IMPLEMENTATION OF A ROBUST TECHNIQUE FOR DOSIMETRIC EVALUATION OF LOW-ENERGY PHOTON SOURCES

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Dedication

This thesis is dedicated firstly to God also to my beloved parents, grandmothers and my friends in Colombia and Germany, which without their support I would not have accomplished this achievement.

Greetings

I greet sincerely Heidelberg University, for giving me the opportunity of participating in the experimental radio oncology investigation group and supporting in the development of my bachelor thesis. Especially I greet my tutor Alexander Stadler for supporting during the whole project development.

Resumen

En éste trabajo se determina un protocolo para la evaluación de fuentes de radiación de fotones de baja energía con una técnica de dosimetría, haciendo uso de películas radiocrómicas. Durante el trabajo se llevan a cabo diferentes secciones que integradas conforman todo el método de evaluación, como los son: El modelado e impresión 3D de las piezas del montaje para la relización de mediciones directas con la fuente, toma de mediciones con el equipo médico en el centro de Womed, calibración del escáner y digitalización de las imagenes obtenidas al radiar las películas radiocrómicas, posterior procesamiento de imagenes en MATLAB y con ello la determinación de curvas de calibración y la identificación mediante estadística de la distribución de las dosis en las películas haciendo uso de la calibración inversa.

Palabras clave: Dosimetría, Radiación, películas radiocrómicas, curvas de calibración, fuentes de radiación con fotones de baja energía, impresión 3D.

Abstract

During this work, the key factor was to provide an evaluation technique of radiation for low-energy photon sources using a robust dosimetric technique, using radiochromic or Gafchromic films. The development process consisted out of several different stages, including modelling and 3D printing of the pieces for the obtainment of direct dose measurements with the source, the process of measuring with the dosimetric equipment, calibration of the scanner and the digitalization of the images obtained when irradiating the films, a posterior image processing in MATLAB and with it the further determination of the calibration curves and final dose calibration.

Keywords: Dosimetry, Radiation, Gafchromic films, Calibration curves, Low-energy photon sources, 3D printing

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1 Introduction

1.1. Cancer

According to the World health Organization (WHO) Çancer is a generic term for a large group of diseases characterized by the growth of abnormal cells beyond their usual boundaries that can then invade adjoining parts of the body and/or spread to other organs".[World Health Organization, 2018] Cancer is the second leading cause of death among the world, with the estimation count of 9.6 million deaths on 2018;

1.2. Radiation Therapy

In radiation oncology pathologies such as cancer are treated by radiating the area with ionizing radiation to kill tumors or damaging tissue. This can be performed by in a single or combined Treatment with chemotherapy.
In order to perform an adequate treatment,several factors must be taken into account:

- Tumor type
- Local and regional extent of the tumor
- Anatomic area of involvement
- Geometric accuracy for the delivery of the dose targeted[Mehta et al., 2010]

1.2.1. Radiation

Radiation can be defined as "energy that comes from a source and travels through space and may be able to penetrate various materials"[Health Physics Society, 2016]Radiation can be classified as non-ionizing (which cannot ionize matter) and ionizing radiation, able to ionize matter by indirect or direct ionization.
Charged particles allow the direct ionization by fundamental interaction with the Coulomb force "the force of attraction or repulsion acting along a straight line between two electric charges is directly proportional to the product of the charges and inversely to the square of the distance between them"[Webster, 1854]
Neutral particles like gamma-rays and X-rays allow the indirect ionization; the energy delivery is given when the energy is transferred to secondary particles in Kinetic Energy Released per unit mass (KERMA) and these secondary particles transfer some their kinetic energy to the medium and radioactive losses are produced as a result of an energy loss.

Generation of ionizing radiation is explained by the photoelectric effect ("emission of electrons or other free carriers when light has contact with any material")[?] and the Compton effect ("is the scattering of a photon by a charged particle, causing the decrease of energy in the photon").[?].

Radiation dose

Radiation dosimetry deals with methods for a quantitative determination of energy deposited in a given medium by directly or indirectly ionizing radiations. There are 3 ways of determining doses for radiation.

- Absorbed dose: is defined as defined as "the deposited energy per unit mass of medium"[Pietrzyk et al., 201 medically as the concentration of energy deposited in tissue as a result of an exposure to ionizing radiation. And it is used in order to assess the potential changes in tissues 1-1[American College of radiology. and America,]

$$D = (\Delta\bar{E}/\Delta m) \tag{1-1}$$

  Where D represents the absorbed dose,E the mean energy imparted by the ionizing radiation and m corresponds to the mass in a finite volume.

- Equivalent dose: is the biological measurement of damage, which is calculated by multiplying the absorbed dose by a quality factor for the type of radiation involved
- Effective dose: Assess the potential for long-term effects that can occur in the future

Kilovoltage

Kilovoltage is defined as the potential difference between anode and cathode in the x-ray tube, in order to generate the collision between electrons and the anode needed for the production of photons of x-rays. [Clínica Universidad de Navarra, 2019] these energy peaks linger in the order of 10 to 400 kVp, and the x-ray beams had been classified as follows

- "Grenz rays—beam potentials from 10 to 20 kVp.
- Contact therapy—beam potentials of up to 50 kVp.
- Superficial therapy—beam potentials of 50 to 150 kVp.
- Orthovoltage or deep therapy—beam potentials from 150 to 500 kVp"[Hill et al., 2014]

In order to characterize the penetrating quality it is needed to take into consideration the half value layer (HVL) which is the thickness that a material should have in order to reduce by half the intensity of radiation entering 1-2

$$HVL = \log_2(0{,}693/\mu) \tag{1-2}$$

Where μ represents the attenuation material, and 0.693 a constant 1-3

$$I = I_0 * e^{-\mu * x} \tag{1-3}$$

Exposure Time and tube current

The exposure time is the time where a surface has been trespassed or in touch with a sum of electric charges that are produced when electrons are liberated by radiation in a specific volume of air. The tube current is measured in milliAmperes (mA) and represents the flow of electrons that flow from anode to cathode in the x-ray tube.

Brachytherapy

One example of the usage of IORT is its application in brachytherapy. Which is a technique that places radioactive material inside or near the tumor in order to shrink it or kill the cancer cells materials such as iodine, palladium or iridium are inserted temporarily at the accurate place "after loading" in molds. The operation can be superficial (skin surface), in natural cavities of the body (intracavitary, intraluminal, intravascular) or inserted in the tissue (interstitial)[Ester, 1981]**1-1**.

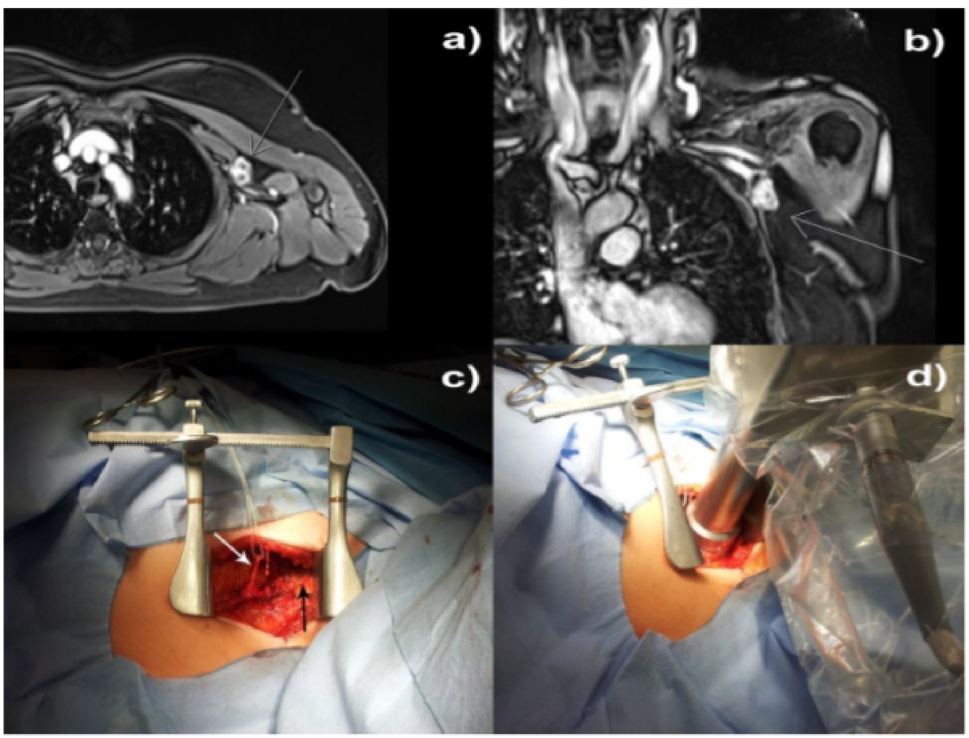


Figure 1-1: Brachytherapy procedure setup

[Eaton, 2012]

1.2.2. Intraoperative Radiation Therapy

"Intraoperative radiation therapy (IORT) is an innovative treatment technique that delivers a single fraction of radiation dose to the tumor bed during surgery"[Barzegar et al., 2017]. This type of radiotherapy can be implemented in three different ways. As brachytherapy, low kilovoltage

intraoperative radiation therapy (low KV- IORT) and intraoperative electron radiation therapy (IOERT).
A typical procedure of IORT consists out of the following steps:

- Maximum safe resection of the tumor.
- Insert the applicator on the cavity.
- Treatment with a single, sterilizing dose.
- Applicator removal.

The magnitude in which the amount of deposited energy is measured by the International System (IS) is known as *Gray*(Gy). Sufficient, high irradiation doses cause damage in tumor cells, which leads to an interruption of cell mitosis.
Cells with higher reproduction rate are the most common to be affected by ionizing radiation, however healthy tissue can be affected too, for that reason it is very important to apply the tumor the highest quantity of dose to the tumor without leading to secondary effects, this is achieved through a clinical plan, which tries to maximize dose in the tumor while sparing healthy tissue or organs at risk (OAR) developed by oncologists and medical physicians. Advantages of IORT are:

- Shortened treatment time, due to the radiation delivery is delivered at the same time as the surgery is performed which eliminates weeks of post-operative radiotherapy sessions.
- Healthier surrounding tissue, as the procedure involves direct contact with the tumor, highest dose amounts are allowed to be delivered to it, meanwhile the surrounding tissue is shielded and spared.
- Reduced risk of re-occurrence, according to statistics the fact of applying dose directly to the tissue diminished the probability of getting once again cancerous tissue in the zone [Eleanor E. R. Harris, William Small, 2017].

The IORT's setups, protocols and measurements are regulated by the international atomic energy agency IAEA, the world health organization WHO, the IRR99 and the IRMER.
The IAEA provides ten safety principles for different areas which can be general or specifics. "The principles are the following:

- Responsibility for safety
- Role of government
- Leadership and management for safety
- Justification of facilities and activities
- Optimization of protection
- Limitation of risks to individuals
- Protection of present and future generations

- Prevention of accidents
- Emergency preparedness and response
- Protective actions to reduce existing or unregulated radiation risks" [IAEA International Atomic Energy A

For the relevance of this experimental practice principles 4,5,6 and 10 are the most relevant and the ones which have to be accomplished in order not to harm further a patient or the personal in charge of performing the measurements, not damaging the equipment or not generating a hostile environment for further work.[IAEA International Atomic Energy Agency, 2000]
The protection mentioned in the item 5 makes broadly reference to the exposure to radiation.Exposure of organs or tissues to the ionization radiation can induce to cellular death in a extensive scale which can lead to organ impairments; whenever this happens the clinical effects are observable after the radiation dose crosses a established threshold. On the other hand, the exposure to ionizing radiation can produce a non-lethal transformation of the cells, when the amount of these cells are considerable the immune system cannot destroy them which may lead to cancer or hereditary effects when affecting somatic cells.
Exposure can occur in different situations:

- Planned exposure situation: in this occasion the protection and safety parameters can be established before the performing the activity when is it a certain or a potential exposure.
- Emergency exposure situation: this situation occurs as a result of an accident or unexpected event, in this situation either preventive or migratory actions shall be considered.
- Existing exposure situation: when there is an existent background of radiation, decisions about needed control and radiation regulation must be taken.

Practices link up to dose constraints and reference levels because, they are used to control the radiation levels with an achievable, economic and environmental purpose and target which are defined by International commission of radiation protection ICRP.

2 Objectives

2.1. General

- Generate a robust protocol for the dosimetric evaluation of low-energy photon sources in order to automatize and characterize the results obtained successfully.

2.2. Specifics

- Design a code in MATLAB useful for receiving and processing images obtained of the radiation process to the EBT3 Gafchromic films.
- Plot the calibration curves corresponding to the Womed ioRT50 and use that information to assign dose values to the pixels of the image.
- Design according to regulations and parameters a proper protocol for measurement obtain.
- Design and 3D print the necessary designs for the setups of different types proposed.

3 Materials and Methods

3.1. Project design

3.1.1. Design

The project was divided into 4 different phases Fig.**3-1**. The first step was to perform a bibliographic review in order to identify which materials and setups were optimal to apply within the whole project, This information was used to 3D design and print a number of setup phantoms, which were used in the measurement process. Finally image processing was performed and reference values were obtained from the measured data.

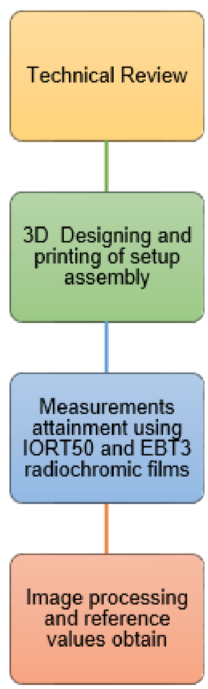


Figure 3-1: General Project diagram

3.2. Technical Review

The project's focus was to irradiate Gafchromic films with an equipment of low energy photon source which protocol's development could allow a specific control of number of measurements to realize, specific setups, and automatic image processing permitting the obtainment of depth dose curves and reference values for doses corresponding to pixels usable at further intraoperative procedures when analyzing images matching to irradiated Gafchromic films analysis.

