are published researches and articles about immobilization devices and couch tops impact for photons dose delivery. Most of the investigations are about attenuation by external devices and how accurately treatment planning system can calculate attenuation comparing with measurements. If couch top has support rails, their position between rails in and rails out (see Fig. 1.4.2) is important factor for dose attenuation.

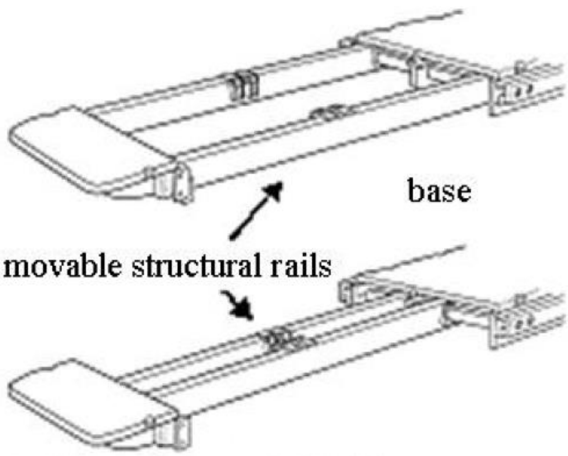

Fig. 1.4.2 Schematic drawing of support rails out and in position (top and bottom picture respectively) [17]

During quality assurance control rails are moved out from the field, but during actual treatment rails can be left in any position. Additionally before starting treatment during portal images rails can be left in out position to avoid obstructing anterior-posterior images [18]. Eclipse™ Treatment Planning System (Varian medical system) have two calculations algorithms: pencil-beam convolution (PBC) and anisotropic analytical algorithm (AAA). Comparison of dose transmission between AAA and PBC algorithms, measured and ideal situation using 6 and 10 MeV photons with different rails position are in Fig. 1.4.3. These results show that when rails are in out position at beam angles from 100^0 to 125^0 and 235^0 to 260^0 attenuation can be as much as 19.5% for 6 MeV and 15% for 10 MeV photons. At beam angles from 135^0 to 225^0 up to 4% and 2.5% respectively, when rails are in the middle position dose attenuation is increased at beam angles from 130^0 to 170^0 and 185^0 to 225^0 up to 14% [5], [19]. Also this investigation results show that Eclipse™ AAA algorithm is more accurate for dose attenuation calculations than PBC.

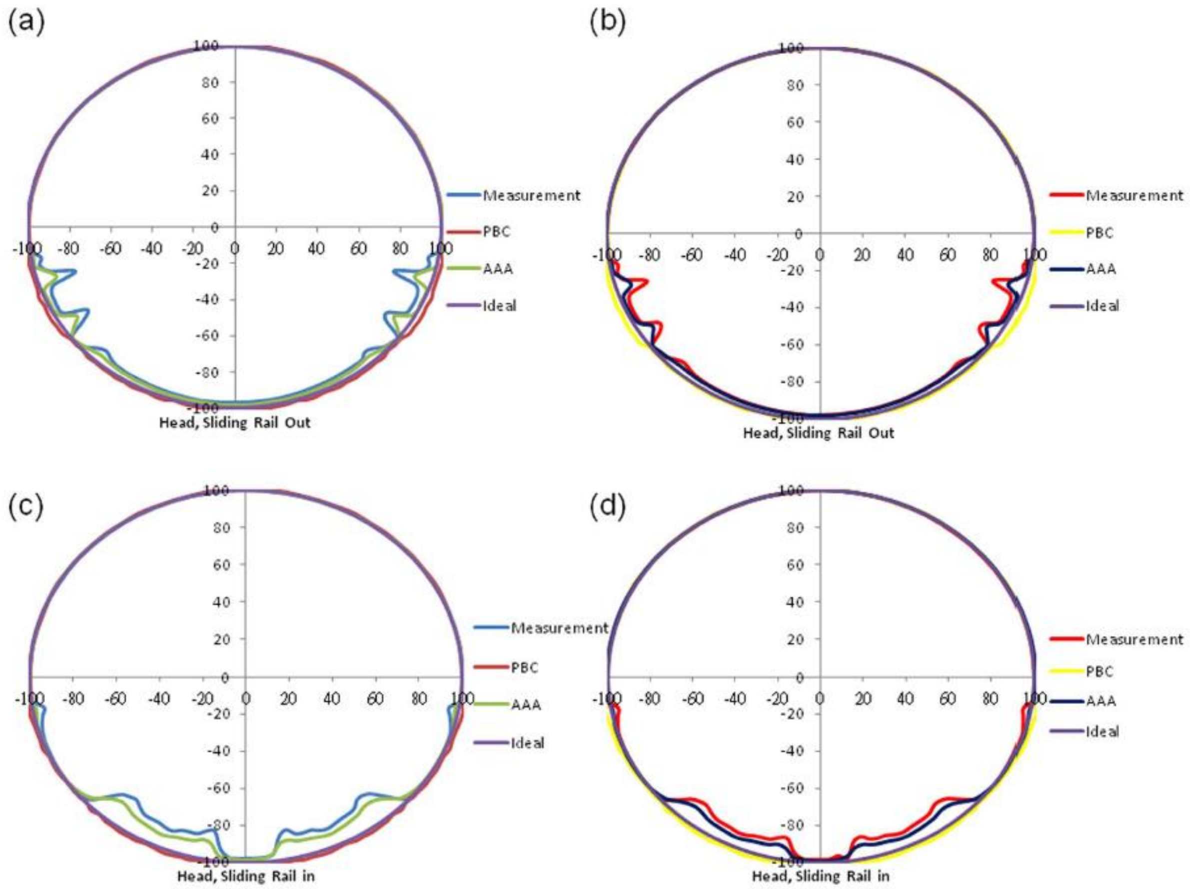

Fig. 1.4.3 Measured and calculated using PBC and AAA algorithm transmission values at the head position for irradiation at (a) 6 MeV with rails on both sides, (b) 10 MeV with rails on both sides, (c) 6 MeV with rails in the middle of the couch top, and (d) 10 MeV with rails in the middle of the couch top. The dashed line is an ideal circle with a radius of 1 unit [5]

Homogenous carbon fibre couch tops are designed without support rails to minimize dose perturbations and imaging artefacts during IGRT. This design couches have different attenuation properties compared with support rails couches. Results of investigation of homogenous design couch top attenuation is show in Fig. 1.4.4.

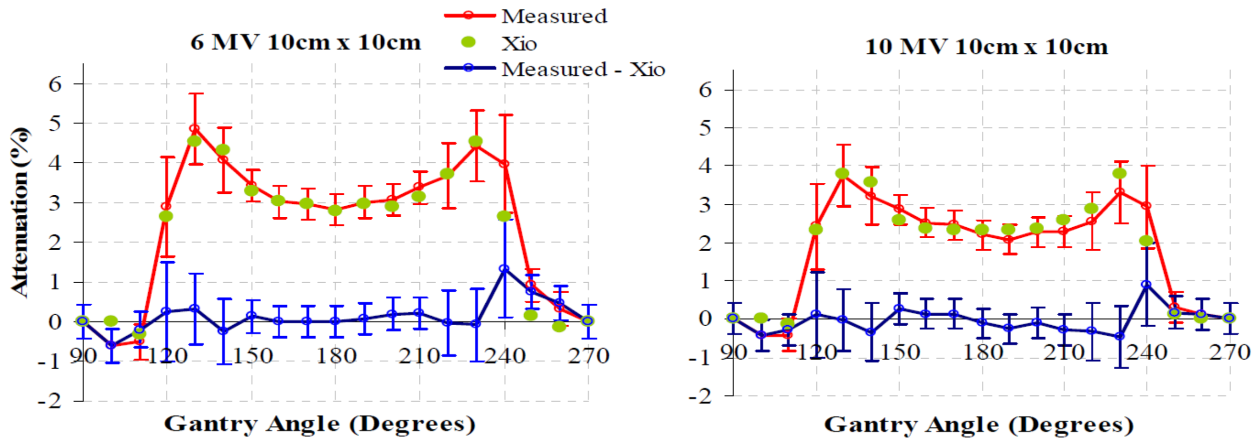

Fig. 1.4.4 6 MeV and 10 MeV photons attenuation measured in a phantom and calculated in XiO and difference between measured and calculated attenuation, SAD - 100 cm, measurement depth - 12 cm [20]

Attenuation is 3% and 2% at 180^0 beam angle for 6 MeV and 10 MeV photons respectively and maximum attenuation are 5 % at approximately 135^0 and 225^0 beam angle [20]. This research shows that Xio® TPS by Elekta can calculate dose perturbations by carbon fibre couch top with 1% accuracy minimizing difference between treatment plan and real radiotherapy treatment.

During actual RT treatment not only couch but other immobilization devices are also beeing used. Immobilization board can be used during various tumour location treatments, for example lung, breast, oesophagus. Depending on the tumour target location photons can have different path length through immobilization board, even at the same angles. Contesse immobilization board have dose absorption of 1% for head and neck area at beam angle of 180^0 and up to 8% for breast lung area at 120^0 beam angle together with couch base, using 6 MeV photons, see Fig. 1.4.5.

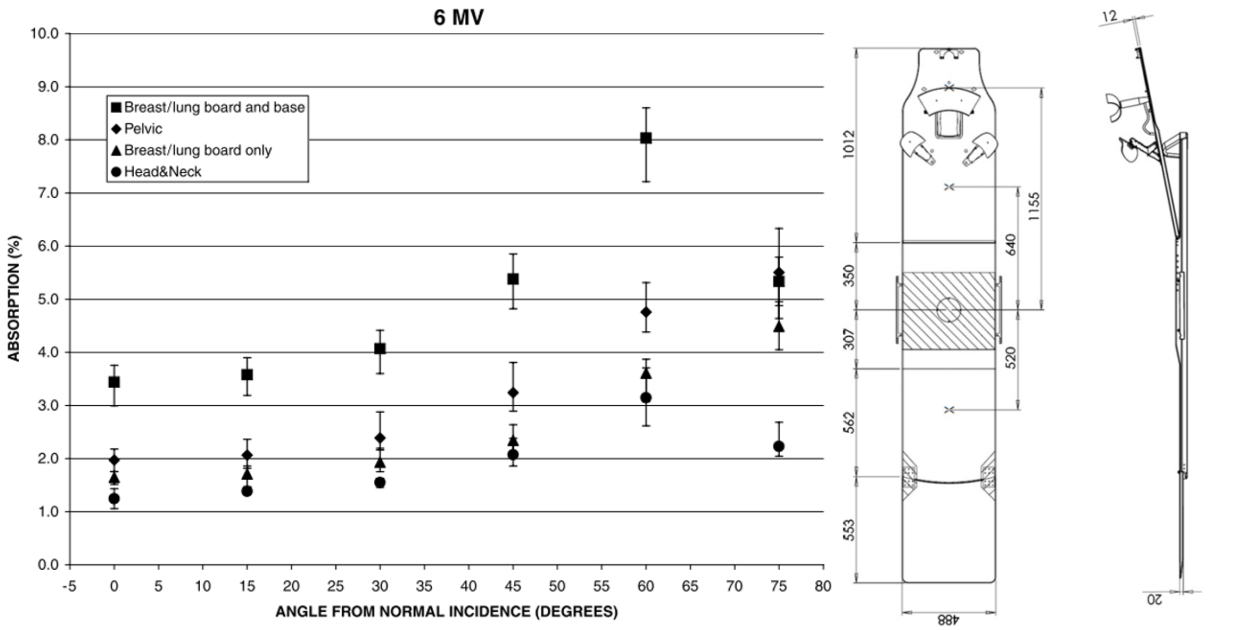

Fig. 1.4.5 Absorption as a function of angle for the Contesse immobilization board using 6 MeV photons [21]

Eclipse™ treatment planning system during dose distribution calculations takes into account only as the body defined structures, see Fig. 1.4.6. Otherwise patient will be treated as in the air and dose during treatment will be less compared to the dose in planning system because of additional path that photons pass.

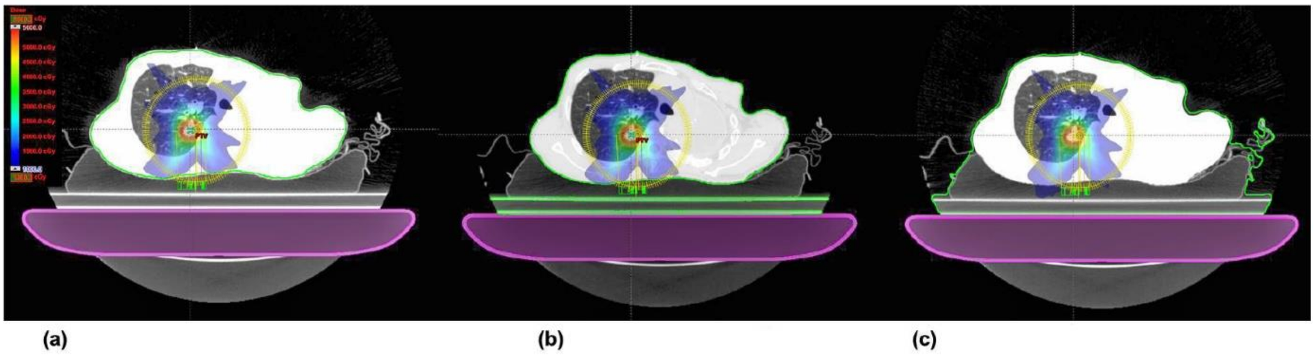

Fig. 1.4.6 Body structures including patient body without the immobilization device (a), with the only Body Pro-Lok (b), and with the Body Pro-Lok as well as the vacuum bag (c) are shown. The body structures are indicated with green line [22]

Investigation results shows that defining Body Pro-Lok couch top with vacuum bag as body structure during VMAT stereotactic ablative radiotherapy reduces dose to the target volume up to 5%, with average of 2% [22]. Biggest difference is when low energy photon beams with high MU passes through immobilization devices.

Another immobilization devices investigation area is mask impact for dose distributions in the build-up region. Photons needs build-up region to reach maximum dose, thus surface dose is quite low even using 6 MeV photons. It is negative effect for tumours at skin surface. Thermoplastic immobilization mask impact for surface dose is investigated. Thermoplastic mask slightly increases surface dose, see Fig. 1.4.7, from 10% to 42% for 6 MeV photons and from 5% to 28% for 15 MeV photons [23]. This is positive effect for HN skin cancer, central nervous system palliative treatment.