3.2.1. Womed ioRT50

The Womed ioRT50 is a special X-ray therapy system that uses a transmission target tube for the "treatment of superficial cancers or skin body cavities or temporarily accessible cancer debridement" [Eckert,]

This unit consists of a mobile trolley joined to a mounted X-ray tube stand, this tube can be turned on two axes and the spring loaded arm can be easily moved with a high precision. Fig. **3-2**. Also, its maximum tube tension of 50kV allows for efficient usage in intraoperative and superficial treatments and fulfills the standards given by the AAMP. Table.**3-1**

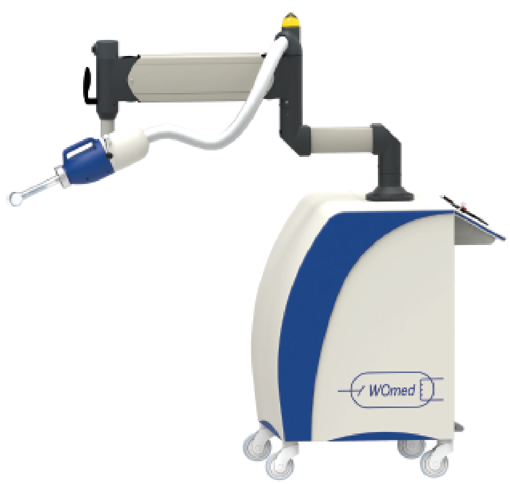


Figure 3-2: Womed ioRT50 external structure
[Eckert,]

Table 3-1: Technical data of the equipment Womed ioRT50 [Eckert,]

Max. high tension [kV]	50, 70
Max. tube current [mA]	8
Max. power [W]	500
Two circuit cooler	water-water
Number of selectable energies (combined for filter, [mA], [kV])	1 (fixed)

3.2.2. Gafchromic films

"The EBT3 Gafchromic films where designed for measurements of absorbed doses of ionizing radiation, particularly suited for high energy photons".[Ashland Inc., 2014] These films have an optimal performance range from 0.2 to 10 Gy and have a three layer structure, external layers are composed by a matte- polyester substrate each one of 125μm and an active internal layer of 28 μm thickness which contains an active component, stabilizers, a marker dye and other components that will give the film a considerable energy-independent response. Fig. **3-3**.

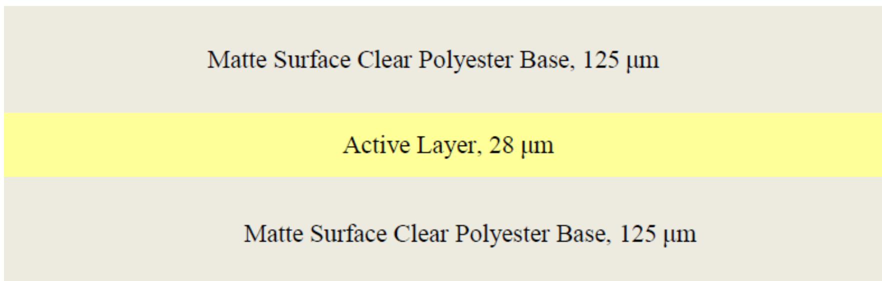


Figure 3-3: Womed ioRT50 external structure
[Ashland Inc., 2014]

The Gafchromic films have technical specifications which will affect the instructions for their use Table. **3-2**.Longtime exposure to light should be avoided, as this leads to changes in film response, but short exposure to room light during measurements doesn't lead to significant changes in optical density [Ashland Inc., 2014] When the film is exposed, a blue color polymer inside the active layer will be formed with a maximal absorption of approximately 633 nm.
The electrons proceeding from the Womed ioRT equipment are generated by the transmission tube

Table 3-2: Technical properties of the EBT3 Gafchromic films [Ashland Inc., 2014]

Property	Gafchromic EBT3 film
Configuration	active layer (28μm sandwiched between 125 μm matte-surface polyester substrates
Size	8" x10", other sizes available upon request
Dynamic Dose Range	0.1 to 20 Gy
Energy Dependency	$<$ 5 % difference in net optimal density when exposed at 100 keV and 18MeV
Dose fractionation response	$<$ 5 % difference in net optical density for a single 25 Gy dose and five accumulative 5 Gy doses at 30 min intervals
Dose rate response	$<$ 5 % difference in net optical density for 10 Gy exposures at rates of 3.4 $Gy/$ and 0.034 Gy/min
Stability in light	$< 5x10^{-3}$ change in optical density per 1000 lux-day
Stability in dark (pre-exposure stability)	$< 5x10^{-4}$ optical density $change/day$ at 23C and $2x10^{-4}$ density $change/day$ refrigerated
Uniformity	Better than +-3 % in sensitometric response from mean; dose uniformity better tan +-2 % with FilmQAPro and triple-channel dosimetry

Another relevant recommendation given by the manufacturer consists on using a 48-bit flatbed color scanner and using a rational function to fit the calibration curve Fig. 3-1

$$d_x(D) = a + \frac{b}{(D - c)} \tag{3-1}$$

Where $d_x(D)$ is the typical pixel density of the film in the scanner channel x at the dose D and a, b, c are equation parameters to be fitted with this equation it is possible to perform single channel dosimetry and multichannel dosimetry. Fig.**3-4** Multichannel dosimetry allows for higher precision to identify changes in the reference generation, for the same data of doses in the different channels (Red, Green, Blue) the changes of the value pixel can be observed.

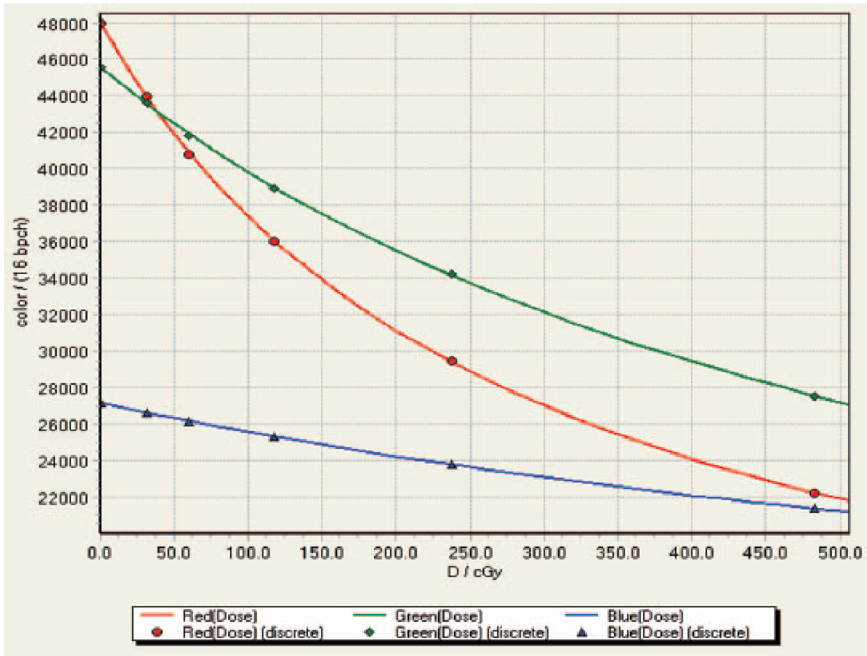


Figure 3-4: Calibration curves of multichannel dosimetry for EBT3 Gafchromic films [Chiavassa et al., 2015]

This function Eqn.1-2 is useful because, "rational behavior with respect to the physical reality that the density of the film increases with increasing exposure yet approaches a near constant value at high exposure"[Ashland Inc., 2014]. This is a clear advantage compared to polynomial fitting which creates undesired oscillation between the data points.

When using the rational functions fewer calibration points are needed, approximately six to eight points, fulfilling the protocol IAEA-TRS 398, which establishes the "Absorbed dose determination in external beam radiotherapy: An international Code of practice for Dosimetry based on Standards of Absorbed dose to water".[De León Alfaro et al., 2015] This protocol describes a standard of absorbed dose to water for applying to radiation beams including kilovoltage x-ray beams $D(w, q)$ to measure a radiation quality factor. Eqn. 3-2 in this case M is the dosimeter reading corrected concerning the influence of air temperature and pressure according to the reference values, N_q corresponds to the calibration factor of the dosimeter in terms of absorbed dose in water using as reference the quality factor Q and the correction factor K

$$D_{W,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0} \tag{3-2}$$

The films were cut in the dimensions of $45x35mm^2$ and it was decided that the images were going to be scanned in an horizontal orientation.[Ashland Inc., 2014]

According to the manufacturer the time between exposure of the filmstrip and scanning will have to be 5 time lesser. The exposure of Gafchromic films to ionizing radiation starts with the solid-state polymerization in crystals of the active component, the process continues with the growth of the crystal matrix of the monomer carbon-carbon interatomic distances, afterwards the polymerization rate decreases. indifferently the scanner m or the scanner n used to obtain the images of the films there is a linear correspondence between the dose net response. Eqn. 3-3

$$ND, s_{n,x} = C * ND, s_{m,x} \tag{3-3}$$

For the equation N makes reference to the net dose either of the scanner n or the scanner m and C is a correspondence constant for the linear correspondence. It is suggested in order to generate an accurate dosimetric evaluation to perform a filter which correct the blurring of the image such as a wiener, this will reduce the influence of nonuniformities of films. The same effect can be obtained by the use of attenuators.
The Laplacian filter is applied in order to correct blurred lines of the image, making the contour strong for further curvature detection.

3.2.3. Flatbed Scanner

The scanner performs a huge role in the dosimetric evaluation procedure; it has the task of digitizing the Gafchromic films previously radiated.
An Epson CP equipment consists of an array of light sensors, an illumination system that uses LEDs, an optical system to focus the light into the sensors and the main structure, which holds the whole elements and it electronic components was used for the purpose of this work.

The evaluation is performed lightening the Gafchromic film which has been previous irradiated and forward placed at the scan tray, subsequent the lightening system and the scanning bar move synchronously. The scan time is influenced by the chosen resolution, which is stated as dots per inch (dpi), in order to find and equilibrium between these 2 parameters it is recommended to use $72dpi$ [Ferreira et al., 2009]

This type of scanner uses charge-couple device optic sensors which do not always reply with the same sensitivity, the variability happens due to:

- Geometric efficiency (size of the scanning bed)
- Light non-uniformities
- Light leaks at the borders of the scanner
- Reflection differences between the borders and center

Influence of scanning direction

The correct alignment between the source of lightening and the sensors will improve the quality of the image digitized; For badly positioned films scanning artifacts like, "Newton's rings"might appear, because of optical interferences. Fig. **3-5**

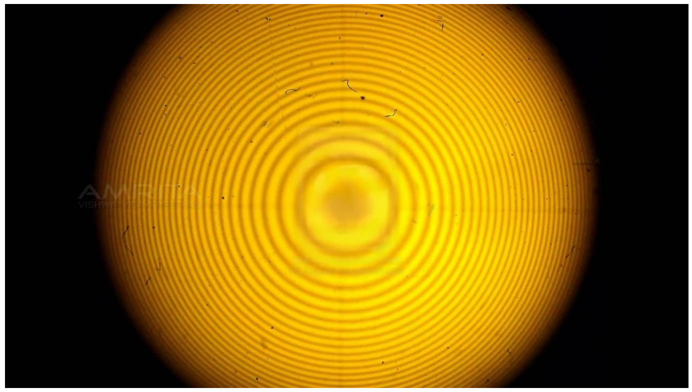


Figure 3-5: Newton's rings interference patterns

When scanning the images it is possible to follow a landscape or a portrait direction [Ashland Inc., 2014] [Ester, 1981], nevertheless according to the literature, maximal response is acquired when scanning the films in vertical orientation. for both cases the behavior of the response are equivalent but in different ranges, that is the reason why every film shall be scanned in the same direction as the others (vertical for this project).

Scanning conditions

In order to perform the digitization of the images, the uniformity of results must be assured. In order to achieve this a prescanning procedure must be performed:

- Clean the scanner from finger prints or corresponding dirt.
- Turn on the printer
- Determination of maximum scanning area (values)
- Setup of scanning mode, which corresponded to 48 bit RGB mode (16 bits per channel color)
- Heat the lamp of the scanner for 15 minutes
- Perform various scans with no films over the bed with the objective of stabilize the illumination of the lamp

3.2.4. Ionization Chamber

An ionization chamber 0,005cm^3 Soft X-Ray Chamber Type 34013 consists of a gas volume between two electrode connected to a high voltage supply. Within this space of volume, the radiation creates ion pairs, the attraction between the charges generated produces a current which can be measured by an electrometer. [Radiation, 2015]
An ionization chamber is a radiation detector, which is in-charged of the conversion of radiation energy to electrical energy, this specific chamber has a plane parallel ionization chamber, where a high voltage electrode plate and a measuring electrode plate are limiting the sensitive volume. Fig. **3-6**

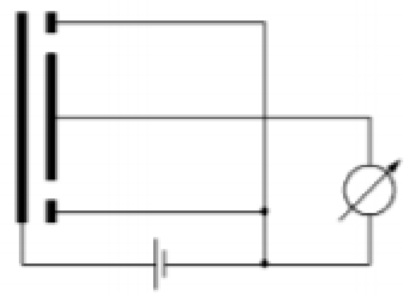


Figure 3-6: Ionization Chamber
[Radiation, 2015]

The ionization chamber is designed in order to measure absolute dose of low-energy photon beams for superficial radiation therapy and solid state phantoms. It has its reference point at the center of the entrance coil,and a thin entrance foil, see Table **3-3** and it can measure quantities for absorbed dose to water.(Fig. **3-7**)

Figure 3-7: Ionization Chamber 0,005cm^3 Soft X-Ray Chamber Type 23344

Table 3-3: Ionization Chamber materials and measures

Entrance foil	0.03 mm PE
Total window area density	2,76mg/cm^2
Sensitive volume	radius 0.85 mm depth 0.9 mm

3.2.5. Slabs

For the measurement there is needed to use a solid water equivalent phantom and slabs of PMMA Fig.**3-8** with dimensions of 13x13 cm^2 as height and width, meanwhile according to the needing of the measurement setup the high of the slabs will vary. (change for proper) Water-equivalency of a material is given if the 3 physical quantities of 3 physical quantities "linear collision stopping power $Scol$, linear radiative stopping power $Srad$ and linear scattering power T". [Borcia and Mihailescu, 2008] Are in agreement that these quantities influence energy and angular distributions of electrons inside of the phantoms, moreover it will affect the depth dose distribution. According to the IAEA international code of practice TRS-398 besides water, plastics in slab form can be used for dosimetric evaluation for low energy electron beam. These materials can be:

- Solid water
- Plastic water
- Virtual water
- Polymethyl methacrylate (PMMA)
- Polystyrene
- Solid water RMI-457
- Solid water WTI[IAEA International Atomic Energy Agency, 2000]

Figure 3-8: Plates of PPMA

3.2.6. MATLAB

"MATLAB® is a programming platform designed specifically for engineers and scientists. The heart of MATLAB is a matrix-based language allowing the most natural expression of computational mathematics"[mathworks Inc,].
In order to obtain the calibration curve and the further depth dose curves it is necessary to develop a program in MATLAB. This code will be able to perform a general evaluation of dose intervals related to the values of pixels covered by the ionization chamber in the film. Fig. **3-9**

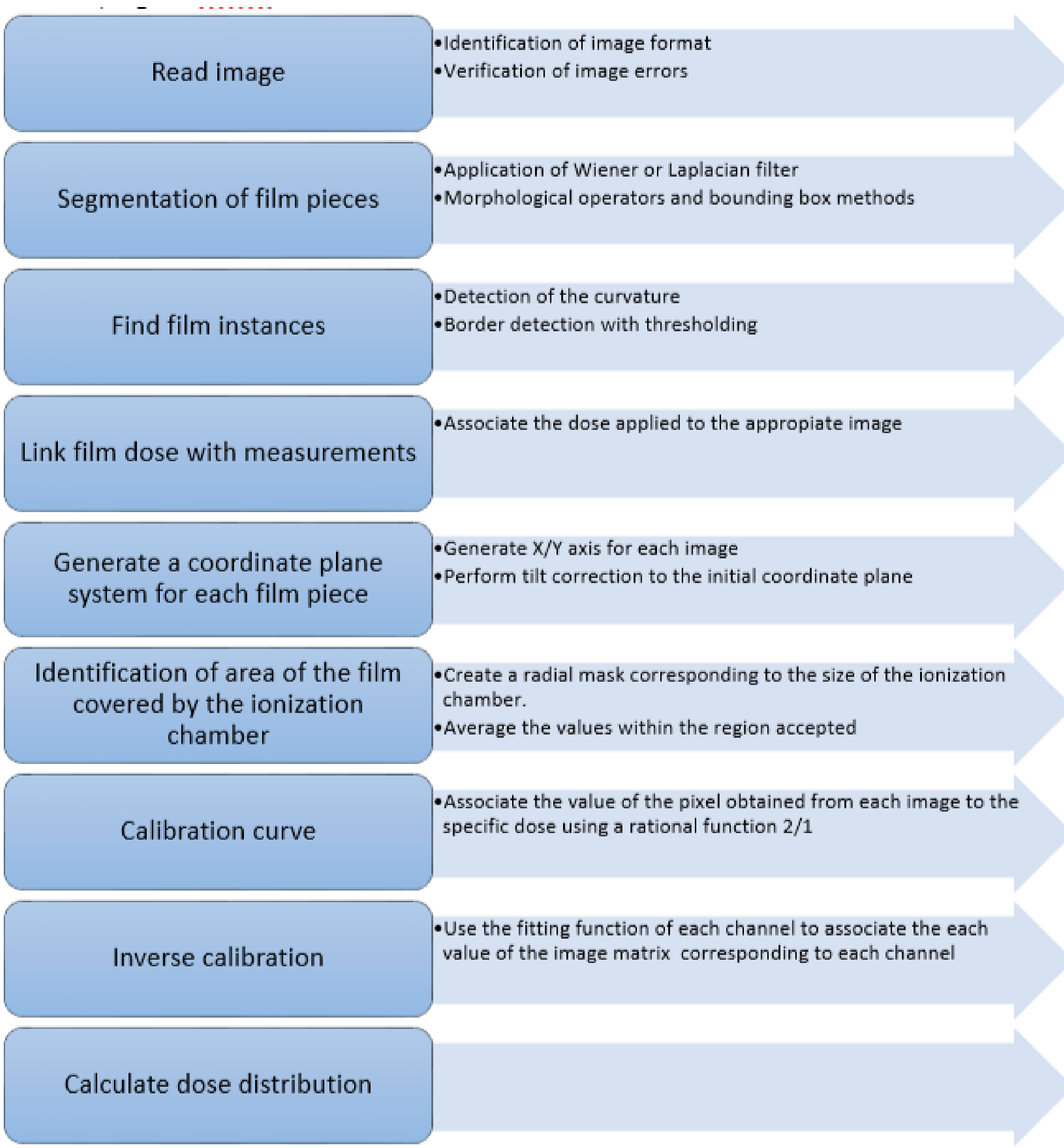


Figure 3-9: MATLAB code structure

3.2.7. FREECAD

"FreeCAD is a 3D CAD/CAE parametric modeling application. It is primarily made for mechanical design purposes, but also serves all other uses where you need to model 3D objects with precision and control over modeling history."[FreeCAD,] All setup pieces used in the course of this project where developed using the workflow described below:

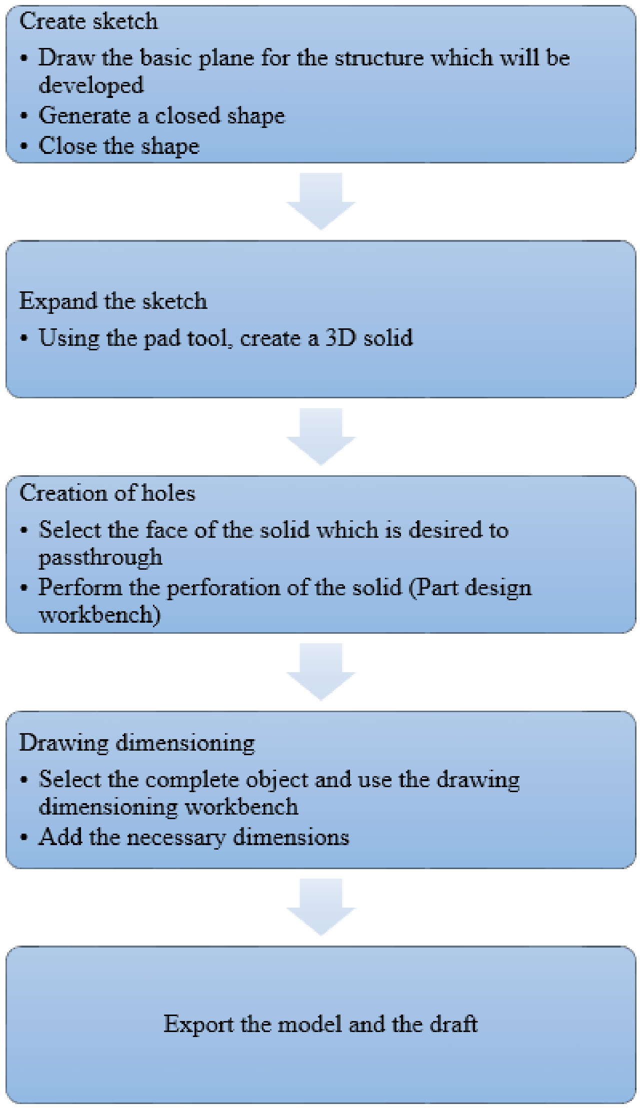


Figure 3-10: Steps for FREECAD modeling of setup pieces

3.2.8. 3D printer

The 3D printer will allow to print the measurement setups parts using a PLA filament with a diameter of 1.75 mm using a PRUSA extruder.[Prusa Research s.r.o., 2019]
For this case the nozzle temperature is set to 215°C and the heat bed to 65°C. PLA material is useful for quick prototyping because of its physical strength, biodegradability and the easiness to print with it. In order to print wide pieces, the printer (Fig. **3-11**) must be set up to begin the process at the origin with a distance from the nozzle to the heat bed of 1.5mm, and displace the nozzle in the z axis 1 cm in order to have a more uniform temperature in the whole model while printing.
With the help of Repetier[Repetier, 2015] host software the STL file exported from FREECAD

can be positioned on a simulated print bed and be transformed into a printable tool path for the 3D-printer. In order to obtain a model without whipping and correct adhesion it is necessary to print with a skirt of 1.5 cm and before each printing it is necessary to clean with alcohol the heated bed, let it dry and after all cover it with hair spray to increase adhesion during the printing process.

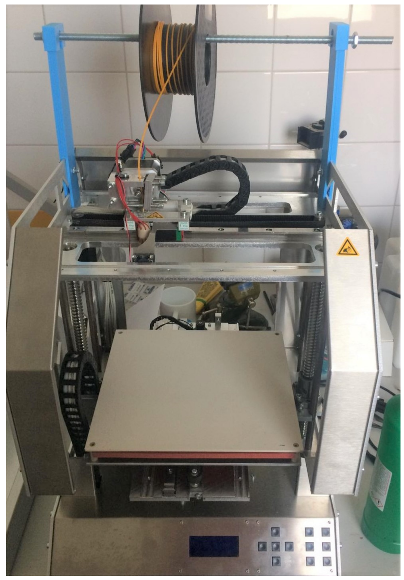


Figure 3-11: 3D Printer

3.3. Measurements obtaining

3.3.1. Radiation Protection

In order to perform the measurements, as the radiation source is only a low energy source, it was sufficient to use lead shielding of a few mm in combination with great distance to minimize exposure to virtually zero. The user must perform the measurements outside the room.

3.3.2. Equipment calibration

Radiochromic film handling

After opening the package which contains the films, they must be stored in a dark and with low humid place; taking into consideration that the EBT3 films have their active layer covered by both sides with clear polyester, films can be handled with clean, bare hands; Nevertheless for this procedure Latex gloves were used in order to avoid the process of cleaning the films. Films must be held by the edges and whenever fingerprints or smudges cover them, they shall be cleaned with an alcohol swab. In order to cut the films according to the desired measurement it is necessary to mark the position at the edges where they must be cut. Without blending the films, the cutting process can be performed with the use of a guillotine, used to cut the films in a size of $130x130mm^2$ Fig. **3-12** or a photo cutter to cut the films in a shape of $35x45mm^2$ Fig. **3-13**.

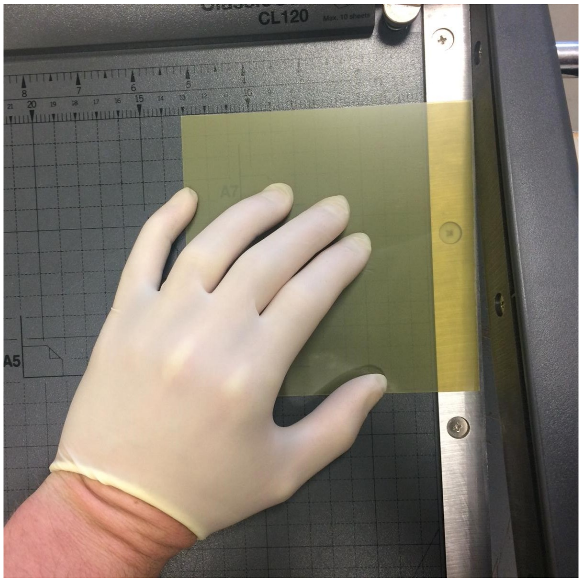


Figure 3-12: Cutting images with the guillotine

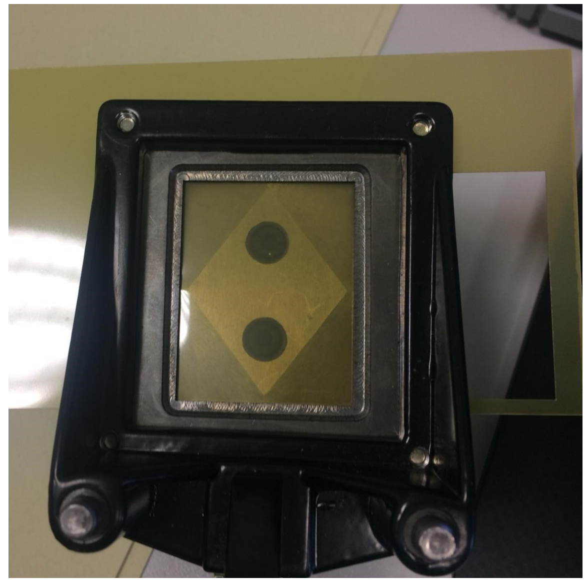


Figure 3-13: Cutting images with the photo cutter

Quality Assurance (QA)

The Womed ioRT50 equipment does not require to perform a daily Quality assurance procedure as other equipments were it is required to initialize the whole procedure:

- Çongruence of radiation and optical fields
- Central beam alignment
- Effective Focal spot size measurement
- Timer Accuracy
- Accuracy of Accelerating Tube Potential
- Linearity of radiation output
- Reproducibility of radiation output
- Total filtration
- Radiation leakage through tube housing
- Exposure rate at tabletop
- Fluoroscopic image quality parameters" [Radiological and Energy,]

Measurements were performed using a freshly calibrated device, which had a valid QA.

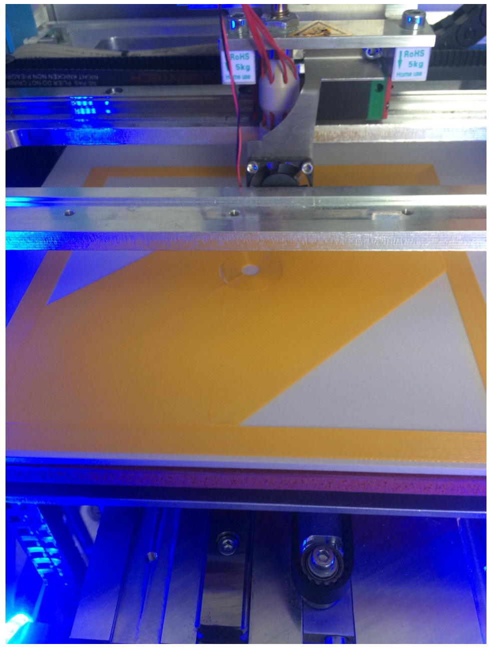


Figure 3-14: 3D Printing process

3.3.3. Setups

Printing

Initially, the process started by cleaning the heating bed and nozzle at every attempt of printing and also configuring the position of the nozzle, which will need to have a distance of about 0.32 mm from the heating bed; temperatures were setup and the imported Gcode which is used for numerical control (It coordinates the position of the extruder, high of the heating bed and the temperature regulation) of the model in order to start printing the model. All of the pieces needed to be printed with a brim and the some of them with a supporting structure, the first one in order to improve the adhesion of the first layer and the second one was used because one of the structures did not have a flat face in which the whole structure could be supported. When the printing process starts it is necessary to verify that the extruded material is flowing correctly, when finishing, the model can be removed from the heating bed with the help of a spatula. Fig. **3-14**

Half value depth and half value thickness Determination

Aluminum is the material most commonly used to determine the HVL of low energy X-ray beams [IAEA International Atomic Energy Agency, 2000], considering the absorption of low energy X rays in air the HVL varies according to the distance from the target; This is the reason why this HVL should be measured as far as possible, with the chamber at the source-chamber distance (SCD) that will be used equally to obtain the measurements of absorbed dose; taking into consideration that this distance will be lower than 50 cm some scatter can affect the expected results, nevertheless, back-scatter factors may be applied in order to reduce the undesired abnormalities.

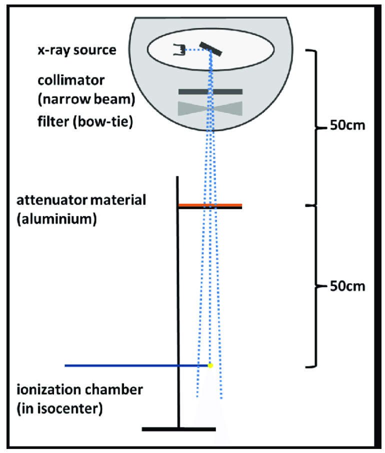
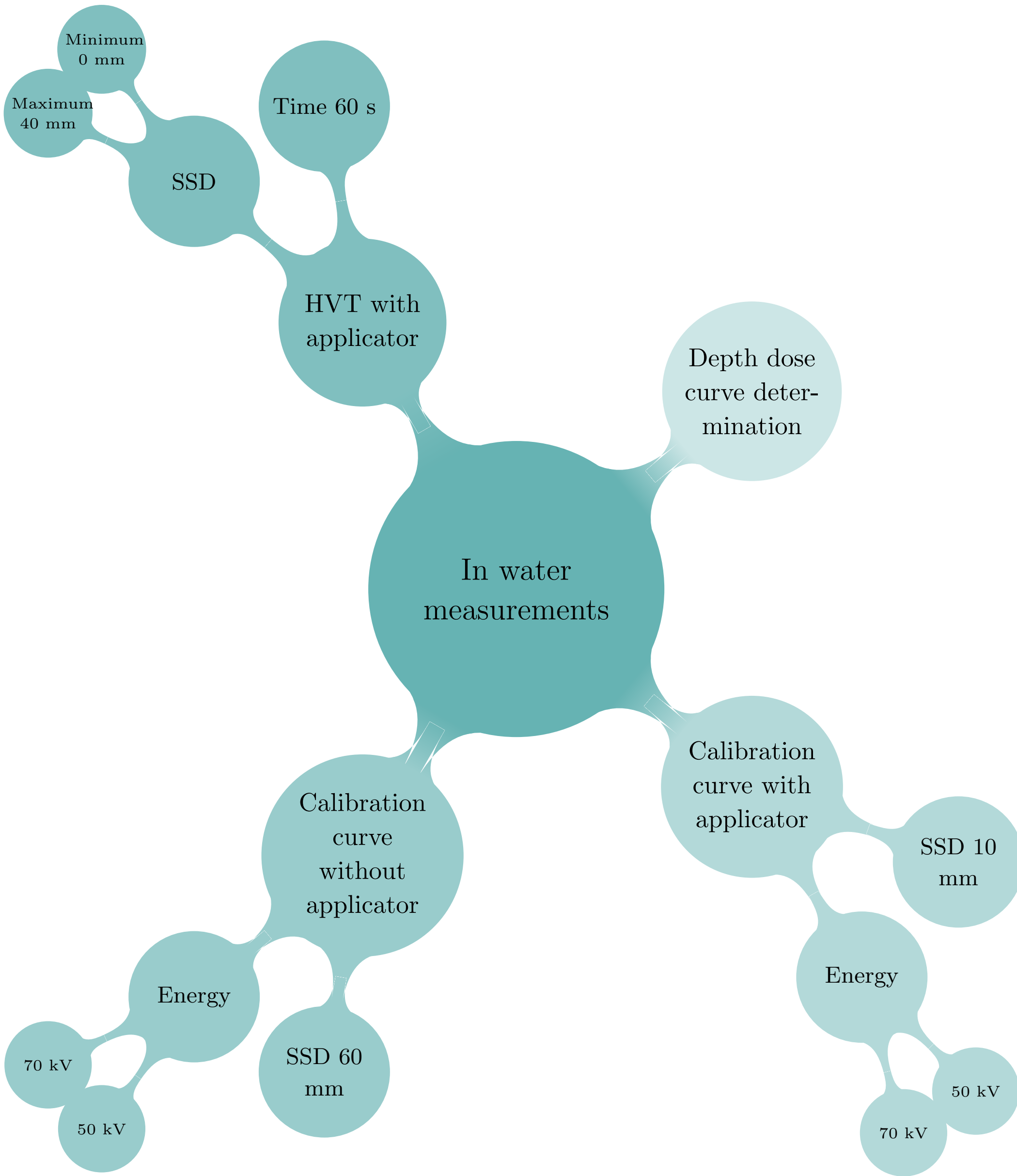


Figure 3-15: HVL measuring setup

By half of the distance between the X-ray target and the chamber, a collimating aperture that allows the pass of the beam just through the chamber is located, filters are placed close to the aperture in order to perform the attenuation; making use of an interpolation method it is possible to obtain the thickness that reduces the air KERMA rate by half. Fig. **3-15** It is important to take into consideration the fact that the ionization current or integrated charge per exposure time is the real parameter measured. [Hill et al., 2014]
According to the international Electrotechnical Commision (IEC) the half value depth is "the depth in tissue at which the absorbed dose is 50 per cent of the surface dose, for specified radiation quality, source-surface distance, and exposed surface area"[Commision, 1981] For this protocol it is relevant to identify by making the behavior of the beam within the tissues or in air, that is the reason why half value depth (HVD) and half value thickness (HVT) [Radiological and Energy,] (The thickness of the water equivalent material in this case) respectively are measured instead of HVL. Both measurements are needed to be taken for the use of a surface applicator.

3.3.4. In air measurements

In water measurements



3.3.5. Measurements Procedure

- Familiarize with the equipment Womed ioRT50
    - Connect the ionization chamber to the dosimeter
    - Turn on the Womed ioRT50 device and set it up to radiation mode
    - Turn on the dosimeter
    - Measure the temperature and atmospheric's pressure (this step should be repeated regularly)
    - Perform a zeroing of the ionization chamber to correct for background radiation

- With the bare source and with the applicator Observe the behaviour of the beam in air and water by performing a depth dose curve which is the curve that relates the absorbed dose that is deposited by radiation beam into a medium while the depth is changed along one axis. Fig. **3-16**

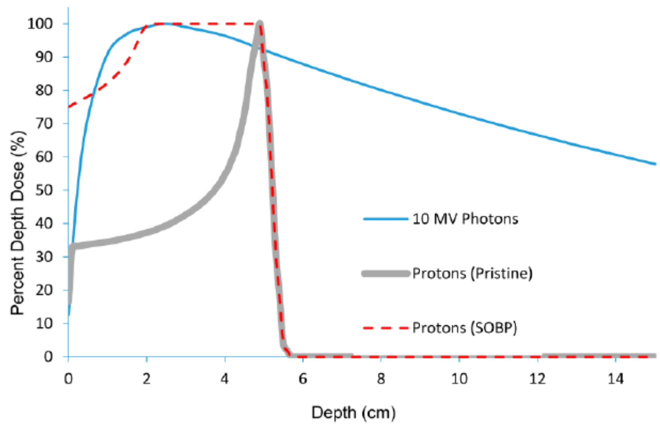


Figure 3-16: Percentage depth dose curves, changing the type of source

- Organize the setups
  Measurements were taken within 2 media, in air and in water with the following settings.
  - In air measurements
    - Half Value Depth.
      As seen Fig.**3-17**, The tip of the source is placed in the cylindrical hole of 3D printed structure, meanwhile the the ionization chamber and the slabs (used for varying the distance between the source and the chamber) are placed within the structure.
    - Calibration curve with out the applicator
      The setup corresponds equally to the one performed to obtain the HVD measurements, the difference lies in the distance between the source and the chamber, which does not change. With the information obtained from the depth dose curve calculate the dose rate and irradiate the film during the appropriate time needed.
      When the beam passes through the Gafchromic film it affects the value of the dose detected by the ionization chamber, that is the reason why the measurements should be repeated twice; one of them just with the ionization chamber Fig. **3-17** and the other one just with the films Fig. **3-18**
    - Calibration curve with the applicator.
      Place the source inside the applicator (which is a device created in order to distribute the dose uniformly in a flat area within a reduced field of iradiaion) and position it from a determined distance over the chamber. For the optimal performance of the data obtainment it is necessary to set up the montage firstly, only using the Gafchromic film and afterwards the ionization chamber.

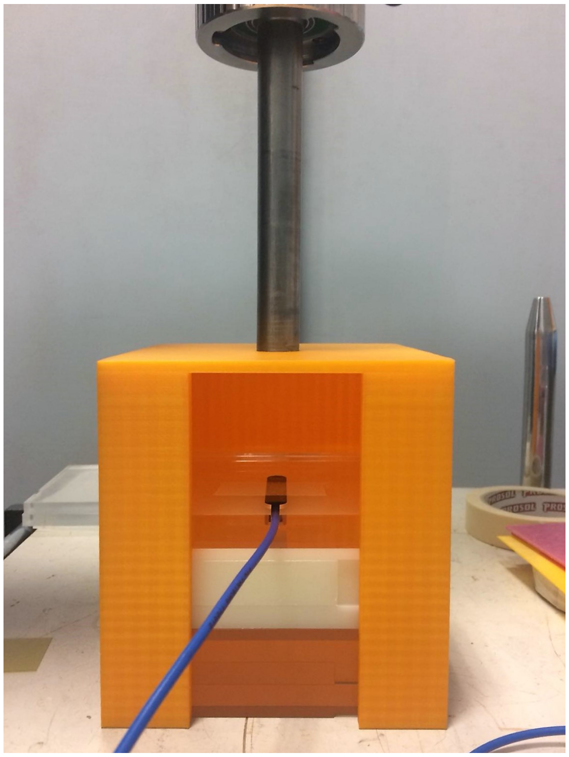


Figure 3-17: Measurements setup in air with the ionization chamber

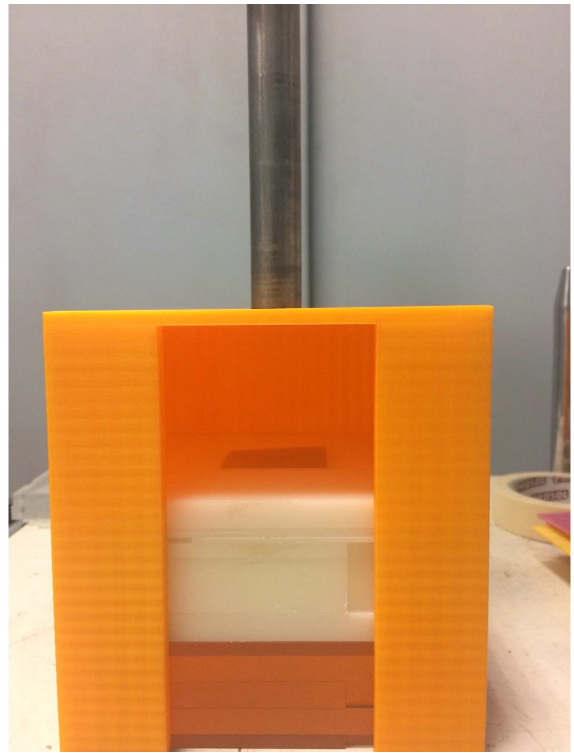


Figure 3-18: Measurements setup in air with the Gafchromic films

- In water measurements
  - Half Value Thickness and calibration curve in air setup.
    As seen Fig.**3-20**, The applicator is placed over the center of the slabs, meanwhile the ionization chamber is placed below them.

    The process will have to be repeated until the value detected is identified by the half, however it is optimal to perform further measurements after.
  - Calibration curve with out the applicator
    Fill the 3D printed holder with the slabs, leaving an space to place the film or the ionization chamber, afterwards add water equivalent material slabs to cover it and place the setup inside the 3D printed holder. Fig. **3-19** On the cylindrical hole of the holder place the tip of the source

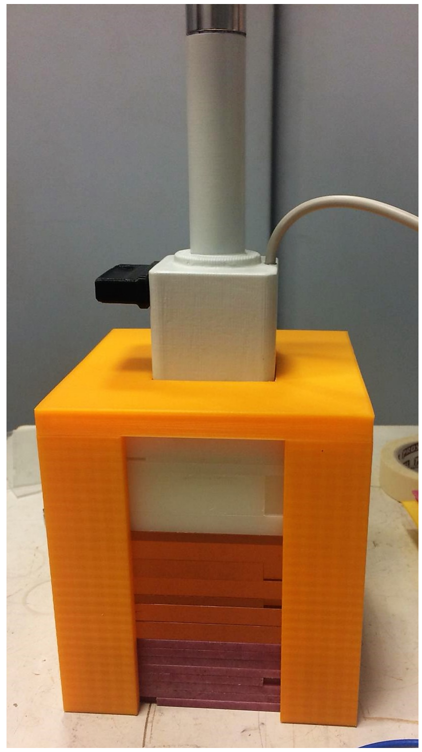


Figure 3-19: Direct measurement montage for in water setup using and applicator

- Calibration curve with the applicator
  Place the slabs, over them place the ionization chamber or the film and finally feel the gap between the source with the film Fig. **3-21** or chamber Fig. **3-20**with water equivalent material slabs with the corresponding distance selected.