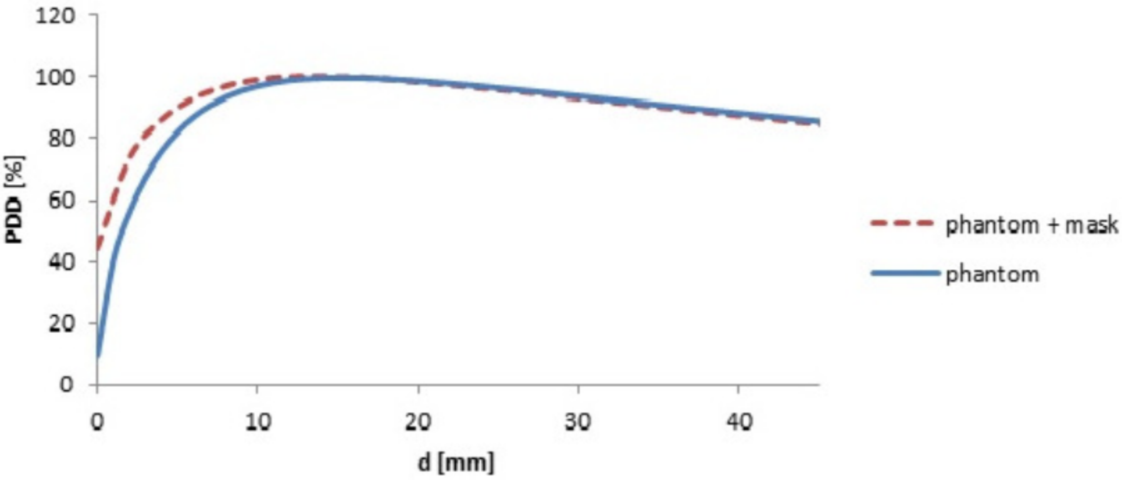

Fig. 1.4.7 The comparison of PDD measured in phantom with and without thermoplastic mask (ϕ = 0.4 cm holes) using 6 MeV photon beams [23]

Radiotherapy treatments plans are compared by dose-volume histograms, minimum, maximum and mean dose to the tumour target and critical organs. Overall one of the most important parameters for treatment plans comparison are: V_{95} – percentage of the PTV (planning target volume), that receives at least 95% of prescribed dose and D_{100} – minimum radiation dose that covers 100% of the PTV. During treatment planning photon beams attenuation by immobilization devices reduces minimum dose to the PTV. It is more significant in the plans that have more beams from posterior side that passes through the couch. By studies of A. Olson [24] V_{95} coverage absolute difference is up to 2.3% and D_{100} up to 71.4% by retrospective comparison of VMAT method HN area RT plans. In test plan immobilization devices were defined as the body structure and RT plan was calculated with the same parameters.

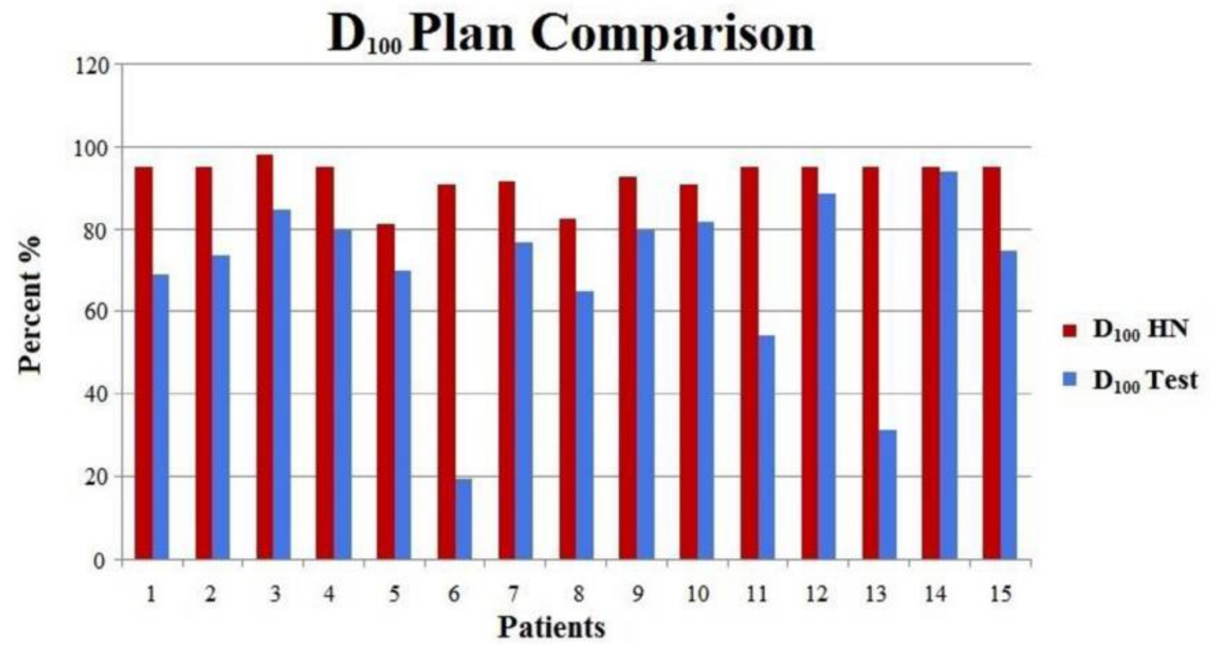

Fig. 1.4.8 A comparison of the dose encompassing 100% of the PTV volume between the HN plan (red) and the test plan (blue) [24]

AAPM task group 176 report and other publications shows that couch tops and immobilization device attenuation should not be ignored. Couch attenuation can be from 1 % to 20 % depending on couch model (homogenous or support bar couch), beam angle, energy and if couch have metallic parts. There are significant less researches of full setup (couch with immobilization board) attenuation. Using homogenous couch top with immobilization board attenuation can be up to 8 % at 120^0 beam angle. Actual attenuation impact for treatment plan depends on used RT technique, number of radiation fields, their energy, angle and field weight. It is worth to investigate actual RT treatment setup attenuation in each department and make a guidelines and recommendations.

2 METHODS AND METHODOLOGY

In this paragraph in details will be described materials and equipment used during this research, investigation method and measurement setup.

2.1 COMPUTED TOMOGRAPHY

Patients for RT treatment are usually scanned with GE LightSpeed RT 16 CT scanner (General Electric Healthcare) existing in Hospital of Lithuanian University of Health Sciences Kauno Klinikos department of Oncology and Hematology. Immobilization devices and phantom for calculations with Eclipse™ treatment planning system were scanned with the same GE LightSpeed scanner. It is a third generation CT scanner, see Fig. 2.1.1.

Fig. 2.1.1 GE LightSpeed RT 16 CT scanner

It has carbon fibre overlay (couch top) with foam core. CT overlay width - 53 cm, height - 4.12 cm and length - 217.17 cm, it is made by Diacor. This overlay is compatible with all Varian Exact couch accessories. It have laser positioning system by LAP Lasers with accuracy of ±1 mm to patient distance. Scan field of view is up to 65 cm, with aperture of 80 cm. X-ray generator is high frequency type, rotation assembly with power rating of 53.2 kW. Available kV settings are 80, 100, 120, 140 while mA range is from 10 to 440 by step of 5 mA. X-ray tube is GE Performix Pro with focal spot size of 0.6 x 0.7 mm that changes into 0.9 x 0.9 mm at 24 kW. Anode heat capacity is 6.3 MHU with maximum of 840 kHU/min cooling rate. Detectors are solid state HiLight/Lumex with total of 888 per row and 16 number of elements along z axis. Effective length of detector array is 20 mm at isocentre.

2.2 TREATMENT PLANNING SYSTEM

Patients Radiotherapy treatment are planning with Eclipse™ treatment planning system (Varian Medical Solutions) version 8.6. This TPS supports photons, electrons, protons, low dose rate brachytherapy, cobalt radiation treatment calculations and IGRT, IMRT, VMAT techniques. Eclipse™ have two different algorithms for dose distribution calculation: pencil-beam convolution (PBC) and anisotropic analytical algorithm (AAA). It has three windows for transverse, coronal, sagittal plane and one for 3D image, see Fig. 2.2.1.

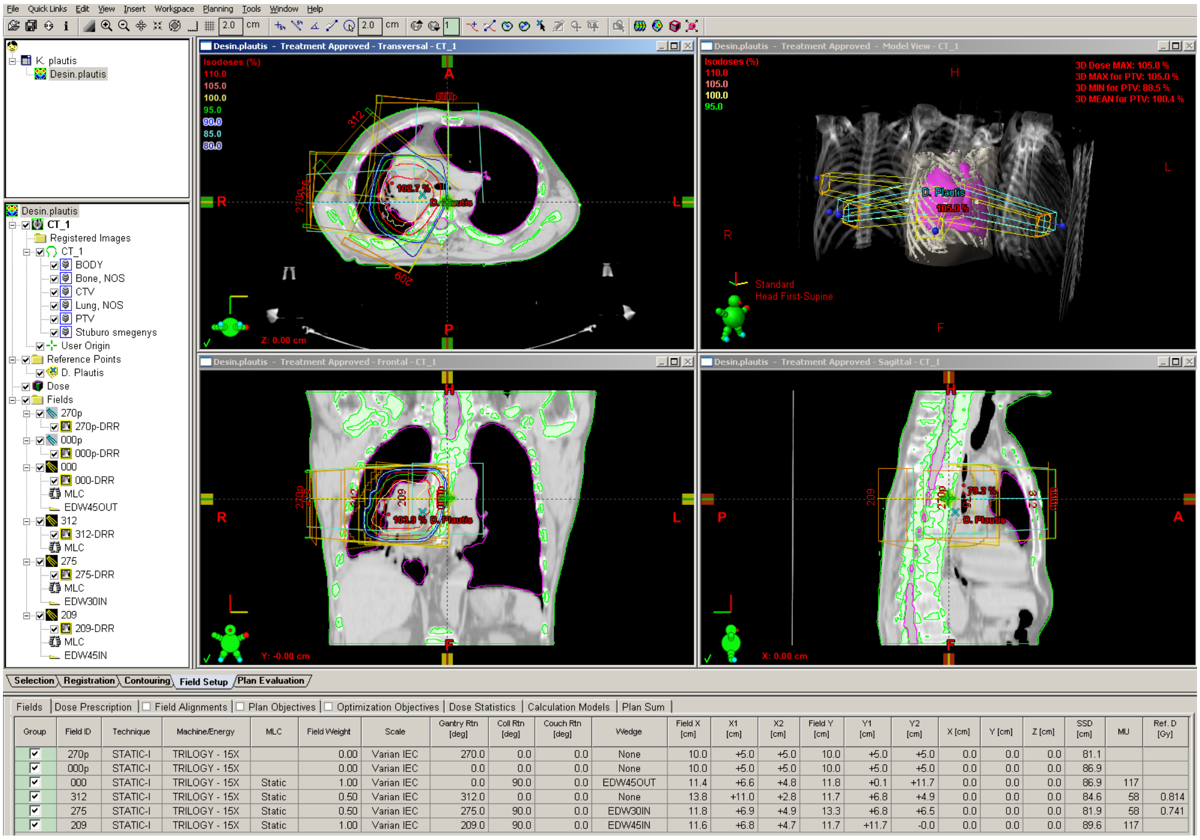

Fig. 2.2.1 Treatment planning system Eclipse™ 8.6 version, treatment fields setup window for lung cancer tumour

In department of Oncology and Hematology Eclipse™ TPS are being used for electrons and 3D CRT, IMRT photons radiotherapy treatment. For volume dose calculation it uses AAA algorithm version 8.9.17 and 8.6.15 version Dose Volume Optimizer for optimization and irregular surface compensation.

The same version Portal Dose Image Prediction for portal dose calculation and Plan Geometry Optimizer for beam angle optimization are being used.

2.3 LINEAR ACCELERATOR

One of the available linac in Hospital of Lithuanian University of Health Sciences Kauno Klinikos department of Oncology and Hematology is Varian Clinac 2100 C/D. All the research measurements were done with this linac. It is configurated for 6 and 15 MeV photons energy and 6, 9, 12, 16 and 20 MeV electrons. With collimator jaws it can have maximum radiation field size of 40 x 40 cm. Radiation field shape are created by 80 multileaf collimator with leaf width of 10 mm. Collimator leaves are divided into two sides and can rotate up to 360^0 around isocentre, thus more precisely adjusting to desired radiation target shape. This linear accelerator power source is klystron. For patient position assurance and if needed adjustments linac have electronic portal imaging device. Before starting radiotherapy treatment low energy 6 or 15 keV portal images at 0^0 and 90^0 or 270^0 depending on target location are taken and by bones compared to CT scan to verified patient position. This Varian Clinac 2100 C/D linac is using for 3D CRT radiotherapy radical and palliative treatment.

Fig. 2.3.1 Varian Clinac 2100 C/D linear accelerator

2.4 TREATMENT COUCH

All linac uses the same Varian Exact IGRT couch. This is homogenous couch made from carbon fibre without any metal or other artefacts creating materials. Couch top is 53 cm width and 200 cm long, it supports patient up to 227 kg, see Fig. 2.4.1. Deflection is less than 4 mm.

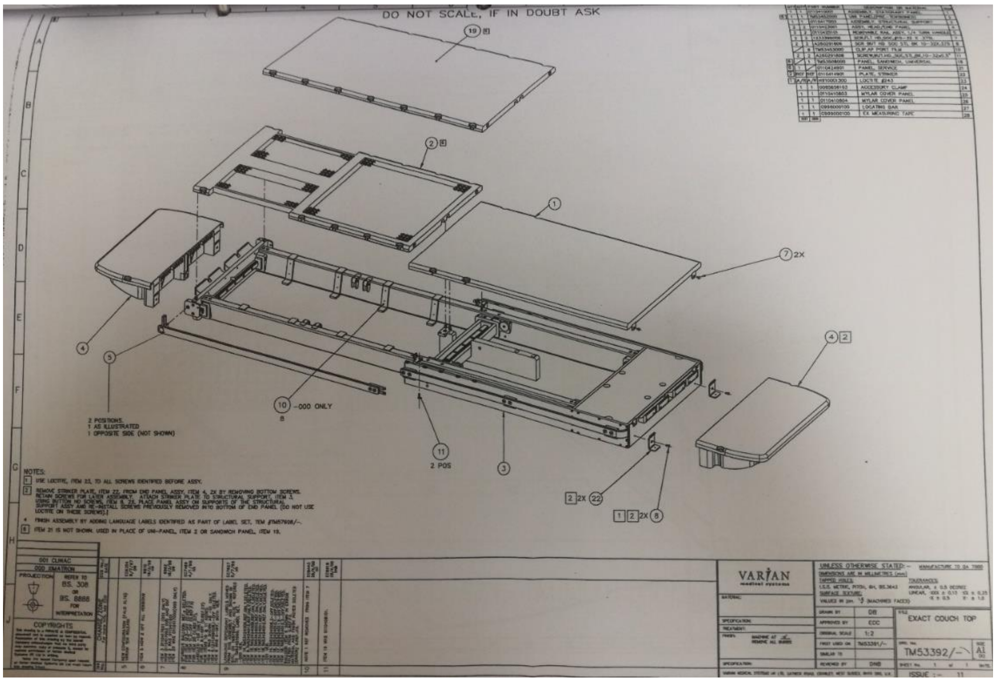

Fig. 2.4.1 Schematic drowning of Varian Exact IGRT couch top

Clinically usable length is 120 cm, that do not have any imaging obstruction. Couch longitudinal range is 145.8 cm, lateral ± 25 cm and maximum lift range 106 cm. It can turn up to ± 100 degrees about isocentre. Water equivalent thickness for head and neck, thorax is 5.2 mm and for lower abdomen, pelvis region - 8.4 mm.

2.5 IMMOBILIZATION DEVICES

During this research most common used immobilization device in the clinic environment – combiboard was investigated. Every linac and CT scanner have the same model combiboard. It is used for patient immobilization during breast, lung, mediastinal and oesophageal tumour radiotherapy treatment. Combiboard is made from carbon fibre and covered with material over arms, head support and thorax area. Combiboard thick is 2 cm and maximum base width is 46 cm, tilting part is 1 cm thick and 25 cm width. This board can be tilted at 5^0, 10^0 and 15^0 degrees. Main head support have three X, Y and Z position. Wedge that prevents patients from sliding can be set in positions from 1 to 9. Arms support height have positions set from 1 to 10 and angle from A to E. All these elements positions are chosen depending on tumour location and individual patient. This allow for better patient fixation, reposition and comfort during RT treatment process.

Fig. 2.2.1 Combiboard immobilization device

2.6 CYLINDER PHANTOM

Dose measurements were made in PTW Freiburg acrylic cylinder phantom. This phantom is 20 cm diameter and 12 cm long. In the middle and on the 8 cm radius circle at 0^0, 90^0, 180^0, 270^0 positions there are 2 cm diameter holes. During measurements ionization chamber detector is placed in specific designed plug and placed into one of the peripheral holes. Other holes are closed by dummy plugs made from the same acrylic material.

Fig. 2.6.1 PTW Freiburg acrylic cylinder phantom

2.7 IONIZATION CHAMBER AND DOSEMETER

Dosimetry measurements was done with PTW Waterproof Farmer® Chamber 30013 and PTW UNIDOS dosemeter model T10001. This chamber has 0.6 cm^3 sensitive volume with 3.05 mm radius and 23.0 mm length. PTV chamber 30013 can measure absorbed dose to water, exposure, air kerma and are used for absolute dosimetry in water, air and solid-state phantoms. Farmer® Chamber 30013 can measure photons from 30 keV to 50 MeV, electrons from 10 to 45 MeV and protons from 50 – 270 MeV. Smallest radiation field can be 5 x 5 cm and up to 40 x 40 cm. Measurements conditions can be from 10 – 40 ^{0}C temperature, 10 – 80 % humidity and 700 – 1060 hPa air pressure. This chamber nominal response is 20 nC/Gy with leakage current of 4 fA and with less than 1 pC/(Gy·cm) cable leakage.

Fig. 2.7.1 PTW Waterproof Farmer® Chamber 30013

PTW UNIDOS dosemeter T10001 can measure dose or charge and dose rate or current. It can be used in radiotherapy, diagnostic radiology and in radiation protection in stationary use. Chamber voltage is 0 V – ± 400 V, increments of 50 V with accuracy ≤ 1 %. This model has accuracy of current and charge measurement ≤ ± (0.5 % + 1 count) and offset current less than ± 1 fA. Non-linearity is less than ± 0.5%. Measurements can be done in 10 – 40 ^{0}C temperature, 10 – 75 % humidity and 700 – 1060 hPa air pressure and requires 15 minutes warm-up period.

Fig. 2.7.2 PTW UNIDOS dosemeter T10001

2.8 BEAM ANGLES IN RADIOTHERAPY USING COMBIBOARD IMMOBILIZATION

During radiotherapy treatment linear accelerator beam rotates around isocentre, point set in the treatment plan. Default isocentre position is patient positioning lasers intersection point, thus in most cases in the middle of the patient. At first most commonly used beam angles during radiotherapy treatment was investigating while using combiboard immobilization device. For this investigation lungs, mediastinal and oesophageal tumour radiotherapy plans were chosen. Usually in these RT treatment plans isocentre is in default position. Beam angles during breast cancer radiotherapy treatment were not investigated because isocentre is always placed into different location, changing two coordinates, x and y. Because of changed isocentre location radiation fields do not passes through immobilization devices, see Fig. 2.8.1. In this figure isocentre is red circle and it is placed into new location so beams passes parallel breast wall. Thus, in breast cancer RT treatment photon beams did not passes through couch top and combiboard or sometimes only very small part of field passes through corner of combiboard.

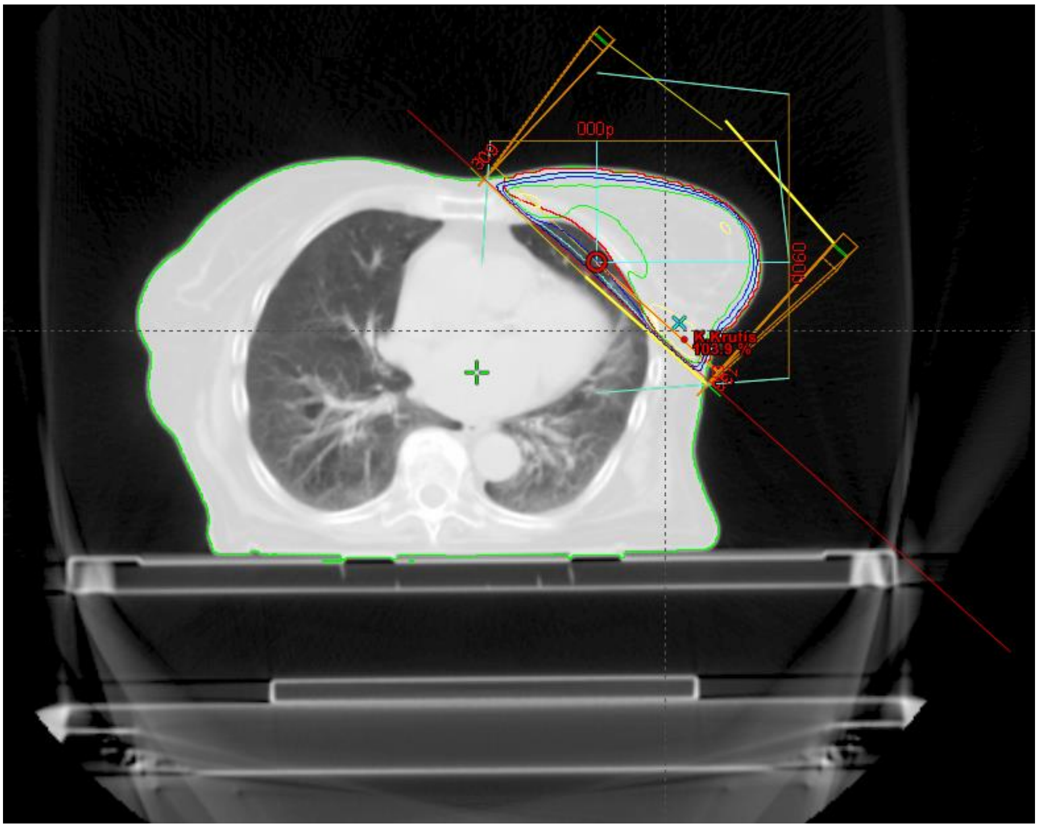

Fig. 2.8.1 Breast cancer RT plan, isocentre is red circle and photons fields do not pass through combiboard, isocentre is red circle

From treatment plans all angles were calculated into one side angle, because they have the same path through couch top and combiboard. If beam angle was more than 180 degree, it was recalculated with 2.1 formula.

$$x = 180 - (y - 180) \qquad (2.1)$$

There *x* – recalculated beam angle ,*y* – beam angle from 181 to 360 degrees.

After this all beam angles were divided into groups. First group is beams that do not pass through couch top and combiboard (0 – 95^0) and other groups are less than 105^0, 115^0, 125^0, 135^0, 145^0, 155^0, 165^0, 175^0, and less or equal to 180^0. Ten degrees step was chosen for optimal data results.

2.9 ATTENUATION EVALUATION WITH IONIZATION CHAMBER

During this research attenuation of Varian Exact IGRT couch top and combiboard was measured in most common used beam angles in radiotherapy with Varian Clinac 2100 C/D. All the relative dose measurements were made in greater depth than photons d_{max}, in this case 10 cm depth. Measurements were done in 20 cm diameter acrylic PTW cylinder phantom.

Firstly, Varian Exact IGRT couch top attenuation was evaluated. Phantom was put on the couch top in the middle, so phantom geometrical centre also would be linac isocentre, as a sagittal and lateral laser passes through the centre of the couch, and the phantom respectively. Traditional measurement distance of 100 SAD or 90 SSD was chosen. Relative dose was measured with PTW Waterproof Farmer® Chamber 30013 set in the geometrical centre of the phantom in specific designed hole and connected with PTW UNIDOS dosemeter model T10001. Measurement set up are in Fig. 2.9.1.

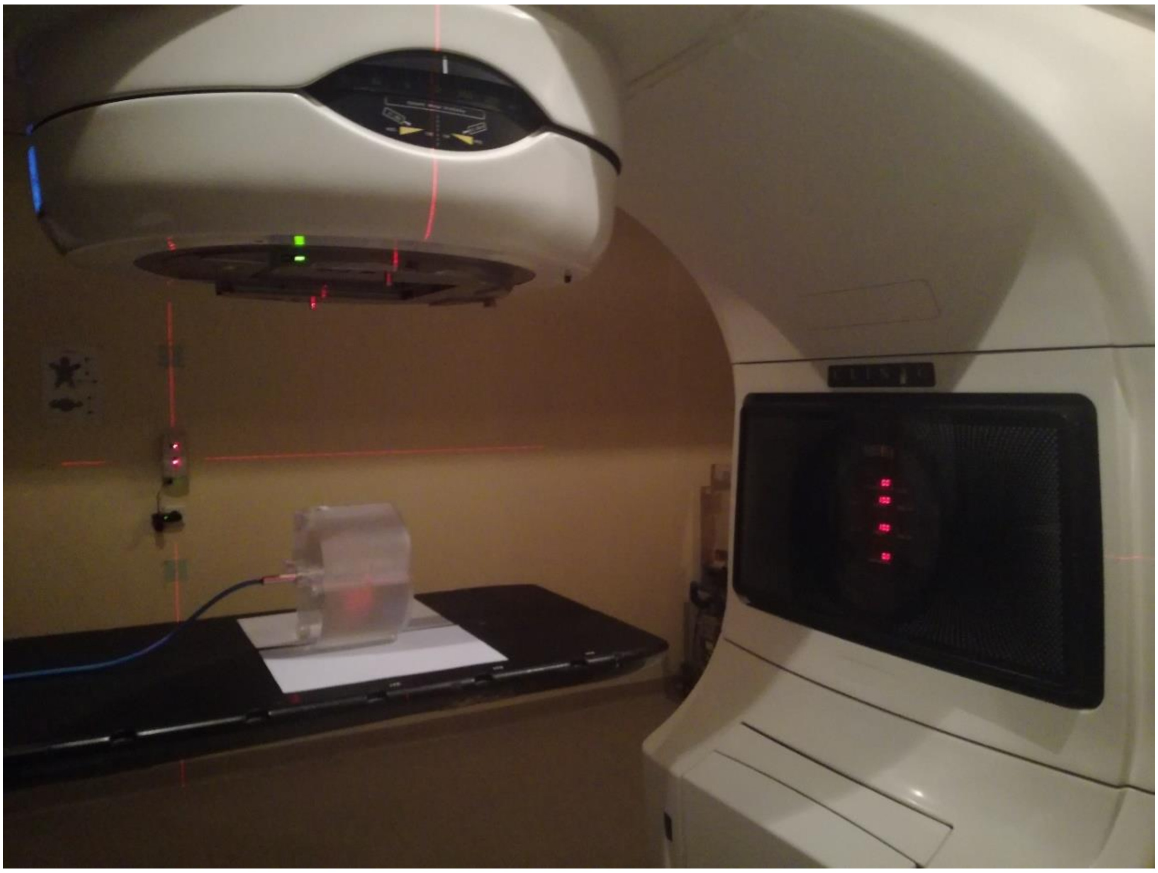

Fig. 2.9.1 Varian Exact IGRT couch top attenuation evaluation set up, lasers passes through phantom geometrical centre

Relative dose measurement parameters was: 10 x 10 cm radiation field size, 100 MU dose and dose rate of 300 MU/min, at beam angles from 180^o to 100^o by step of 10^o. Attenuation (a) was calculated using 2.2 formula. 100 MU machine output means approximately 1 Gy absorbed dose.

$$a = 100\% \cdot \left(\frac{d_{open} - d_{angle}}{d_{open}}\right) \quad (2.2)$$

There: a – attenuation, d_{open} – open field relative dose, d_{angle} – relative dose at specific beam angle.

Open field relative dose was measured at the same radiation field parameters of 10 x 10 cm field, 100 MU, dose rate of 300 MU/min in cylinder phantom set in linac isocentre without any immobilization devices in path of photons. Attenuation at beam angles from 180^0 to 260^0 is the same because immobilization devices are symmetrical and relative dose is measured at the isocentre. Measurements were completed with both 6 and 15 MeV energy photons and repeated three times, open field relative dose was measured at the beginning and in the end of measurements.

Secondly combiboard attenuation was measured using the same equipment and method at two different locations: in the lung, and in the top of oesophagus (neck area). Combiboard was placed on the top on the couch with the same configuration as usually for patient immobilization during lung, lower oesophagus area tumour treatment. Combiboard setup: inclination angle - 5^{o}, arm support at A and 1 position. PTW cylinder phantom was placed in clinically acceptable lung area and set as it is geometrical centre would be linac isocentre with 100 cm SAD or 90 SSD, see Fig. 2.9.2 below.

Fig. 2.9.2 Couch with combiboard attenuation evaluation set up for lung area, oblique beam angle

All the other parameters, like radiation field size, dose, dose rate and beam angles were the same as during couch attenuation measurement. Relative dose was measured with both 6 and 15 MeV energy photons. Attenuation was calculated with the same 2.1 formula and open field relative dose was measured as previously described. The same set up and attenuation calculation method was repeated for top of oesophagus, lymph nodes location. This time combiboard inclination was set at 5^{0} angle, arm support at A and 7 position. Cylinder phantom was positioned in this lymph nodes position as it is geometrical centre would be linac isocentre with 100 SAD, see Fig. 2.9.3 below.

Fig. 2.9.3 Couch with combiboard attenuation evaluation set up for lymph nodes, oesophagus location, lasers passes through phantom geometrical centre

2.10 ATTENUATION CALCULATIONS WITH TREATMENT PLANNING SYSTEM

To calculated attenuation of immobilization devices with Eclipse™ treatment planning system, first CT scans are required. CT scanning was performed with GE LightSpeed RT 16 CT scanner. Combiboard with the same configuration of 5 degree inclination, arm support at A and 1 position as a during relative dose measurements was placed on CT overlay. PTW acrylic cylinder phantom was placed on top of the combiboard, in the lung area as it was during attenuation evaluation with ionizing chamber, see Fig. 2.10.1 below.