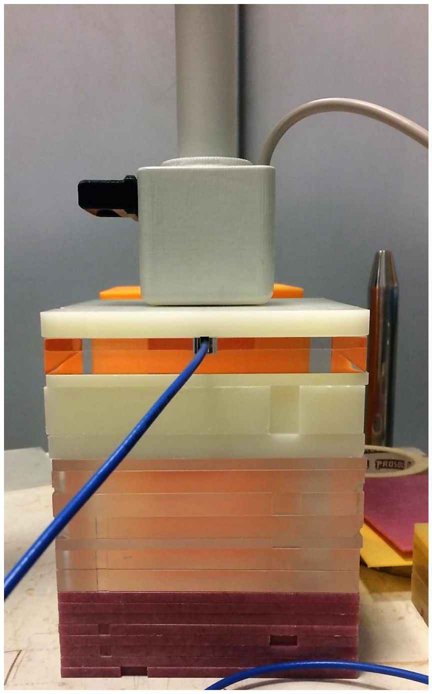


Figure 3-20: Measurements in water with the ionization chamber using the applicator

Figure 3-21: Measurements in water with Gafchromic films using the applicator

- Take the measurements
  The range of doses which will be applied to the films during the whole procedure is from 0 Gy to 10 Gy, using a source voltage of 50 kV or 70 kV, there must be taken as minimum 4 in order to obtain a proper fitting function. In order to carry out the measurement process, it is necessary to follow the next steps:
  - after selecting the parameters desired of the equipment.
  - Setup the corresponding montage.
  - Initiate the procedure and get out of the room where is it performed.
  - Register the results
- Scanning process
  - Clean the scanner with it corresponding tissue
  - Turn on the scanner
  - Allow for the light array to heat up for 10 to 15 minutes
  - Place the films as centered as possible in the scanning bed, from 0 Gy value to 10 Gy value from left to right. Try to leave an space between each film. Take into consideration that the scanning process will be performed in vertical orientation.

- In the settings of the scanner deactivate any image correction filter and perform the previously mentioned setups.
- Take out the paper references and scan the image; when exporting it make sure the format of it is .TIFF or .bmp. Fig. **3-22**

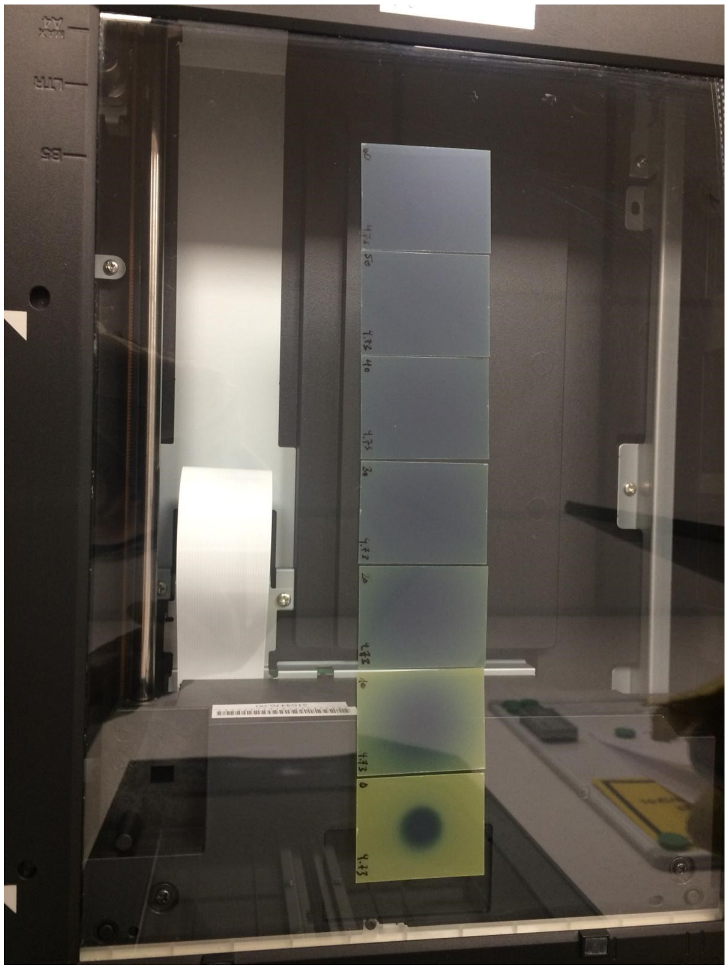


Figure 3-22: Film placement in the scanner

4 Results

The project was divided in different sections in order ti perform a correct dosimetric evaluation:

4.1. Phantoms designing and 3D printing

. The evaluation procedure measurements were performed with a direct measurement setup, using the applicator or the bare source.

4.1.1. Direct setup without applicator

For this type of montage to figures with the same design but different heights were designed. For measurements without a large distance between the source and the chamber required the height corresponded to 70 mm with the bare source Fig. **4-1** Fig. **4-2**, on the other hand, measurements which needed a large gap were performed in the setup with the height of 150 mm. Fig. **4-3** Fig. **4-4**.

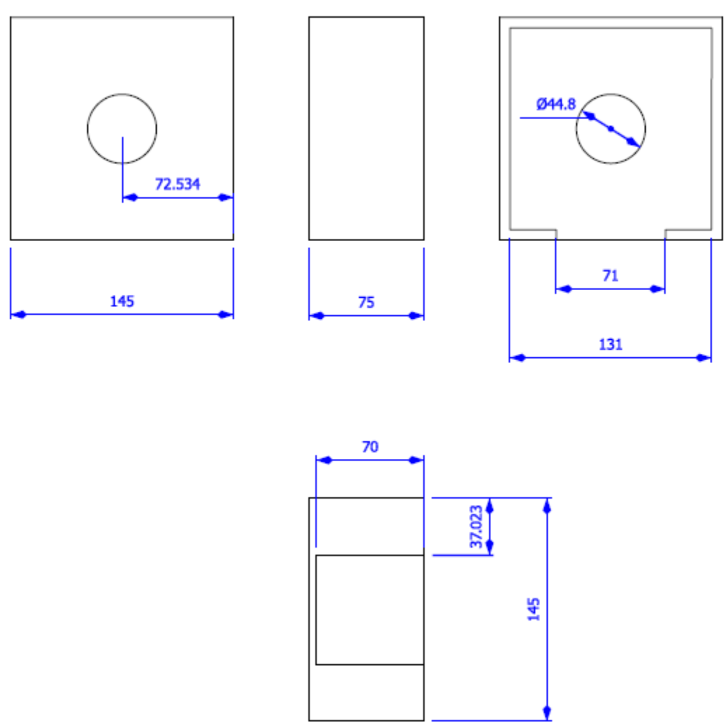


Figure 4-1: Direct measurement setup plane without applicator with 70 mm height

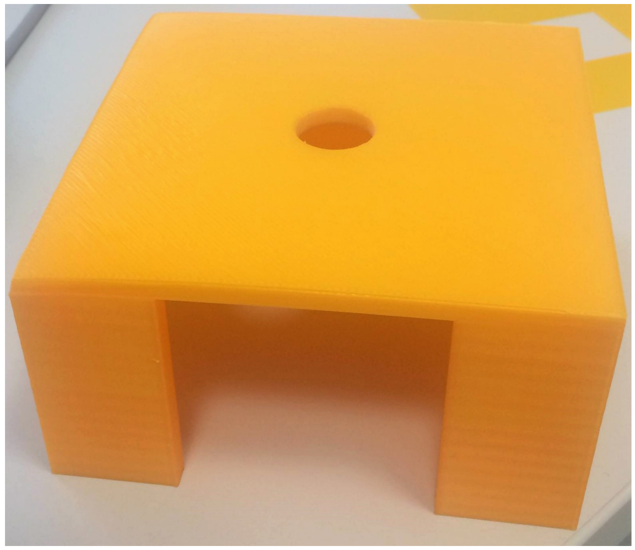


Figure 4-2: Phantom of direct measurement without applicator setup 70 mm height

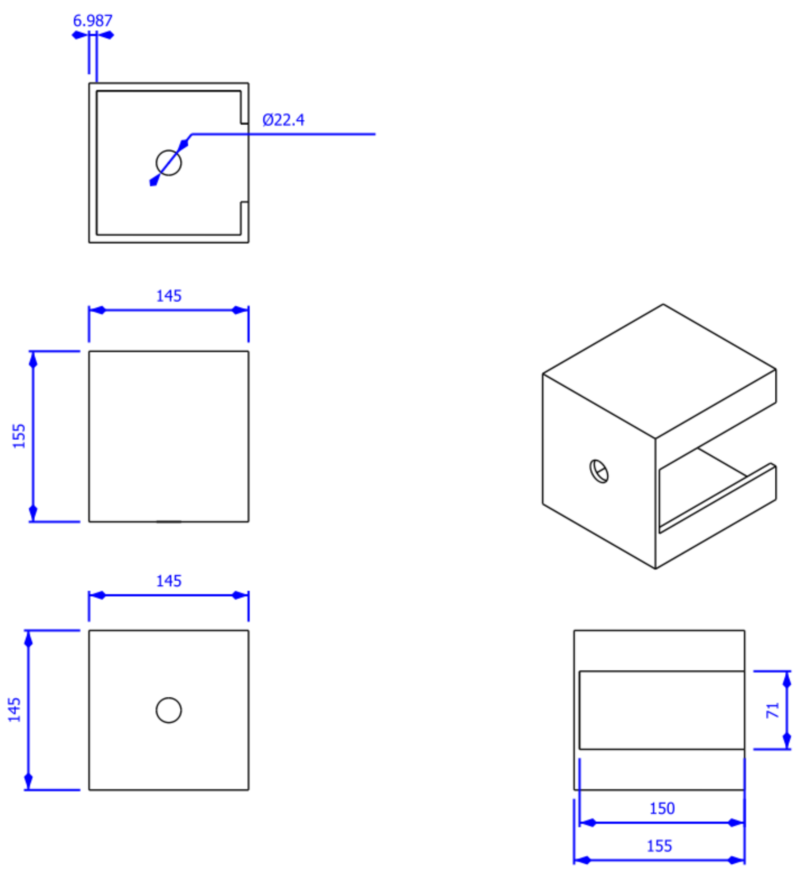


Figure 4-3: Direct measurement setup plane without applicator with 150 mm height

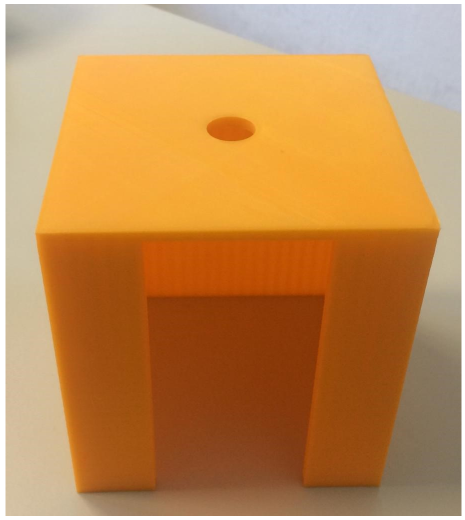


Figure 4-4: Phantom of direct measurement without applicator setup 150 mm height

4.1.2. Direct setup with applicator

Measurements with the applicator only used a phantom with 150 mm height Fig. **4-6** Fig. **4-5**. Nevertheless, due not uniformities presented in the top on the phantom and scattering effects with the applicator the result was inaccurate measurement. This is the reason why the piece was not used during the procedure and the setup was performed manually as showed before.

Figure 4-5: Direct setup with applicator

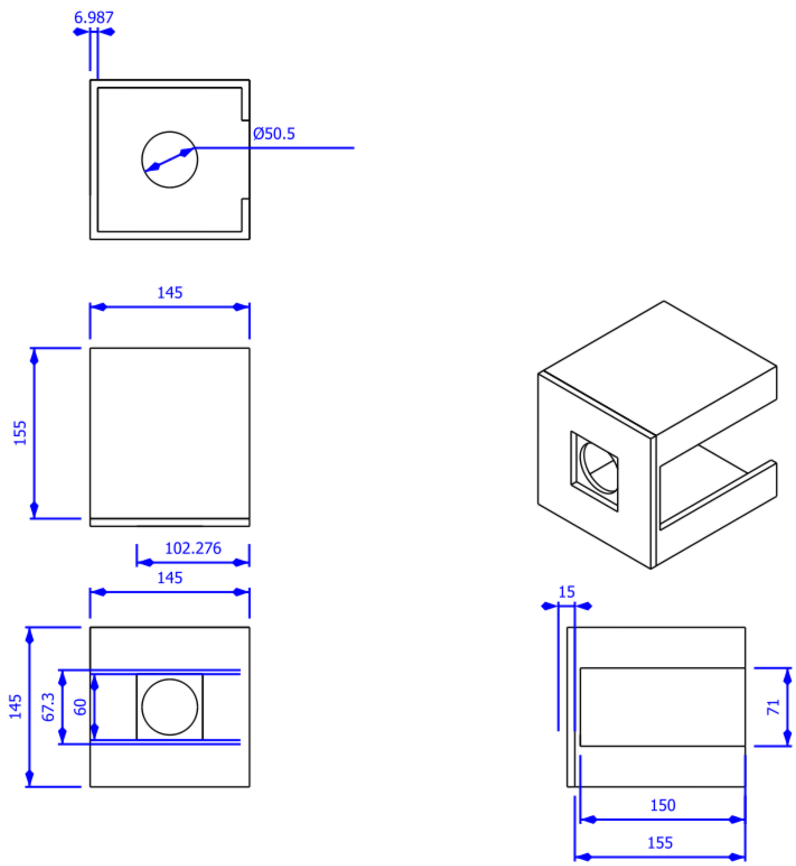


Figure 4-6: Phantom of direct measurement without applicator setup 150 mm height

A guide to place the film in the center of the slabs was designed and 3D printed, however, at the moment of performing the montages the film was found too loose on within the guide, therefor it was decided that this would not be used for this procedure but for further evaluations, printing it with 45 x 35 mm and no extra gap as performed in here. Fig.**4-7** Fig. **4-8**