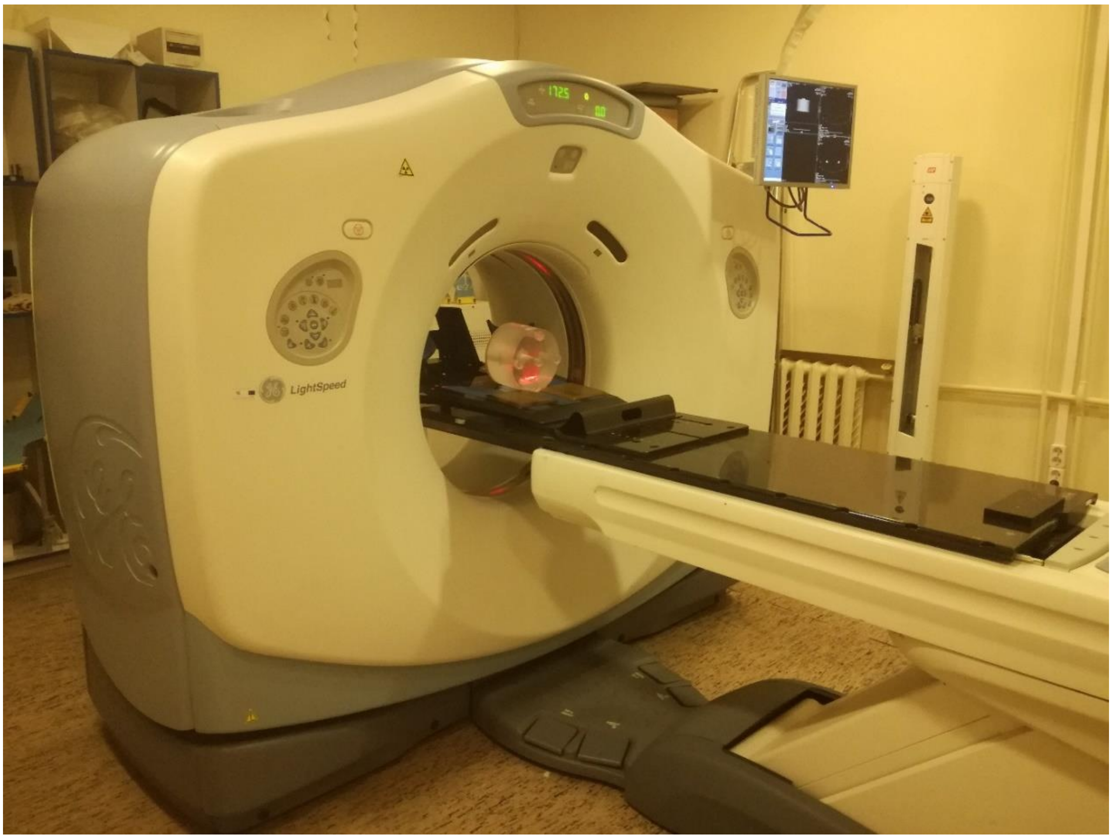

Fig. 2.10.1 Couch with combiboard set up for CT scanning, for calculation of attenuation in lung area with Eclipse™

During CT scanning, at first two scouting images were performed at 0 and 90 planes with settings of 120 kV, 20 mA to verified position and adjust scanning width and length. Scanning was performed with RT chest radical protocol, parameters: 140 kV tube voltage, 440 mA tube current, with 1.25 mm thick of slices. After CT scanning acquired DICOM (Digital Imaging and Communications in Medicine) images were imported into Eclipse™ TPS and cylinder phantom with a combiboard and couch top were defined as the body structures. In Eclipse™ TPS photons attenuation by combiboard and couch top was calculated using AAA algorithm. Point of interest was set in the geometrical centre of acrylic cylinder phantom. Photon beam parameters was the same as during measurement: 10 x 10 cm radiation field size, 100 MU, 100 cm SAD, beam angles from 180^{o} to 100^{o} by step of 10^{o} for both 6 and 15 MeV energy photons.

3 RESULTS

3.1 BEAM ANGLES IN LUNG, OESOPHAGEAL CANCER RADIOTHERAPY

Specific tumour location radiotherapy treatment plan template is adapted to each individual patient situation. Lungs, mediastinum and oesophagus treatment plan templates parameters are show in table 2. By default, these tumour locations treatment template plans have three photon beams. In lung treatment plan two beams are from anterior side and one oblique posterior beam that passes through couch top and combiboard, all beams are 15 MeV energy. Oesophagus treatment template have three 6 MeV photon beams from anterior side.

Table 2. Radiotherapy treatment plans templates

Tumour location	Beam angle	Beam angle (Recalculated into one side)	Energy, MeV
Left lung	0	0	15
	312	48	15
	231	129	15
Right lung	0	0	15
	55	55	15
	123	123	15
Oesophagus, mediastinum	0	0	6
	60	60	6
	297	63	6

During treatment planning, template is adapted to each patient individually so beam angle adjusted that it would cover PTV as much as possible while sparing critical organs. In lung, oesophagus treatment plans it is important to minimize radiation dose to the spinal cord, heart. Beams weight, energy and if needed beams number, accessories are chosen to maximize PTV coverage with 95% isodose, but not exceeding maximum of 107% 3D dose.

In past three months (February, March and April) lung, mediastinum and oesophagus RT treatment beams angles were investigated and results are in Fig. 3.1.1. Statistically about two-thirds (64%) beams are from posterior side, beam angle from 0 to 95 degrees. They do not pass through couch top and combiboard.

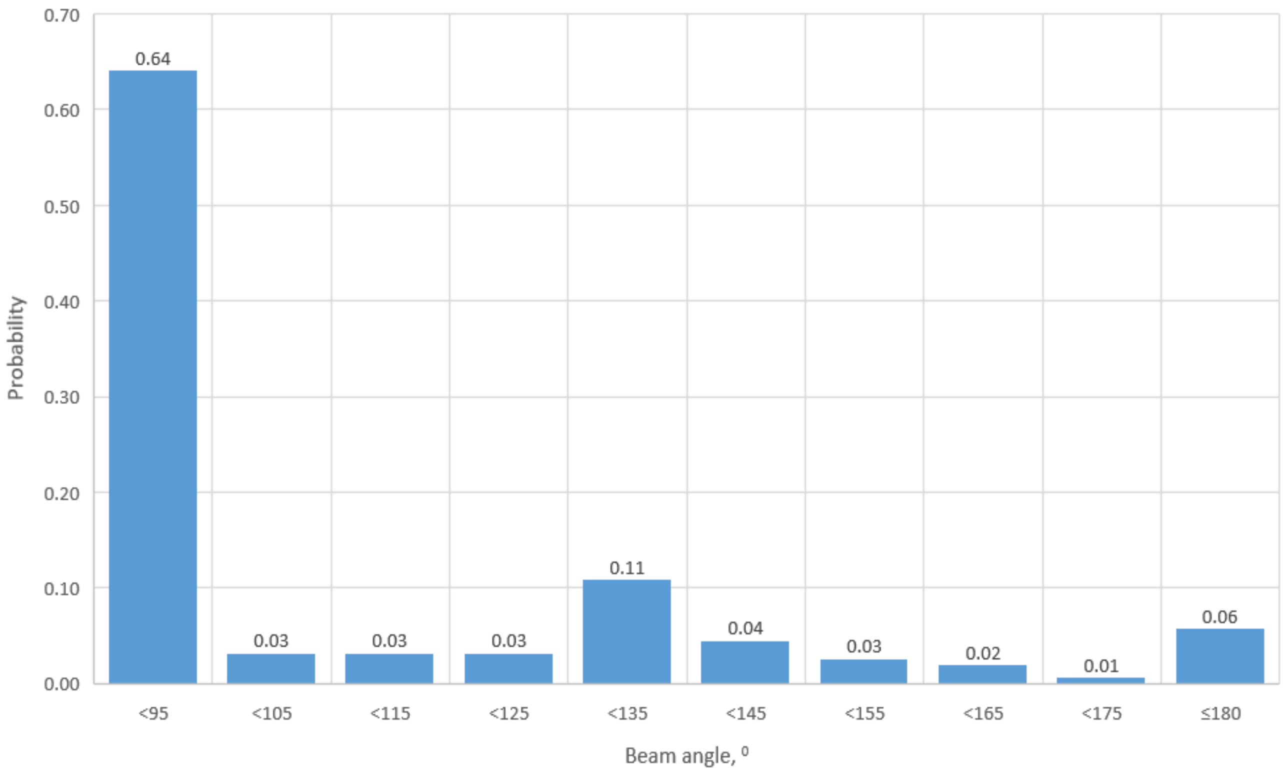

Fig. 3.1.1 Beam angles in lung, mediastinal and oesophageal tumours radiotherapy treatment plans

Thus 36% of all beams passes through immobilization devices. From these angles groups most common beam angles are between 125 and 135 degree. It is angles from the template and 11% beams from all the beams are in this group. Others more common beam angle groups are for 135 – 145^0 and 175 – 180^0 with 4% and 6% respectively. These results show that in most cases each plan have at least one beam from posterior side.

3.2 MEASURED ATTENUATION WITH IONIZING CHAMBER

At first Varian Exact IGRT couch and full setup couch plus combiboard attenuation of 6 and 15 MeV photons was measured in lung area. 6 MeV photons attenuation measurement results are in Fig. 3.2.1. Couch attenuation is less than 2% at beam angles from 180 to 150 degrees. Attenuation increases at lower angles and reaches maximum of 3.13% at 120^0. Attenuation increases because photons needs to travel longer distance through couch to reach measurement point (linac isocentre). At lover beam angles (110^0 or less) photons are not attenuated but even have secondary radiation and attenuation is negative by 0.5%. Similar tendency can be see for full setup attenuation. At beam angles from 180^0 to 130^0 attenuation is nearly linear ranging from 5.94% to 6.51% and drastically decreasing to 3.89% at 120^0 and to -0.78% at 100^0. Combiboard attenuation (difference between full setup and couch) is neglectable at 100^0 – 120^0 and about 4.5% at 140^0 – 180^0.

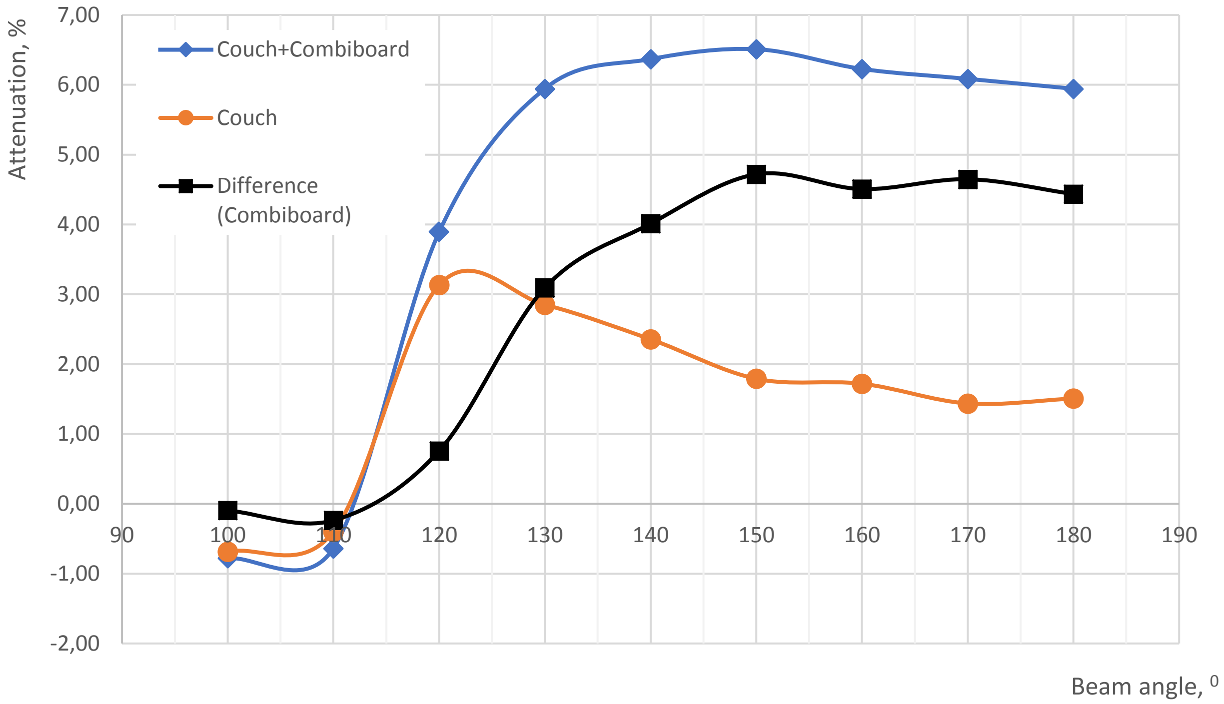

Fig. 3.2.1 Measured 6 MeV photon beams attenuation by immobilization devices during lung radiotherapy

Similar attenuation tendency can be see for 15 MeV photon beams in lung area, Fig. 3.2.2. As expected 15 MeV energy photons are attenuated less than 6 MeV. Treatment couch attenuation is about 0.5% at $180^0 – 150^0$ and maximum at 120^0 beam angle decreased from 3.13% (6 MeV) to 1.35%. Full setup attenuation is about 4% (3.85% – 4.21%), 2% less compared to 6 MeV photons. Secondary radiation at beam angles from 110 – 100 degrees increased from less to more than 1%.

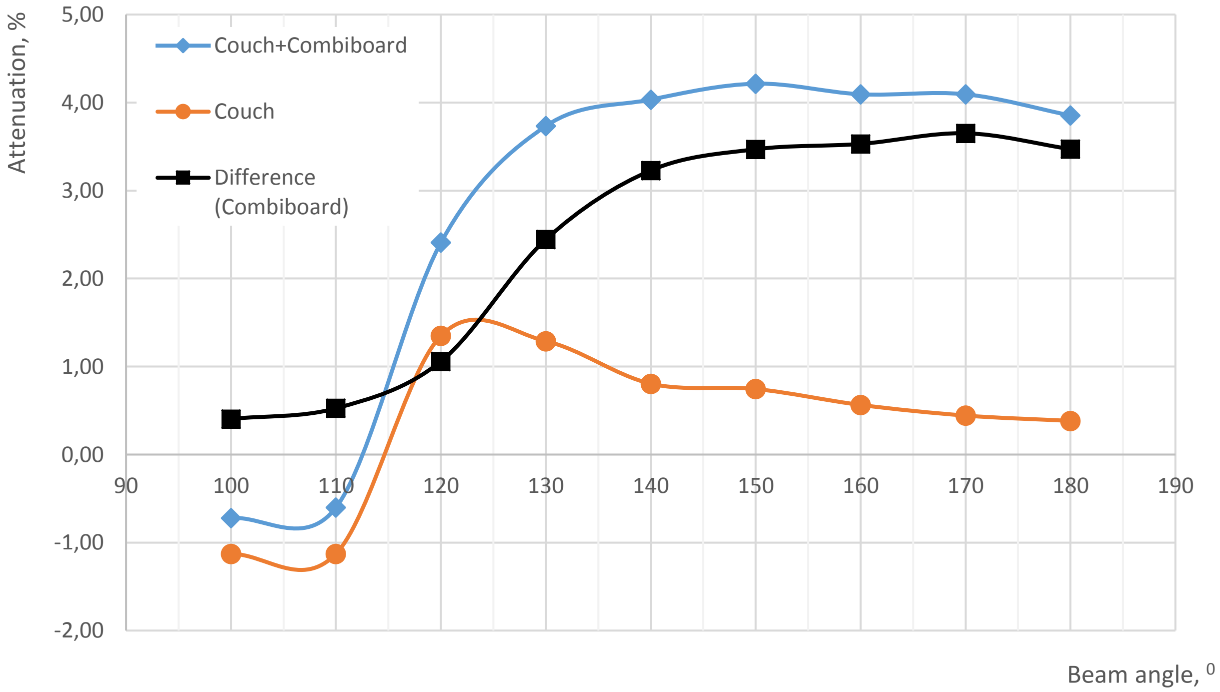

Fig. 3.2.2 Measured 15 MeV photon beams attenuation by immobilization devices during lung radiotherapy

Attenuation measurement results at top of oesophagus, neck area is quite different compared to lung area. There are big increases in attenuation to 11% and 7.56% for 6 MeV and 15 MeV photon beams respectively at 140^0 beam angle and second attenuation peak at 120^0 with 8.34% and 5.56%. This attenuation increase can be explained by merge of arm support between main combiboard base. In this area attenuation for 6 MeV and 15 MeV photon beams even at 110^0 – 100^0 angles are about 3% and 2% respectively because beam passes through part of combiboard.