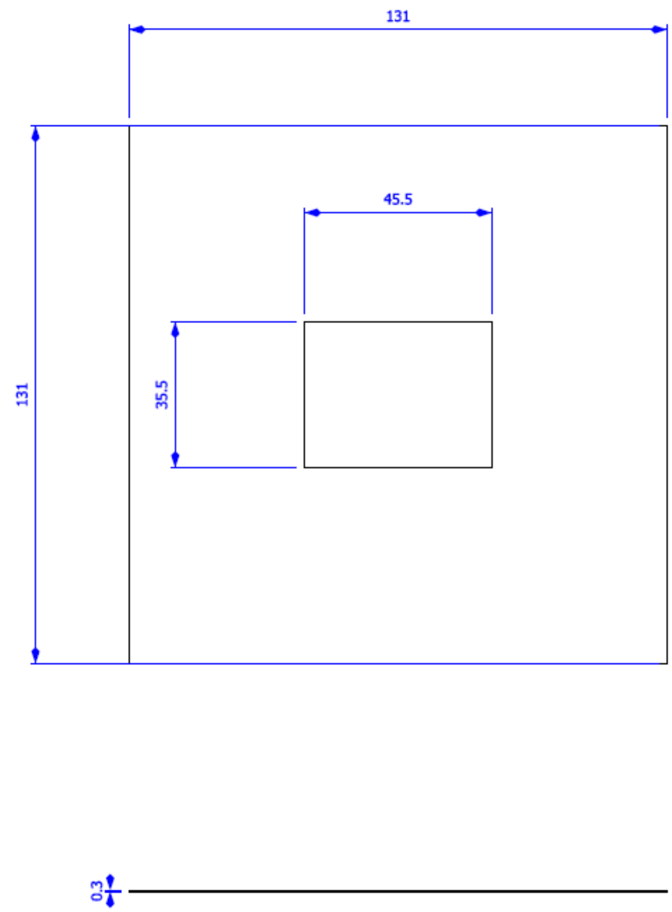


Figure 4-7: Plane for the guide to localize properly the film in the setups

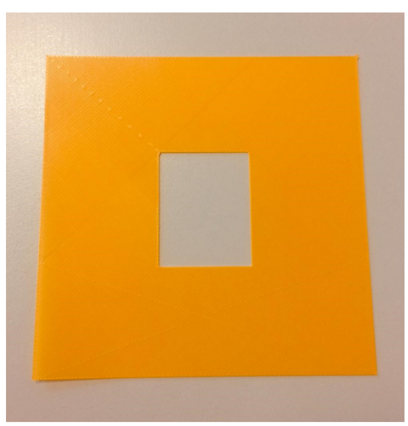


Figure 4-8: Film guide 3D printed

4.2. Depth Dose curve determination

A depth dose curve was determined for the bare source in air. Fig. **4-9** and with the applicator fig. **4-10**

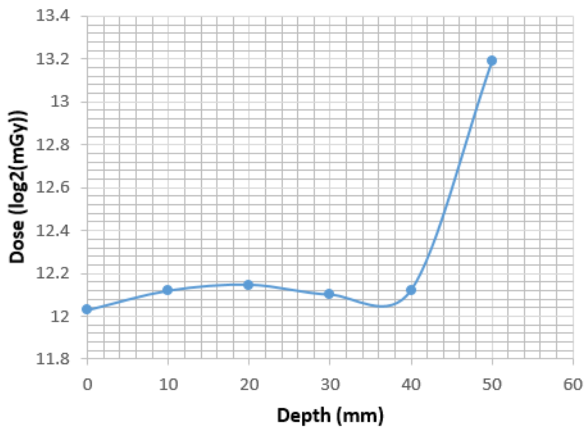


Figure 4-9: Depth Dose curve for direct in air with the bare source setup

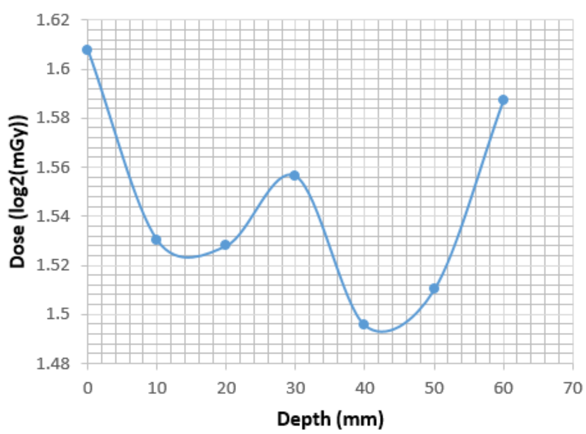


Figure 4-10: Depth Dose curve for direct measurement in air with the applicator

It is possible to observe that the applicator changes the behaviour of the beam. for both cases a dose rate (mGy/s) was calculated with an average value of 6.8(mGy/s) which assuming that the initially measured calibration curve was accurate, it was useful to predict the time values to radiate the films.

4.3. HVD and HVT determination

Using the printed phantom and as an attenuator material the air gap for 50 kV it was possible to determine the HVD Fig. **4-11**, the depth corresponded to 35 mm

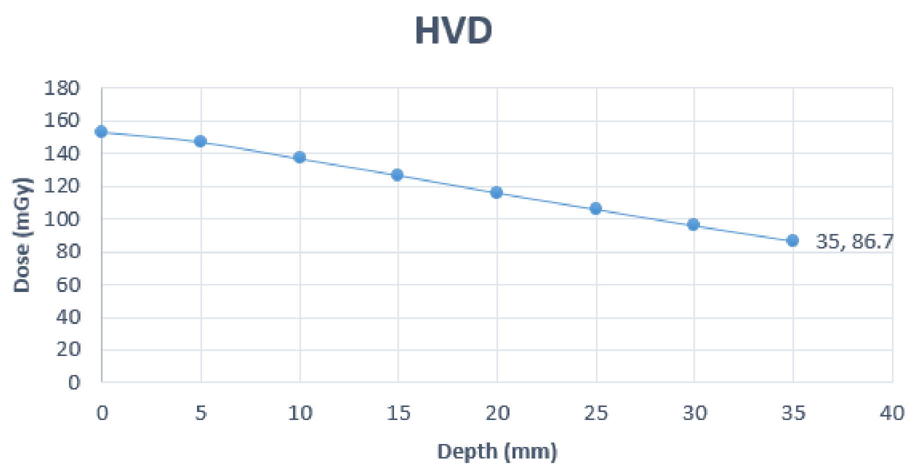


Figure 4-11: HVD for a 50 kV energy

HVT were not determined with the phantom, the attenuator material corresponded to the slabs. The procedure was performed for a 50 kV energy Fig. **4-12** and the depth value corresponded to 40 mm and for a 70 kV energy Fig. **4-13** the depth value corresponded to 50 mm.

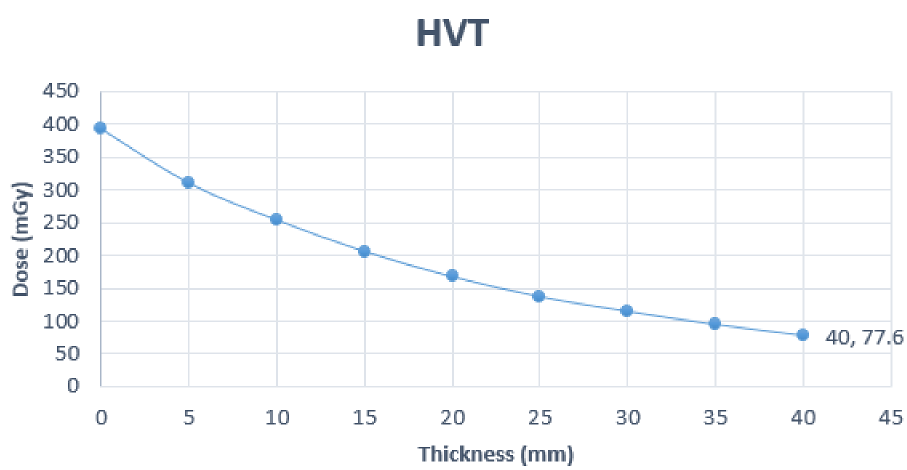


Figure 4-12: HVT for a 50 kV energy

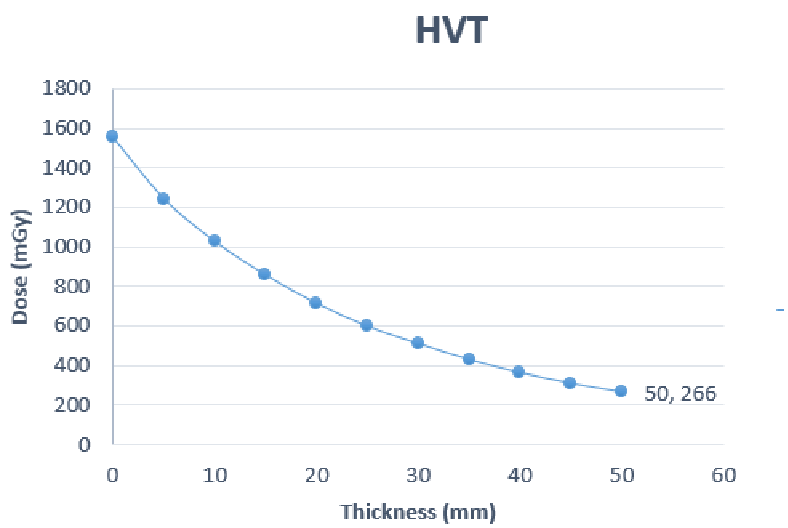


Figure 4-13: HVT for a 70 kV energy

4.4. Digitalization (case 1)

After performing the irradiation of the films and the ionization chamber, the resulting images were scanned and the numerical data stored, following the previous protocol.
As an example it is chosen the data-set from the measurements with applicator, 50 kV energy source and in water equivalent material with 10 mm depth. Fig. **4-14**

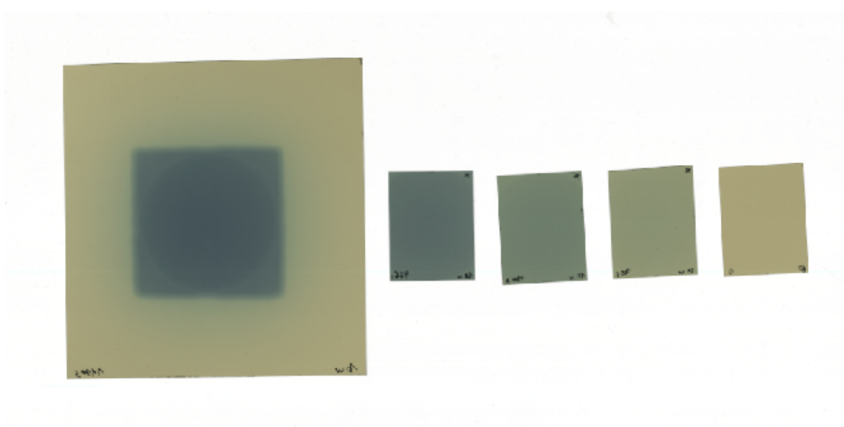


Figure 4-14: Original scanned images, using applicator, 50 kV energy source

4.5. Automatic dosimetric evaluation (case 1)

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4.5.1. Data collection and possible errors detection

In order to obtain reliable results it is important to verify that the data inserted by the user satisfies the standards previously measured.
The dose values detected by the ionization chamber for this image are the following Table.**4-1**:

Table 4-1: Dose Value per image (case 1)

Film	Dose value (Gy)
1	4.9821
2	1.9929
3	0.7954
4	0.2934
5	0

4.5.2. Identification of the number of films

Using Otsu and morphological operators a mask was generated to cut image in the different films, which were detected like black and white components (5) .

4.5.3. Individual cutting of the films

Each film was cut using a bounding box including 6 pixels extra from the background. Fig.**4-15**

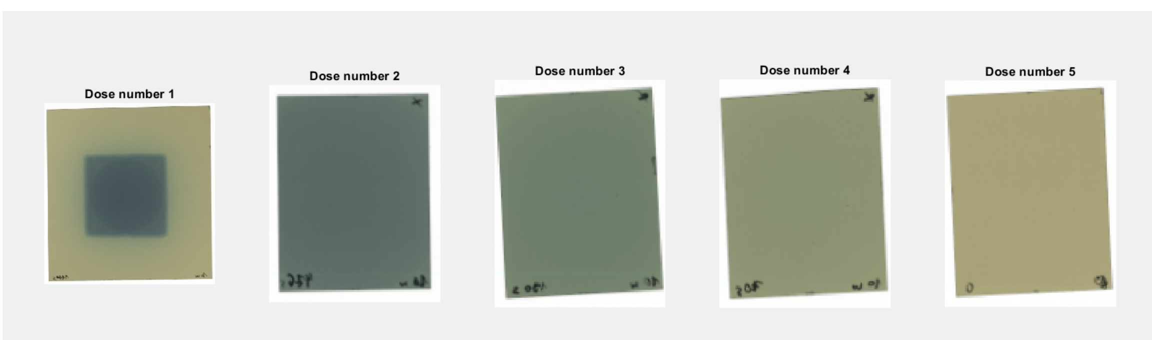

Figure 4-15: Individually cut films

4.5.4. Curvature detection

The contour of each film was generated; With a further application of a curvature detection the edges of each film were identified, as seen in the following images. Fig.**4-16** Fig.**4-17** Fig.**4-18** Fig.**4-19** Fig.**4-20**
As the images in the border did not present a uniform value of pixels due to foldings, scattering from the light of the scanner or marker marks various local maximums were detected additional from the 4 values of the edges (red dots marked and circle blue marks) or some of the were extreme atypical values, minimum, and maximal values were selected empirically to thresholdize.