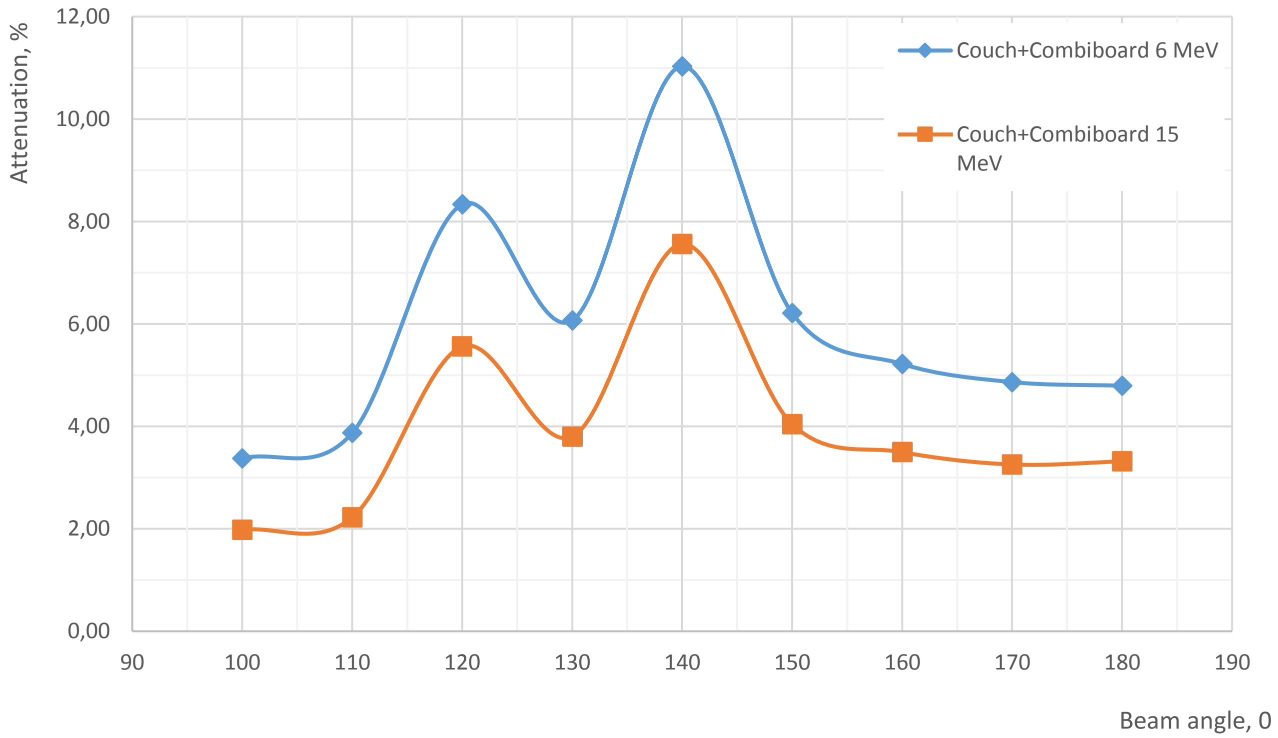

Fig. 3.2.3 Measured 6 MeV and 15 MeV photon beams attenuation by full immobilization setup during top of oesophagus (neck area) radiotherapy

These measurements results show that attenuation by immobilization devices are neglectable, less than maximum allowed 2% radiation dose delivery inaccuracy, only for Varian Exact IGRT couch top during specific angles. Couch can be ignored using 15 MeV photons during at all beam angles and cannot be ignored for 6 MeV photons at 115^0 – 145^0 and 215^0 – 245^0 beam angles. During tumour treatment in abdominal area for patient immobilization couch are used with head and knee support and from posterior side 15 MeV energy photon beams should be used instead of 6 MeV. During couch and combiboad immobilization setup photons attenuation exceeds maximum allowed 2% deviation at 120^0 – 240^0 beam angles for both photons energies. Couch with combiboard immobilization are using for patient with lung, mediastinal, oesophageal, breast tumours and photons attenuation from posterior side are further investigated. During treatment of tumour in top of oesophagus area combiboard or long thermoplastic mask is used for immobilization. Attenuation measurement results shows that thermoplastic mask immobilization should be preferred method to deliver accurate radiation dose to the tumour.

3.3 CALCULATED ATTENUATION WITH TREATMENT PLANNING SYSTEM

After CT scanning and image reconstruction DICOM images were imported into Eclipse™ treatment planning system. PTW Freiburg acrylic cylinder phantom was auto contoured and defined as the body structure because it is soft tissue equivalent and have Hounsfield units (HU) ranging from 92 to 164 with average of 130 HU. Both immobilization devices are made from carbon fibre and combiboard HU are in range from -950 to -910 and CT overlay from -900 to -935. It was needed to manually contour and define as the body structure both immobilization devices because they have such HU. Reconstructed image 2D slice and 3D view with posterior oblique beam are in Fig. 3.3.1.

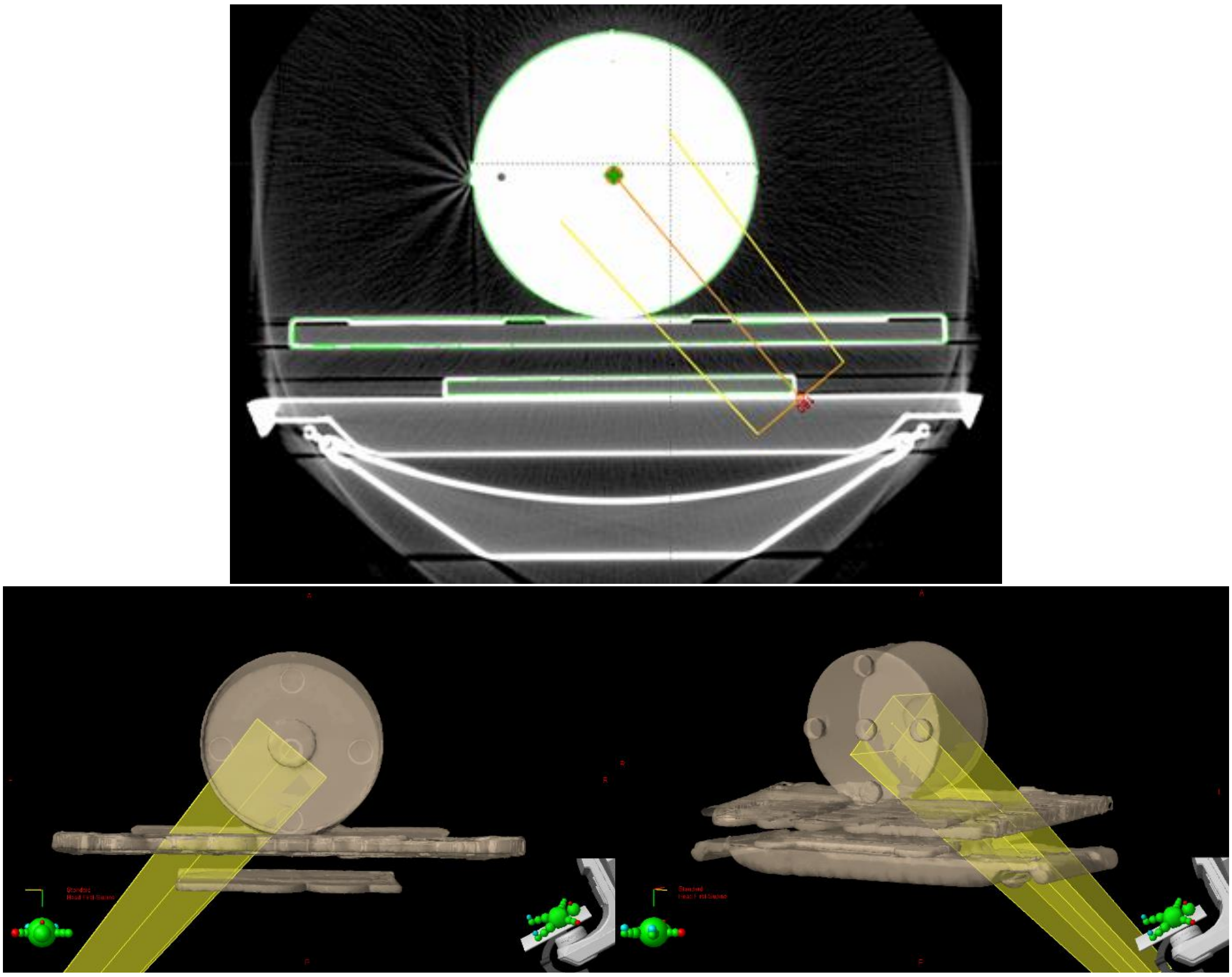

Fig. 3.3.1 With CT scanned and reconstructed lung area evaluation setup in Eclipse™ TPS, in the top 2D profile, left corner 3D image with combiboard defined as the body and in the right corner CT overlay and combiboard defined as body structure

These CT images enables to see exactly how photon beam passes through couch top and combiboard. With Eclipse™ TPS photons attenuation only by combiboard and by CT overlay with combiboard were calculated. Attenuation calculations results are in Fig. 3.3.2.

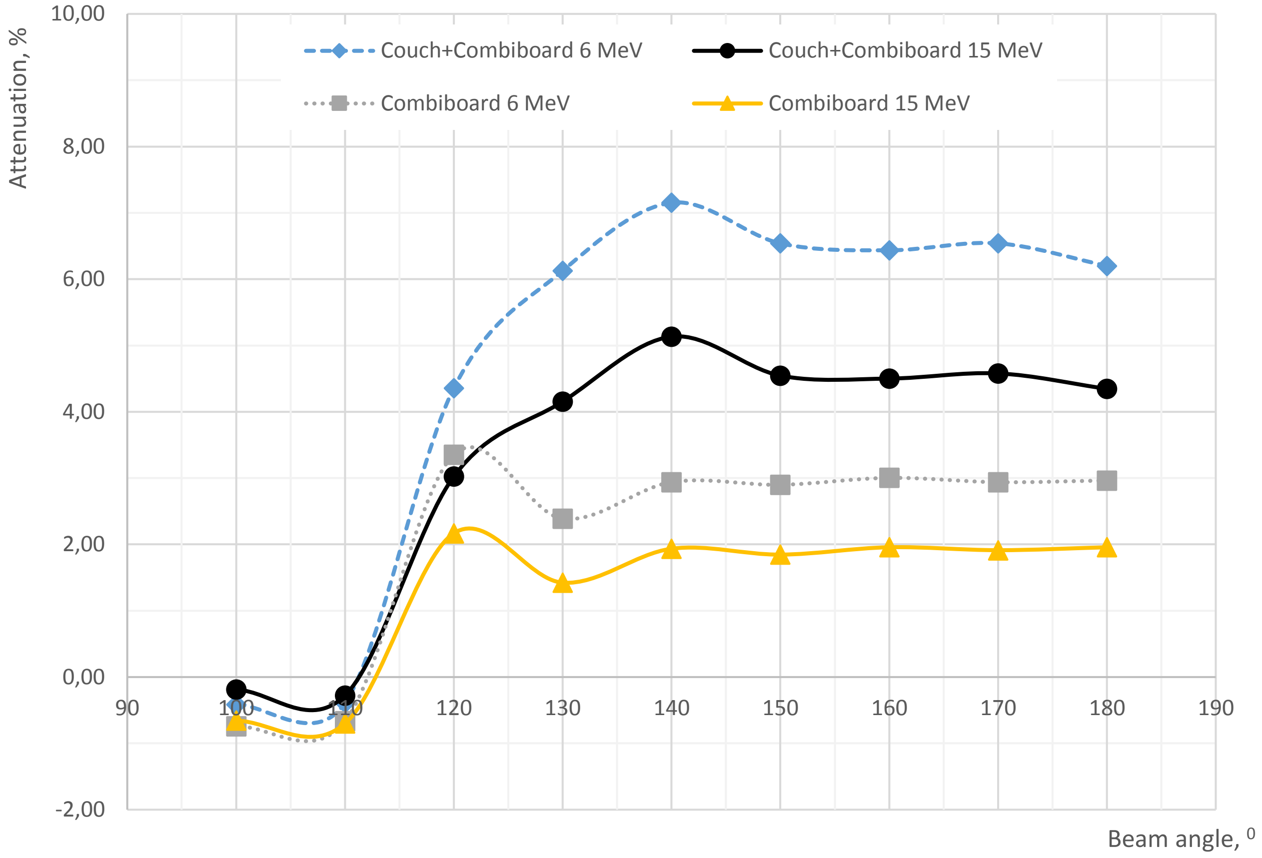

Fig. 3.3.2 Calculated with Eclipse™ TPS 6 and 15 MeV photon beams attenuation by immobilization devices during lung area radiotherapy

Attenuation by combiboard have linear tendency for both photons energies at 120^0 – 180^0 beam angles. 6 MeV photons is attenuated by about 3% and 15 MeV by 2%. Attenuation decreases at 130^0 angle for both energies: 0.6% for 6 MeV and 0.55% for 15 MeV. This can be explained by narrowed combiboard tilting part compared with main board, 25 cm versus 46 cm and starting from 130^0 angle photon beams do not passes through it. Attenuation by CT overlay and combiboard are increased to ~ 6.5% for 6 MeV and to ~ 4.5% for 15 MeV photons. At 130^0 beam angle attenuation starts to decrease and at 120^0 radiation field mostly passes through combiboard. During 110^0 – 100^0 angles there is 0.25 – 0.75% secondary radiation. CT scan with phantom in top of oesophagus (neck area) shows how photon beams passes through arm support, Fig. 3.3.3. This explains and confirms why during measurement there was huge attenuation increase at 120^0 and 140^0 beam angle.

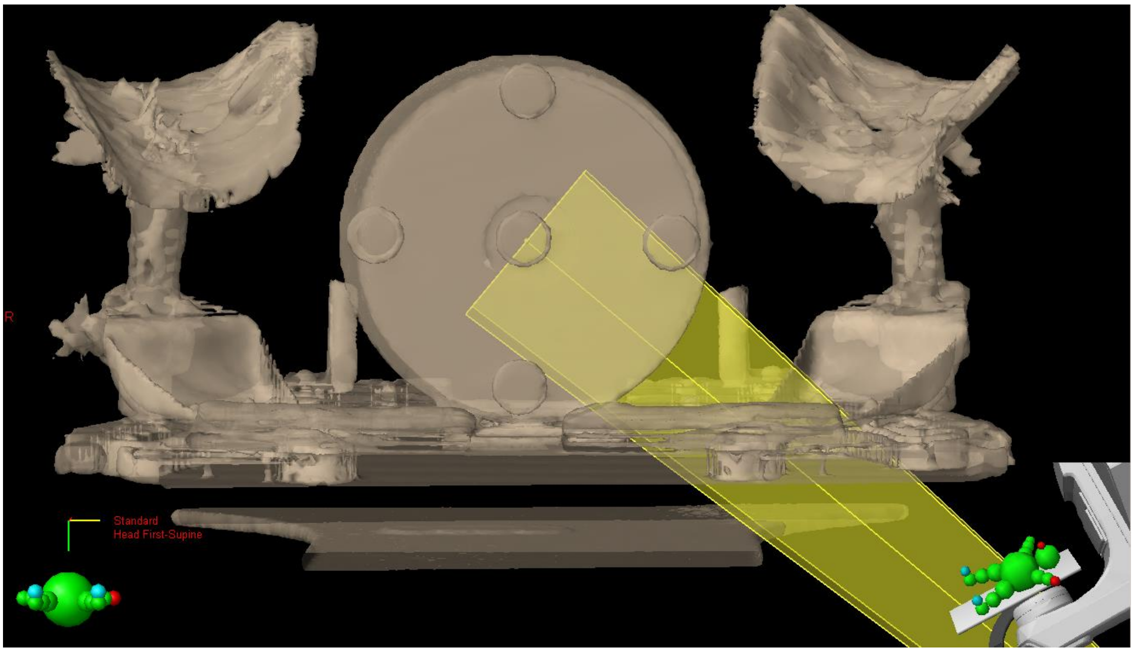

Fig. 3.3.3 Reconstructed top of oesophagus (neck area) evaluation setup in Eclipse™ TPS

With both methods: measurement with ionizing chamber and calculation with Eclipse™ TPS acquired results are compared in Fig. 3.3.4.

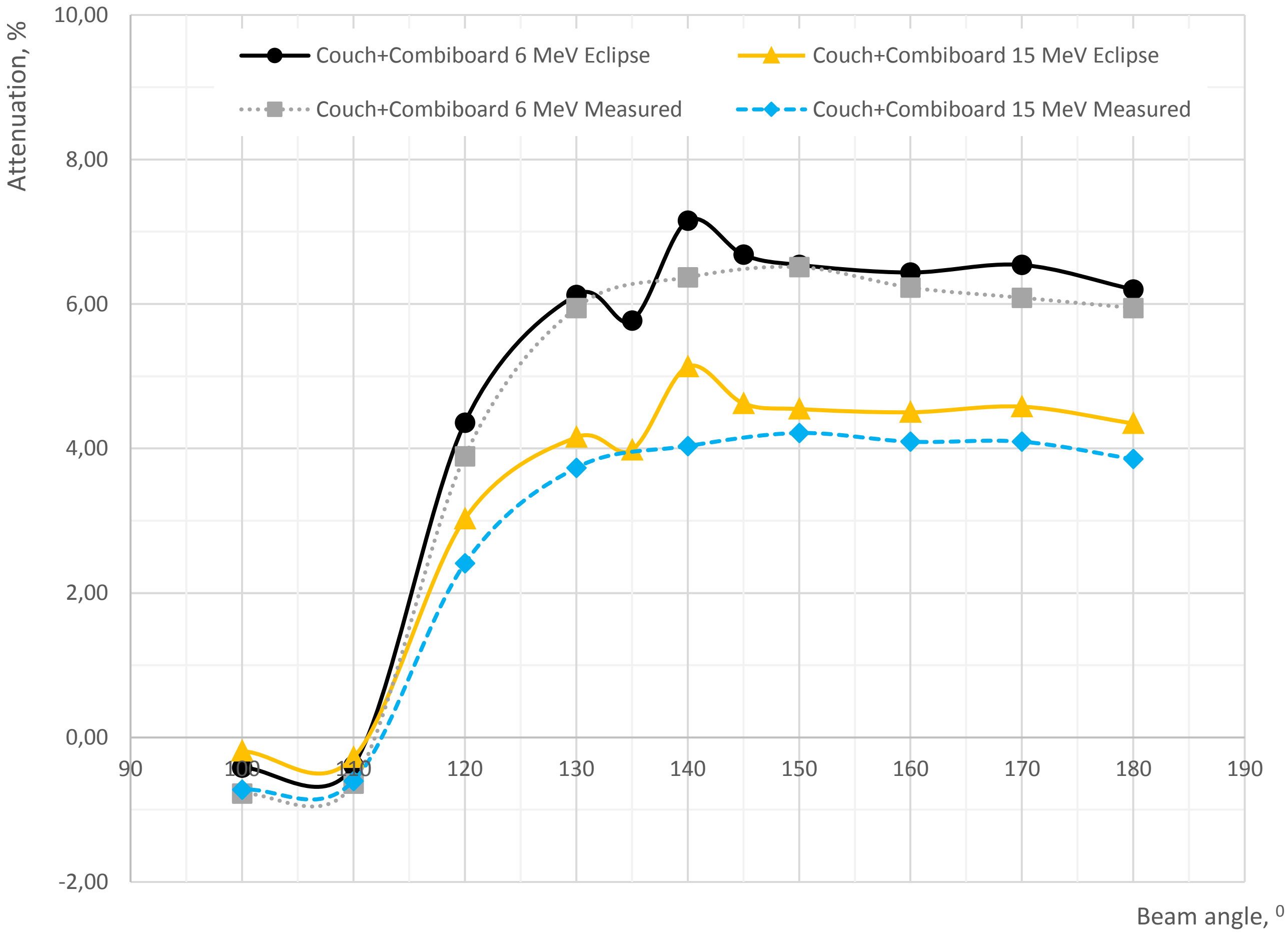

Fig. 3.3.4 Comparison between measured and calculated with Eclipse™ TPS 6 and 15 MeV photon beams attenuation by full immobilization setup during lung area radiotherapy

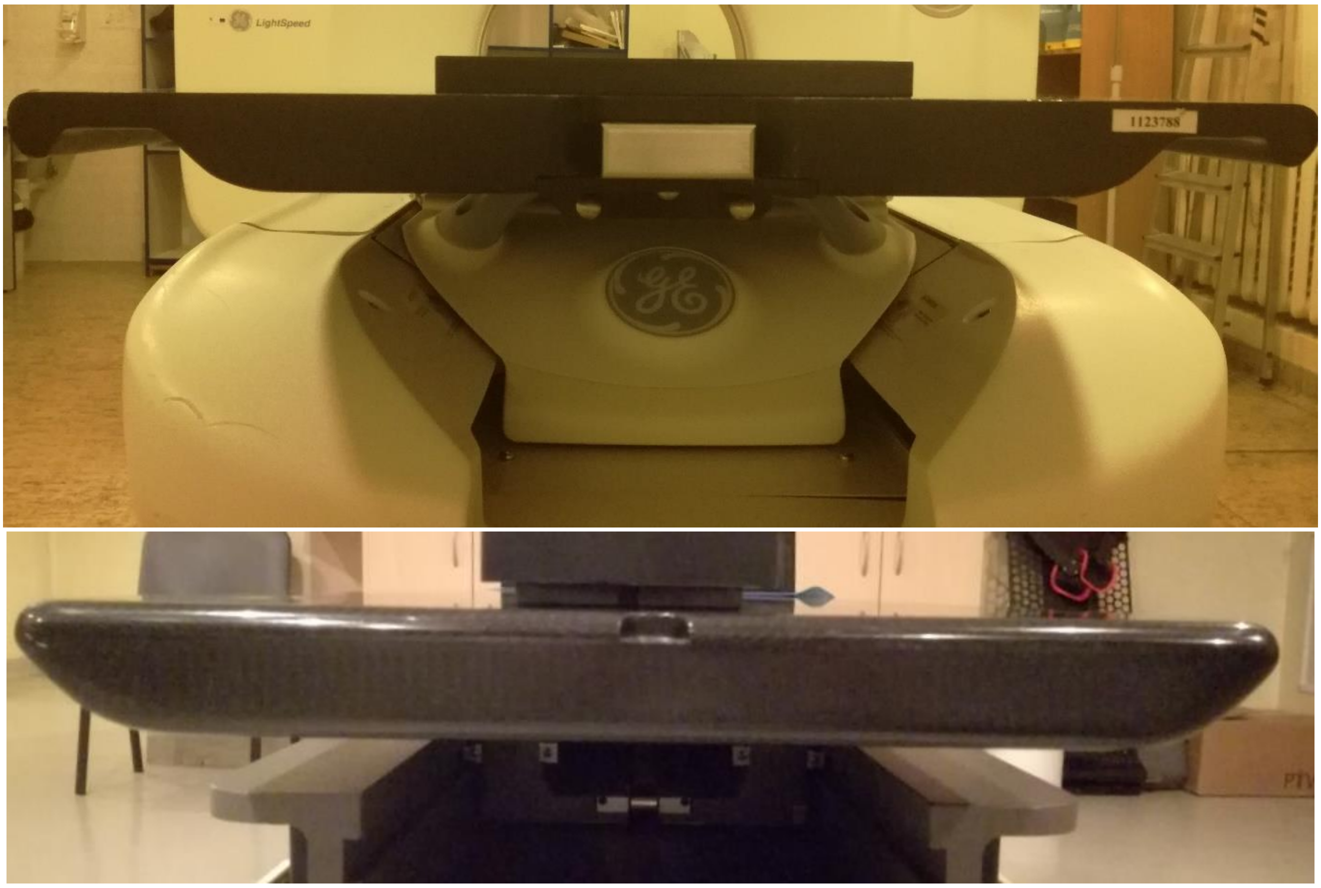

Fig. 3.3.5 Top - Diacor CT overlay profile and bottom - Varian Exact IGRT couch top profile

Both tops are 53 cm wide and made from carbon fibre. CT top have different bottom side corners, so it can be mounted on GE LightSpeed RT 16 CT scanner cradle.

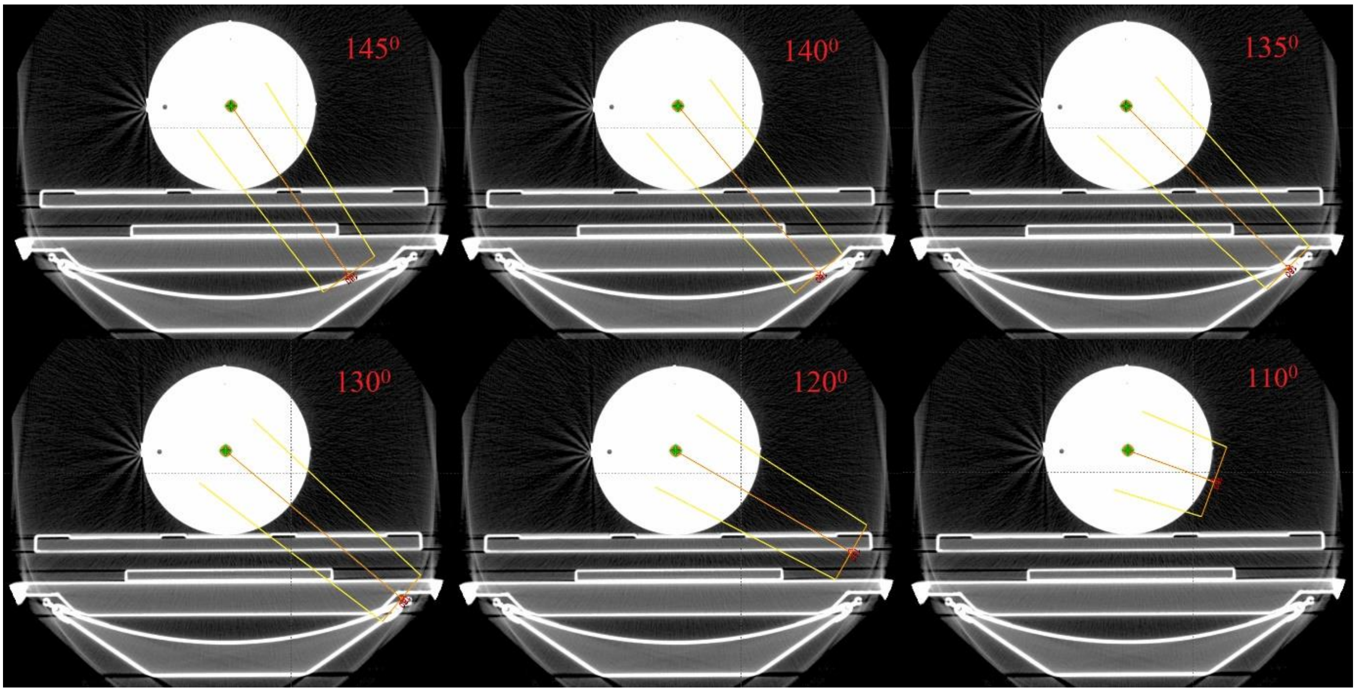

Fig. 3.3.6 Comparison between path of photons in different beams angles during attenuation investigation using Eclipse™ TPS

At 140^0 angle photon beam have longest 5.45 cm path through CT overlay and passes through 1 cm think tilting part and 2 cm thick main combiboard plate, see Fig. 3.3.6. After rotating 5^0 to 135^0 radiation beam passes through slimmer 4.8 cm part of CT overlay and only through main combiboard part, see Fig. 3.3.6. CT overlay thick at 180^0 are 4.12 cm, at 150^0 are 4.7 cm and at 145^0 are 4.9 cm.

Other possible reasons for up to 0.5% difference in calculated attenuation are manually contoured immobilization devices and their possible inhomogeneity. In radiotherapy plans investigation 4% from all beam angles are between 135^0 and 145^0. It can be assumed that about 12% (4·3 because lung, mediastinal and oesophagus RT plans have minimum 3 photon beams) of all RT plans in this location have beam at these angles. Table top difference will not allow to contour both immobilization devices and always have accurate attenuation results, because of attenuation difference at 140^0 beam angle.

Another problem that can prevent from contouring immobilization devices in TPS is CT scan FOV (field of view). Field of view depends on CT scanner itself and used protocol during patient scanner procedure. For example, GE LightSpeed RT 16 CT scanner head protocol FOV is 36 cm, chest – 65 cm, limbs – 50 cm. Depending on patient size CT couch can be ascended or descended and even in 65 cm FOV scan, width can be shorter than 53 cm CT overlay or 46 cm combiboard, see Fig. 3.3.7.