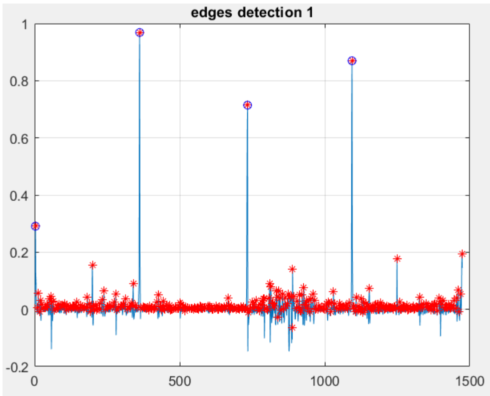

Figure 4-16: Curvature and edges detection for film 1

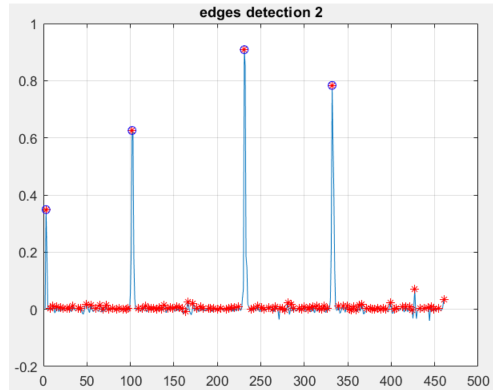

Figure 4-17: Curvature and edges detection for film 2

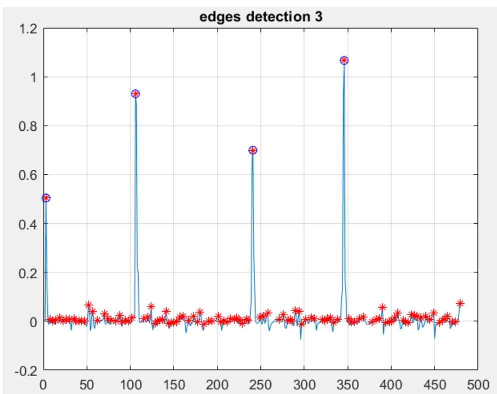

Figure 4-18: Curvature and edges detection for film 3

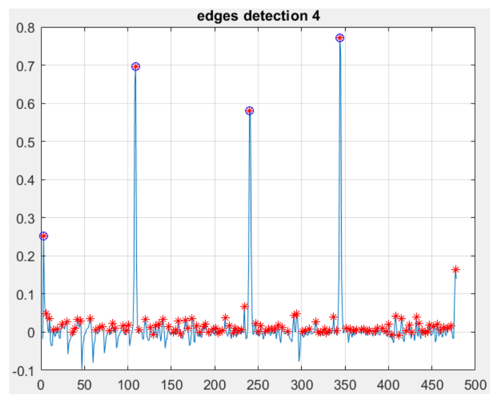

Figure 4-19: Curvature and edges detection for film 4

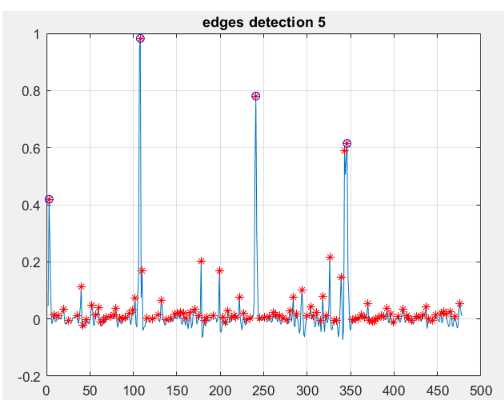

Figure 4-20: Curvature and edges detection for film 5

4.5.5. Coordinate plane generation

knowing the points corresponding to the corners of each image allow to generate the border vectors **4-21**.

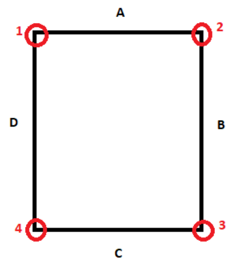

Figure 4-21: Structure of the external vectors and edges points per image

Later, with the mean points between each vector it was possible to trace the X and Y axis for images and the identified origin of the plane. Nevertheless, as the images were placed manually each film presented a tilt angle, with this angle, using a rotation matrix a new coordinate system could be calculated. Fig.**4-22** Fig.**4-23** Fig.**4-24** Fig.**4-25** Fig.**4-26**

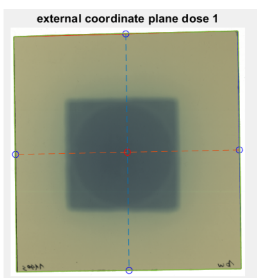

Figure 4-22: Coordinate system over the film 1

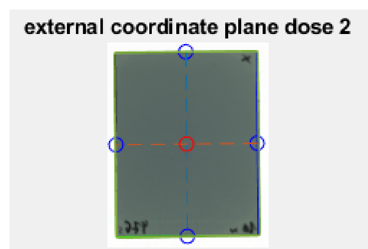

Figure 4-23: Coordinate system over the film 2

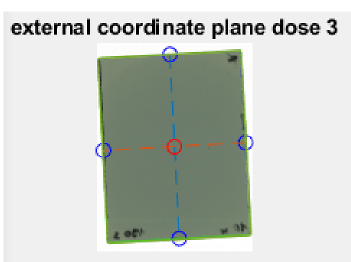

Figure 4-24: Coordinate system over the film 3

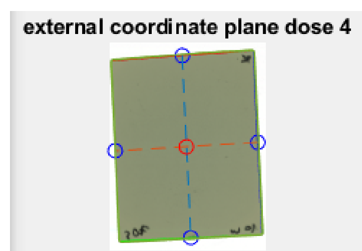

Figure 4-25: Coordinate system over the film 4

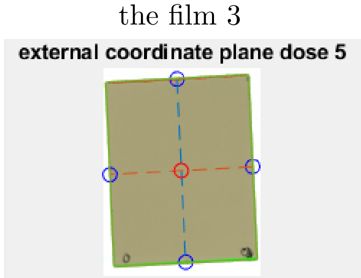

Figure 4-26: Coordinate system over the film 5

Generating a coordinate system for each film is only possible if the tilt is less than 45 degrees. The origin of the coordinate plane also corresponds to the center of a radial mask which radius corresponded to the radius of the ionization chamber.

4.5.6. Determination of the calibration curve

Each channel of color of the film was analyzed for further evaluation, the film number 1 was selected to show the variation between the values of the background and the center because, the size of the film was bigger than the other ones and it is possible to identify in a clear way the regions Fig. **4-30**, it is possible to observe the major variation in the channel blue between the background and the center of the chamber.

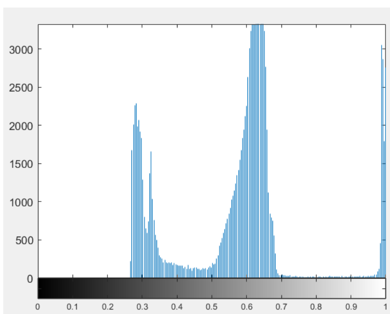

Figure 4-27: Histogram for film 1 in red channel

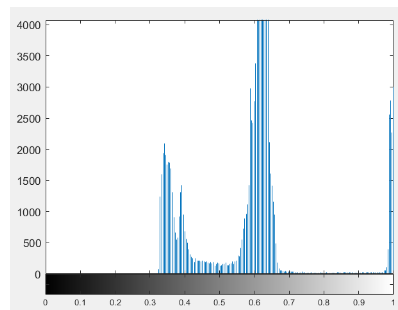

Figure 4-28: Histogram for film 1 in green channel

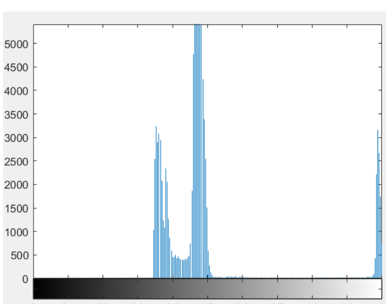

Figure 4-29: Histogram for film 1 in blue channel

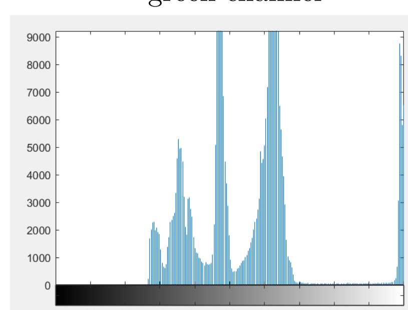

Figure 4-30: Coordinate system over the film 4

The average of the values of pixels was calculated within the unmasked region in each image for each channel. it is possible to observe that the major changes in the pixel density corresponds to the channels red and green Table.**4-2**

Table 4-2: Pixel density per channel per film

Film	Pd in red	Pd in green	Pd in blue
1	0.2708	0.3313	0.3471
2	0.3461	0.4074	0.3923
3	0.4277	0.4877	0.4221
4	0.5381	0.5721	0.4519
5	0.6610	0.6343	0.4719

The rational function was applied in order to obtain a fitting function which related the dose value provided by the user and the pixel density per channel. Obtaining as a result the following calibration curves Fig.**4-31**

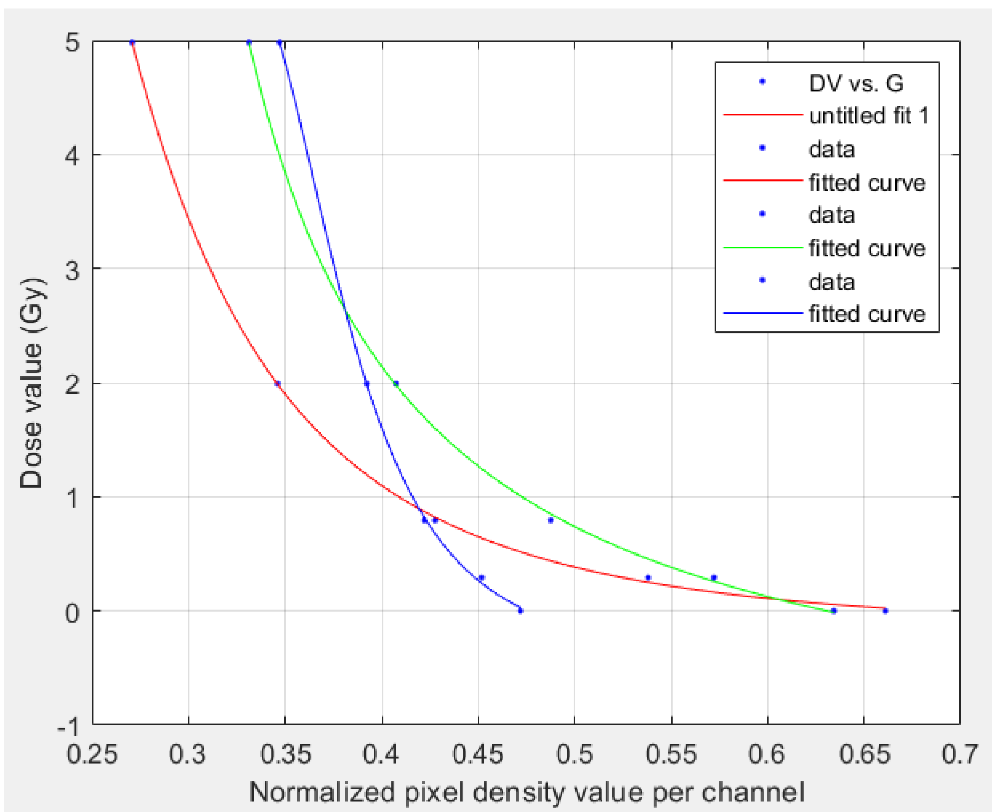

Figure 4-31: Calibration curves per channel

4.5.7. Dose calibration

For each image and color channel an dose calibration was performed. for the film number 1 which presented the highest dose it can be seen at the center of the image the highest dose Fig.**4-32** and at the superior border Fig.**4-33** a considerable diminution for channel red.

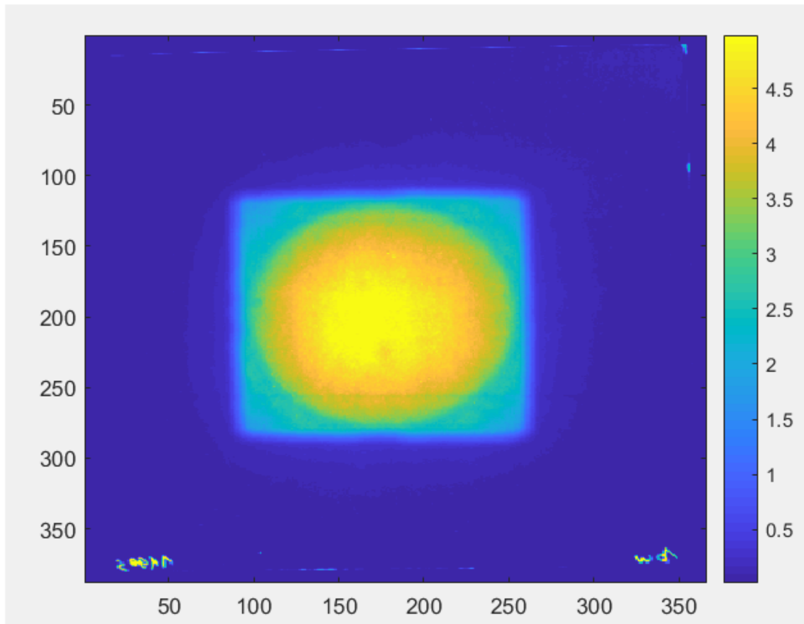

Figure 4-32: Dose calibration values for film 1

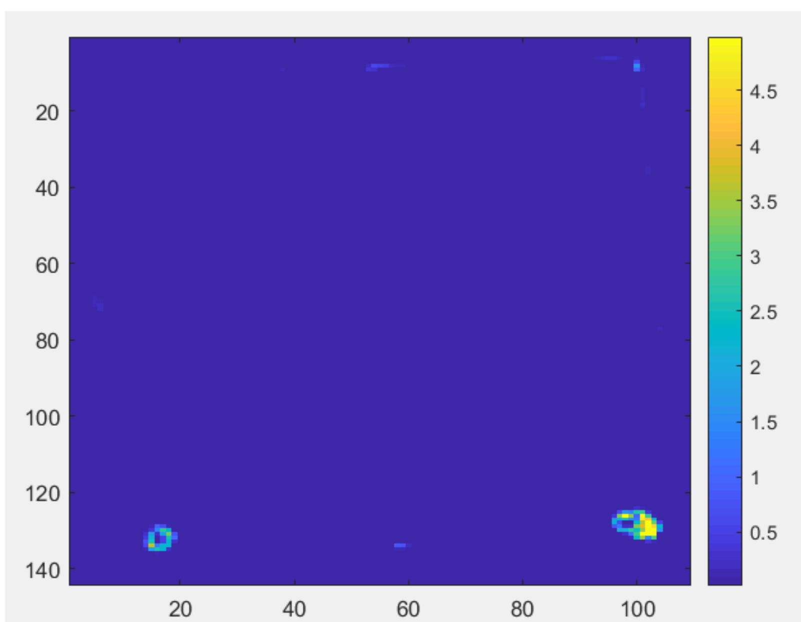

Figure 4-33: Dose calibration values for film 5l

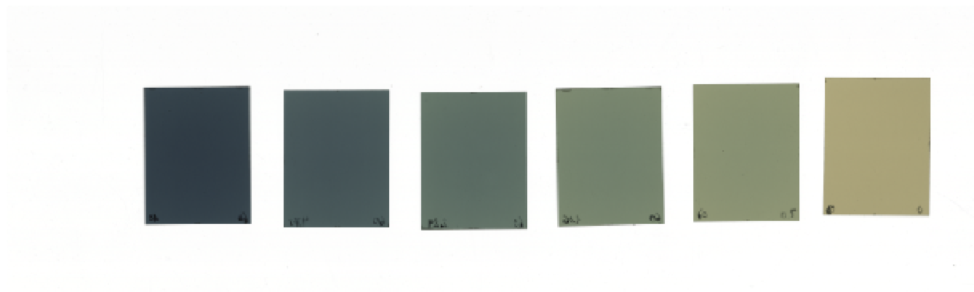

Figure 4-34: films radiated with an energy of 50 kV, using the applicator, in air with a 60 mm gap.