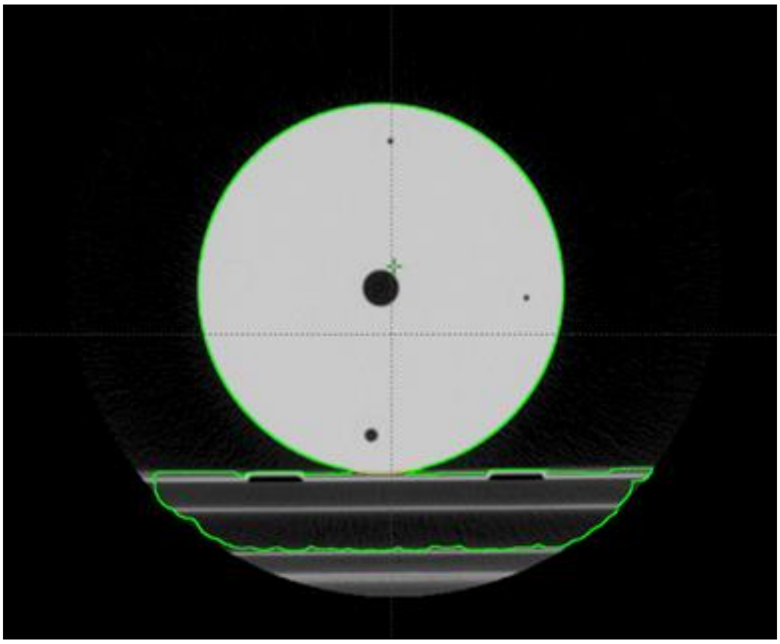

Fig. 3.3.7 46 cm width combibaord and 53 cm width CT overlay are not fully scanned in 50 cm field of view CT scan

The same immobilization device setup was scanned with small 50 cm FOV and attenuation was calculated as previous described in methodology. Attenuation calculation results between full and not full contoured immobilization device setup are in Fig. 3.3.8.

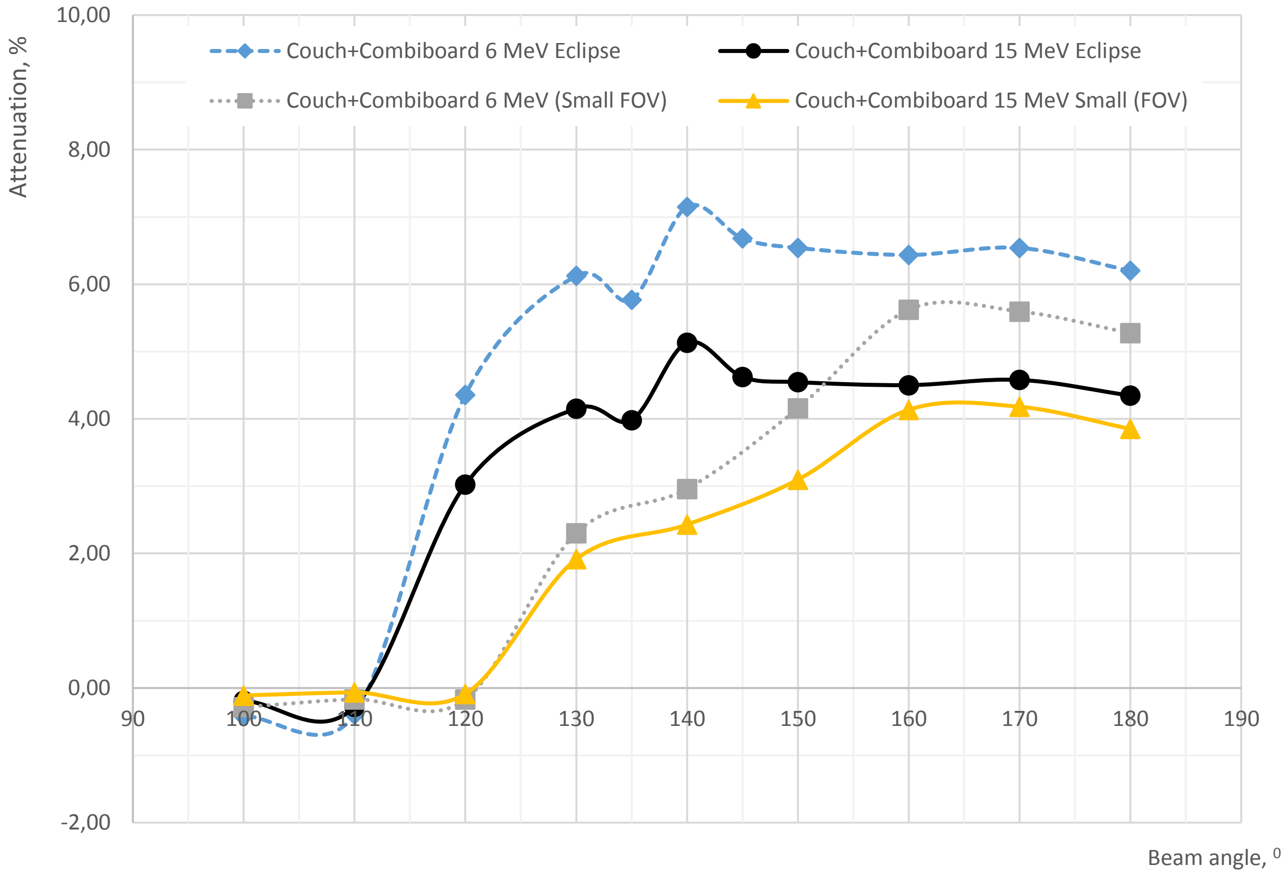

Fig. 3.3.8 Attenuation comparison between full and not full scanned immobilization devices, attenuation calculated with Eclipse™ TPS for 6 and 15 MeV photon beams during lung area radiotherapy

Even at 160^0 and 180^0 beam angles there is difference between attenuation in these two different situations, 1% for 6 MeV and 0.4% for 15 MeV photons. Starting at 150^0 beam angle in small FOV CT scan radiation field passes only through part of immobilization devices difference are more than 2% for 6 MeV photons. Because in thorax area radiotherapy most common used posterior side beam angles are from 125^0 to 145^0 not always would be possible to contour entire immobilization device and thus minimize difference between treatment and the plan.

3.4 INFLUENCE OF PHOTONS ATTENUATION TO RADIOTHERAPY PLANS

In RT treatments plans not all the beams are from posterior side and in each plan they can have different configurations. It was further investigated impact of photons attenuation by immobilization devices for real radiotherapy treatment plans. For this investigation three different completed RT treatment course plans was chosen. These plans were chosen because entire CT overlay and combiboard are in FOV and they have radiation field from posterior side. Each plan has different radiation fields configurations: number of beams, energies, angles and field weight. For every RT plan additional test plan (first test) was created with contoured CT overlay and combiboard and added to the existing body structure, see Fig. 3.4.1.

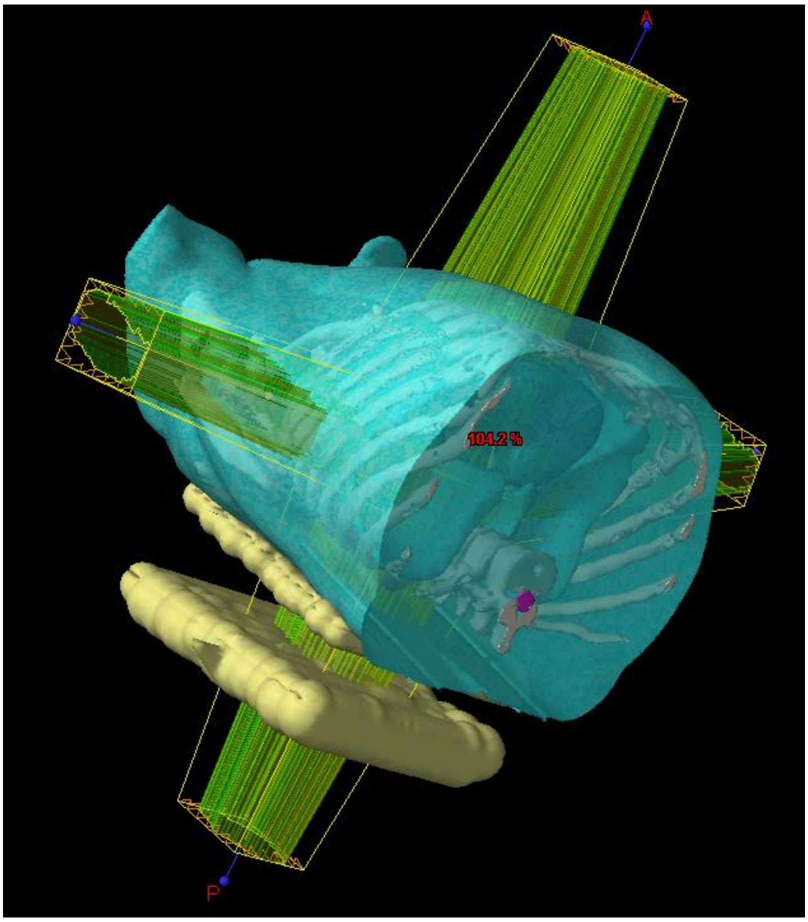

Fig. 3.4.1 From CT scans reconstructed 3D patient image with couch top and combiboard defined as body structures (yellow structure)

These test plans were calculated with the same radiations fields parameters as original completed treatment RT plan. Because not always patient CT scans contain full immobilization devices and can be contoured, second test plan (second test) was created. In this test plan posterior side 130^0 – 230^0 angle beams MU were multiplied by attenuation coefficient, 6 MeV photons by 6% and 15 MeV photons by 4%. This test plan parameters and PTV coverage with 95% isodose was compared to the original plan.

First tested plan was oesophagus radical 3D CRT treatment plan with 25 fractions and 2 Gy each. It is four 6 MeV photon beams box configuration plan without accessories, see table 3. In this plan one radiation field passes through both immobilization devices vertically at 180^0 angle.

Table 3. Radiotherapy treatment plan information

Oesophagus radical radiotherapy treatment plan				
Prescribed dose 25 fractions x 2 Gy, total 50 Gy				
Beam angle, ^{0}	Photons energy, MeV	Accessories, wedge	Field weight	MU
0	6		1	221
270	6		1	188
73	6		1	178
180	6		1	206
	Original plan		Immobilization devices contoured as body (first test)	
3D max dose	106.6%		104.2%	
3D max dose for PTV	106.6%		104.2%	
3D min for PTV	77.1%		76.3%	
3D mean for PTV	99.4%		97.9%	

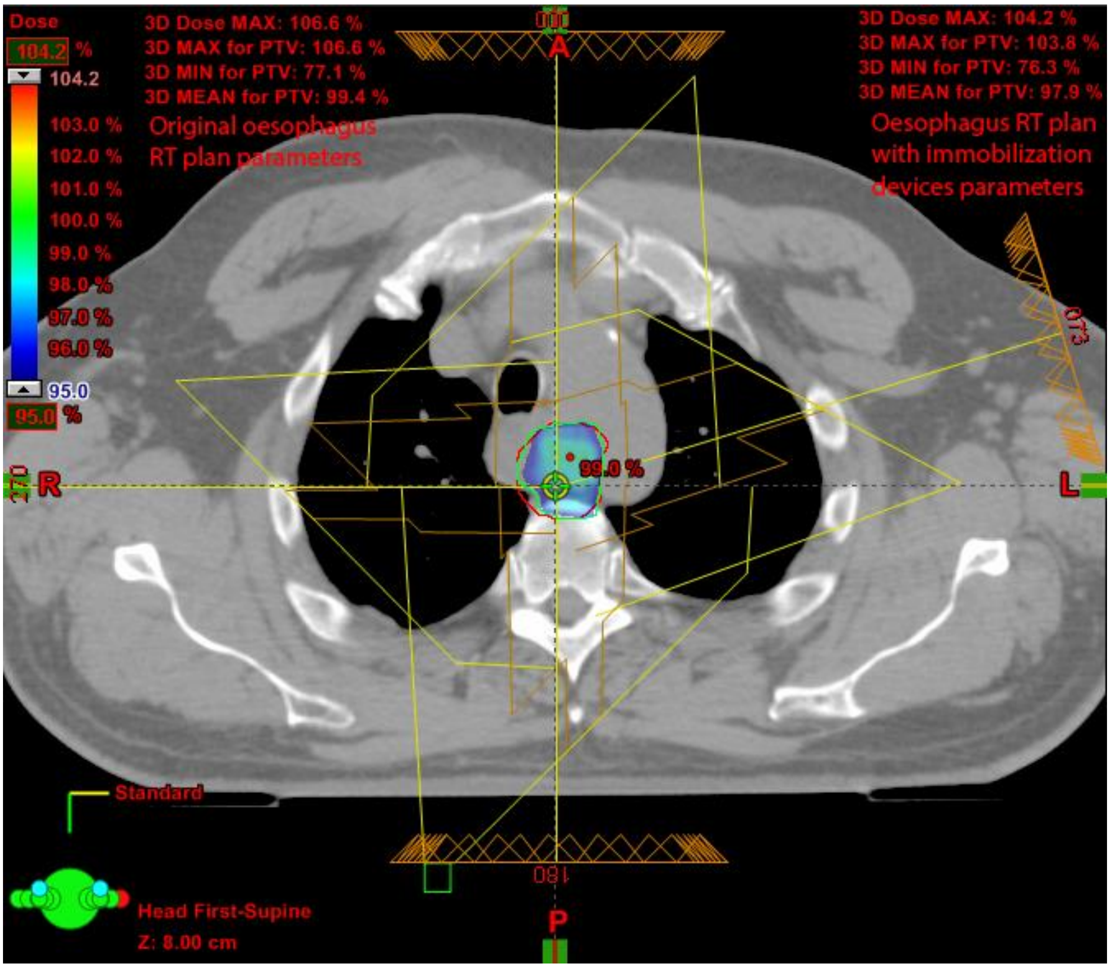

Fig. 3.4.2 Calculated oesophagus radiotherapy treatment plan with immobilization devices defined as body structures, red line is PTV, green line is original plan 95% isodose, test plan 95% isodose is in colourwash

Plan comparison results shows that, maximum 3D dose to PTV decreased by 2.4% from 106.6% to 104.2% and minimal dose to PTV by 0.8% from 77.1% to 76.3%. Mean dose for PTV decreased by 1.5% from 99.4% to 97.9%. RT treatment planning goal is to achieve at least 95% of the prescribed dose to the PTV without exceeding maximum 107% 3D dose and 102% mean dose, while sparing as much as possible critical organs. Most importantly there can be seen decrease of PTV coverage with 95% isodose, to at least 2 cm at the top and bottom of PTV. Comparison of PTV coverage with 95% isodose are in Fig. 3.4.2, green line is original plan 95% isodose and test plan isodose are in colourwash. In this situation there is not significant RT treatment plan quality decrease, then one radiation field from four passes through couch and combiboard.

Next chosen plan for investigation was oesophagus palliative 3D CRT treatment plan with three 6 MeV photons radiation fields, see table 4. This plan enables to compare if there is difference between then 1/4 and then 1/3 of radiation fields passes through immobilization devices.

Table 4. Radiotherapy treatment plan information

<table>
<tr><td colspan="6">Oesophagus palliative radiotherapy treatment plan</td></tr>
<tr><td colspan="6">Prescribed dose 12 fractions x 3 Gy, total 36 Gy</td></tr>
<tr><td>Beam angle, ^{0}</td><td>Photons energy, MeV</td><td>Accessories, wedge</td><td colspan="2">Field weight</td><td>MU</td></tr>
<tr><td>0</td><td>6</td><td>EDW45IN</td><td colspan="2">1.12</td><td>177</td></tr>
<tr><td>75</td><td>6</td><td></td><td colspan="2">0.88</td><td>137</td></tr>
<tr><td>134</td><td>6</td><td>EDW45OUT</td><td colspan="2">1</td><td>158</td></tr>
<tr><td></td><td>Original plan</td><td colspan="2">Immobilization devices contoured as body (first test)</td><td colspan="2">Immobilization devices contoured as body with correction coefficient (second test)</td></tr>
<tr><td>3D max dose</td><td>106.9%</td><td colspan="2">105.2%</td><td colspan="2">107%</td></tr>
<tr><td>3D max dose for PTV</td><td>106.5%</td><td colspan="2">105.2%</td><td colspan="2">107%</td></tr>
<tr><td>3D min for PTV</td><td>88.2%</td><td colspan="2">86.9%</td><td colspan="2">88%</td></tr>
<tr><td>3D mean for PTV</td><td>101.4%</td><td colspan="2">99.7%</td><td colspan="2">101.3%</td></tr>
</table>

In this plan three radiation field configuration enables to minimize radiation dose to the critical organ – hearth and one lung. In this field configuration: one field almost always are from anterior side at 0^0

angle, this field deliver radiation dose to the front of PTV and uses virtual dynamic wedge to minimize dose to the side there is another beam. Beam from posterior side is rotated so it will not deliver radiation dose to the spinal cord and also uses wedge to reduce dose to the left side of PTV. Third beam is from the left side and is aligned to the side of PTV.

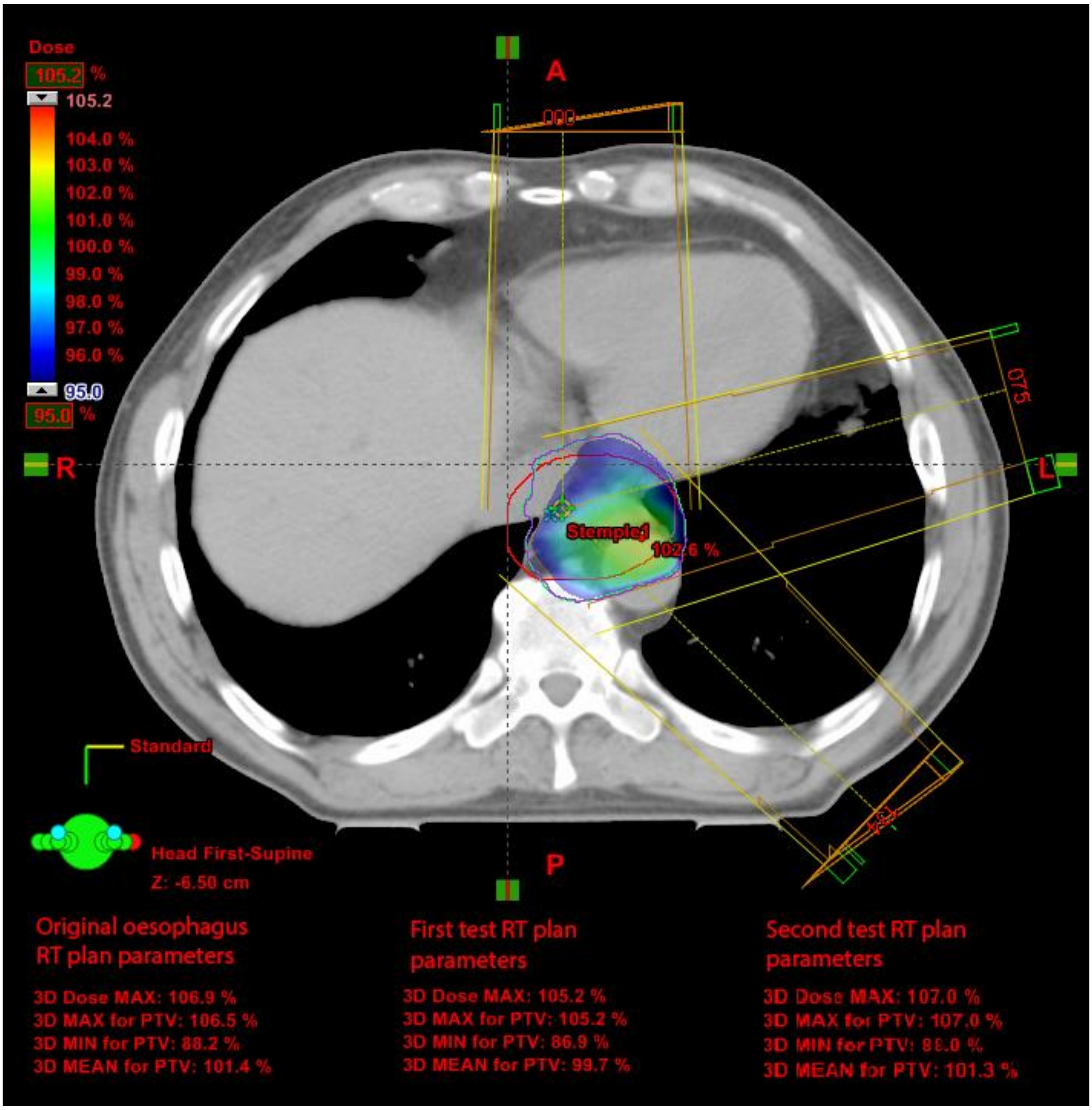

Fig. 3.4.3 Calculated oesophagus radiotherapy treatment plan with immobilization devices defined as body structures, red line is PTV, green line is original plan 95% isodose, test plan 95% isodose is in colourwash and violet line is 95% isodose of plan with correction coefficient

Comparison between original plan, first test plan with contoured immobilization devices and second test plan with correction coefficient for posterior side beam are in Fig. 3.4.3. In second test plan 134^0 angle photon beam MU was corrected from 158 to 167. Because of this photon beam attenuation, anterior-right area of PTW are not covered with 95% isodose, see Fig. 3.4.3. This 95% isodose decrease can be seen in 3 cm from top and bottom of PTV and even reached CTV. Oesophagus RT plan maximum 3D dose in the original plan was 106.9% and in first test plan it was decreased by 1.7% to 105.2% and in second test plan it was 107%, 0.1% more than in the original. Minimum dose to PTV decreased by 1.3% and in corrected plan was only 0.2% lower. Mean dose for PTV have similar changes, in first test plan decreased by 1.7% and in second test plan it is 0.1% lower than in the original. Comparison between these two investigated plans shows there is similar decrease in plan statistics but in RT plan with 3 radiation fields there is significant impact for 95% isodose compared to plan with 4 fields.

Third investigated plan is right lung palliative 3D CRT treatment with four 15 MeV photon beams. Because of higher photons energy there should be less attenuation impact for RT plan. In this plan beam from the right side is split into two beams with lower field weight to better adjust radiation dose to the shape of PTV. All original, first and second test plan parameters are in table 5. In second test plan 209^0 angle photon beams MU was changed from 117 to 121.

Table 5. Radiotherapy treatment plan information

Right Lung palliative radiotherapy treatment plan				
Prescribed dose 12 fractions x 3 Gy, total 36 Gy				
Beam angle, ^{0}	Photons energy, MeV	Accessories, wedge	Field weight	MU
0	15	EDW45OUT	0.99	117
312	15		0.49	58
275	15	EDW30IN	0.49	58
209	15	EDW45IN	0.99	117

	Original plan	Immobilization devices contoured as body (first test)	Immobilization devices contoured as body with correction coefficient (second test)
3D max dose	105%	104%	105%
3D max dose for PTV	105%	104%	105%
3D min for PTV	88.5%	87.6%	88.4%
3D mean for PTV	100.4%	99.1%	100.2%

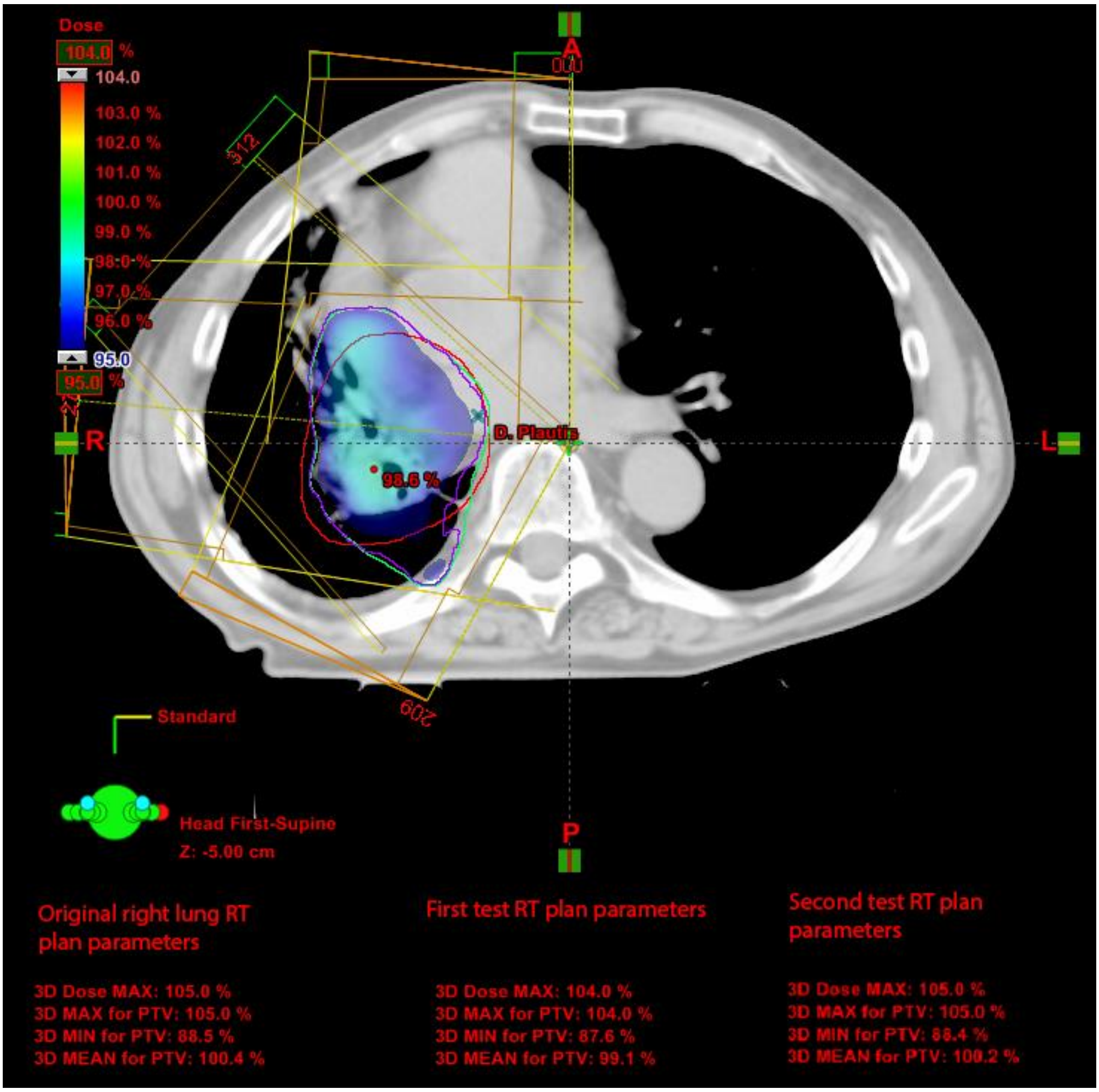

Fig. 3.4.4 Calculated right lung radiotherapy treatment plan with immobilization devices defined as body structures, red line is PTV, green line is original plan 95% isodose, test plan 95% isodose is in colourwash and violet line is 95% isodose of plan with correction coefficient

Even if 15 MeV energy photons are used there is decrease of 95% isodose in left side of PTV, see Fig. 3.4.4. Immobilization devices reduced maximum dose by 1% to 104% and in second test plan after using correction coefficient it become the same as in the original plan. Minimal dose in first test plan decreased from 88.5% to 87.6% and in second test plan it was lower by 0.1%. Due attenuation mean dose in test plan decreased by 1.3% and after using correction factor for 209^0 beam it was lower only by 0.2%. In this RT plan there is about 1% difference in plan main parameters between original and first test plan, but still there is significant difference of 95% isodose at 2 cm from the top and bottom of PTV.

To summarize these three plans investigation shows that immobilization devices caused attenuation of one posterior side radiation field reduces total delivered dose parameters in RT plan by

0.8% - 2.4%. This impact can be higher in RT plans with uncommon beams configurations. Also, this attenuation causes significant decreased of PTV coverage with 95% isodose for RT plan with three radiation fields. In plan with 6 MeV energy x-ray photons this coverage decrease even reaches CTV. In RT plans with four radiation field (box configuration) there was no significant decrease of PTV coverage with 95% isodose. Usually for lung, oesophagus RT plans three radiation field configuration is preferred because it saves one lung, minimizing radiation to it. Using correction coefficient for posterior side 130^0 – 230^0 angle beams MU reduces total dose difference up to 0% – 0.2% and makes almost identical PTV coverage with 95% isodose. This correction can ensure that prescribed radiation dose would be as much as possible the same as during patient radiotherapy treatment.

CONCLUSIONS

When patient is immobilized using couch, head and knee support 6 MeV photon beams should not to be used at 115^0 – 145^0 and 215^0 – 245^0 beam angles.

For immobilization during neck area radiotherapy treatment thermoplastic mask should be used instead of combiboard.

Couch with combiboard immobilization have higher than 2% attenuation at 120^0 – 240^0 beam angles, and linear 6% and 4% attenuation at 130^0 – 230^0 angles for both 6 and 15 MeV photon beams respectively in thorax area radiotherapy.

During lung, mediastinal and oesophageal tumours radiotherapy evaluating posterior side photon beam attenuation by couch and combiboard, decreases total dose delivery up to 2.4% and significant decreases coverage top and bottom of PTV with 95% isodose

Contouring computed tomography overlay with combiboard can reduce attenuation difference to less than 1.1% for individual posterior side photon beams.

During lung, mediastinal and oesophageal tumours radiotherapy couch and combiboard should be contoured and defined as body structure, but not always they are the same, fully scanned in computed tomography and requires manually contouring.

During lung, mediastinal and oesophageal tumours radiotherapy planning 6% and 4% correction coefficient for 6 MeV and 15 MeV photon beams MU respectively may reduce attenuation caused the total dose delivery difference up to 0 – 0.2% and make almost identical PTV coverage with 95% isodose.

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