4.6. Digitalization (case 2)

The procedure was repeated successfully for the image obtained of the films radiated with an energy of 50 kV, using the applicator, in air with a 60 mm gap. Fig.**4-34**

4.7. Automatic dosimetric evaluation (case 2)

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4.7.1. Data collection and possible errors detection

The dose values detected by the ionization chamber for this image are the following Table. **4-3**:

Table 4-3: Dose Value per image

Film	Dose value (Gy)
1	9.34
2	4.27
3	2.092
4	0.9932
5	0.4667
6	0

4.7.2. Identification of the number of films

After the application of the Otsu and morphological operators mask was applied to the image, the program detected 6 films.

4.7.3. Individual cutting of the films

Each film was cut using a bounding box including 6 pixels extra from the background.

4.7.4. Curvature detection

The contour of each film was generated; With a further application of a curvature detection the edges of each film were identified, as seen in the following images. Fig.**4-35** Fig.**4-36** Fig.**4-37** Fig.**4-38** Fig.**4-39** Fig.**4-40**

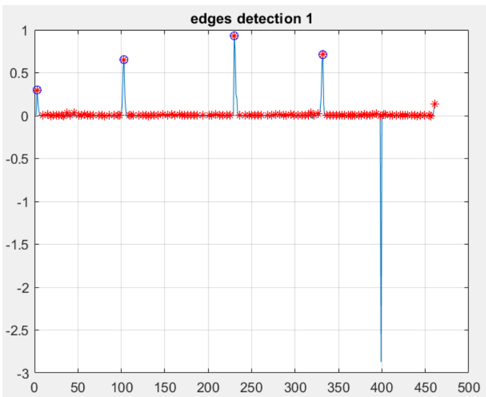

Figure 4-35: Curvature and edges detection for film 1 (case 2)

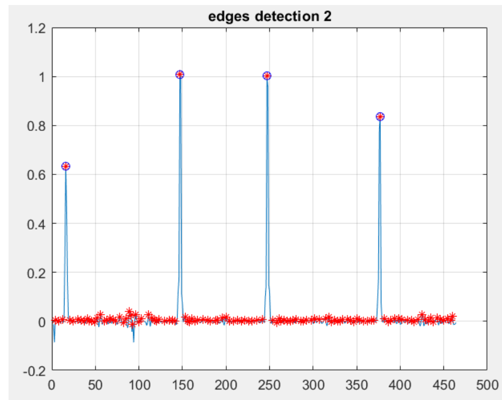

Figure 4-36: Curvature and edges detection for film 2 (case 2)

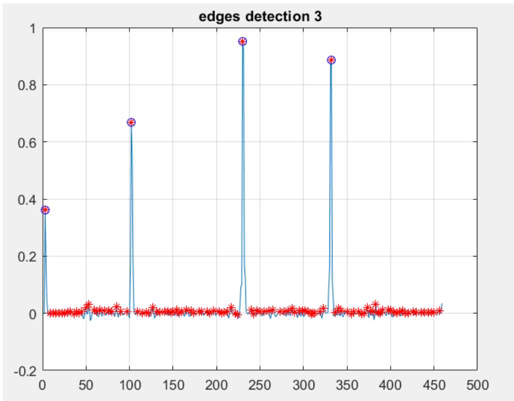

Figure 4-37: Curvature and edges detection for film 3 (case 2)

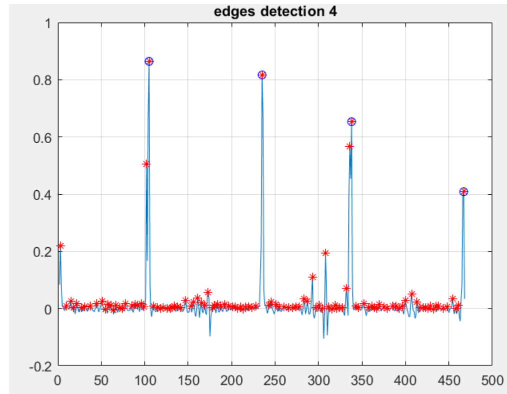

Figure 4-38: Curvature and edges detection for film 4 (case 2)

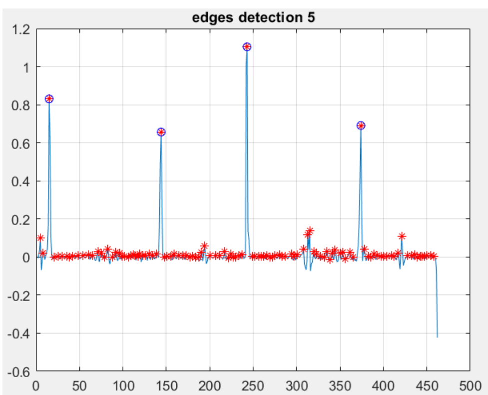

Figure 4-39: Curvature and edges detection for film 5 (case 2)

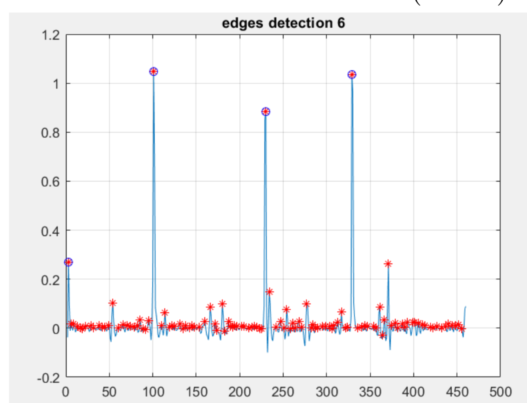

Figure 4-40: Curvature and edges detection for film 6 (case 2)

4.7.5. Coordinate plane generation

The external bounding vectors and the edges of each film were detected. With the mean points between each vector it was possible to trace the X and Y axis for images and the identified origin of the plane. Nevertheless, as the images were placed manually each film presented a tilt angle, with this angle, using a rotation matrix a new coordinate system could be calculated. Fig.**4-41** Fig.**4-42** Fig.**4-43** Fig.**4-44** Fig.**4-45** Fig.**4-46**

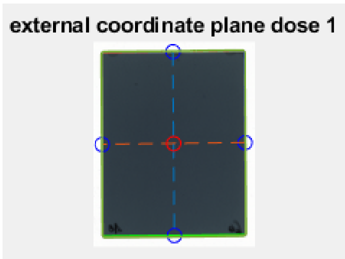

Figure 4-41: Coordinate system over the film 1 (case 2)

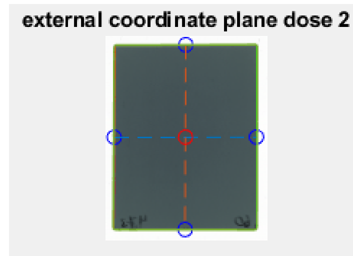

Figure 4-42: Coordinate system over the film 2 (case 2)

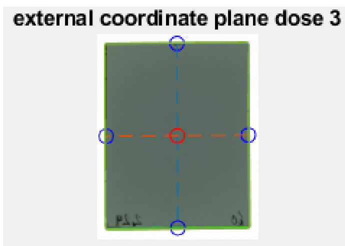

Figure 4-43: Coordinate system over the film 3 (case 2)

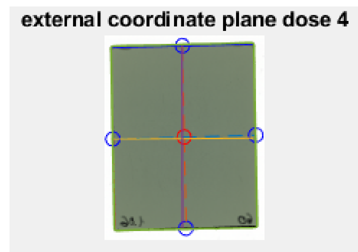

Figure 4-44: Coordinate system over the film 4 (case 2)

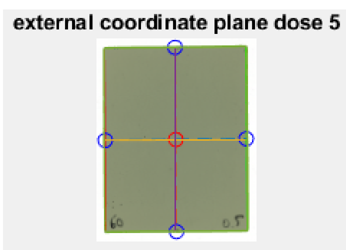

Figure 4-45: Coordinate system over the film 5 (case 2)

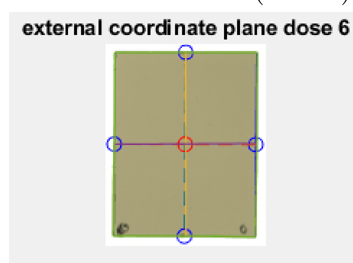

Figure 4-46: Coordinate system over the film 6 (case 2)

Generating a coordinate system for each film is only possible if the tilt is less than 45 degrees. The origin of the coordinate plane also corresponds to the center of a radial mask which radius corresponded to the radius of the ionization chamber.

4.7.6. Determination of the calibration curve

Each channel of color of the film was analyzed for further evaluation.
The average of the values of pixels was calculated within the unmasked region from the radial mask applied to the original image. In each image for each channel. it is possible to observe that the major changes in the pixel density also corresponds to the channels red and green Table.**4-4**

Table 4-4: Pixel density per channel per film (case 2)

Film	Pd in red	Pd in green	Pd in blue
1	0.1872	0.2327	0.2717
2	0.2680	0.3259	0.3410
3	0.3547	0.4191	0.3893
4	0.4486	0.5057	0.4261
5	0.5318	0.5667	0.4486
6	0.6686	0.6403	0.4756

The rational function was applied in order to obtain a fitting curve which related the dose value provided by the user and the pixel density per channel. Obtaining as a result the following calibration curves Fig.**4-47**

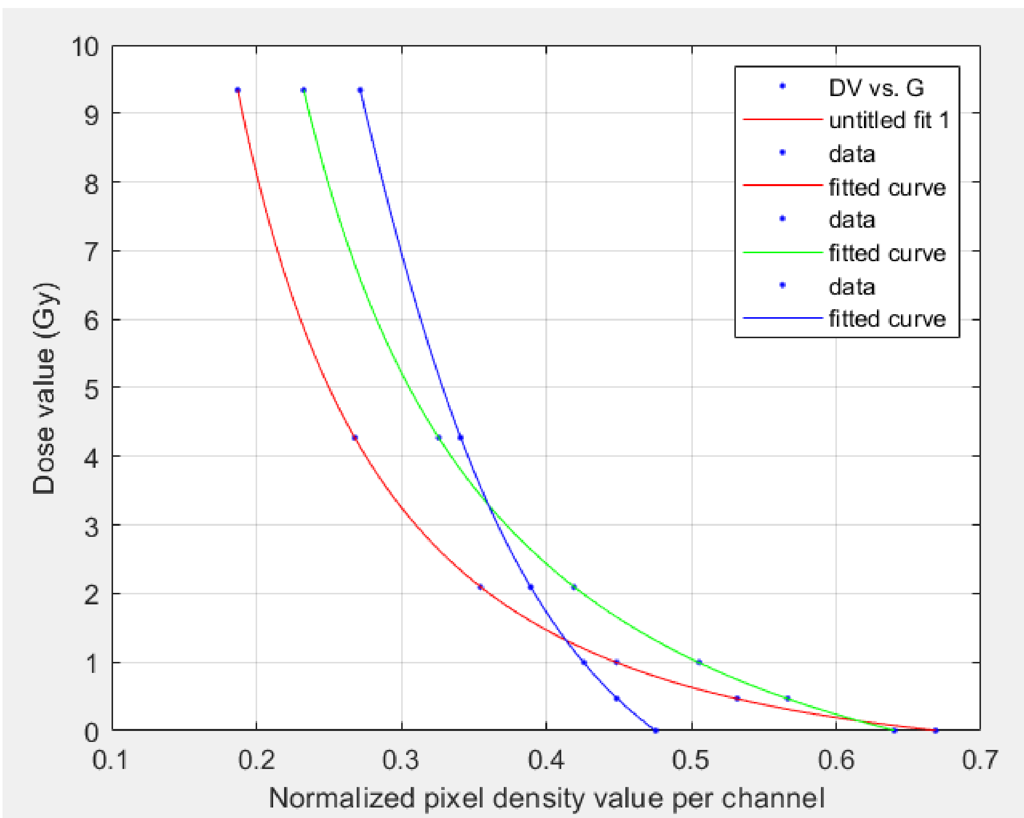

Figure 4-47: Calibration curves per channel (case 2)

4.7.7. Dose calibration

After the calibration curves were obtained, for each channel of color of the films a dose value was assigned. After that, the values of the channels were averaged and the dose values could be showed from the maximum **4-48** to the minimum **4-49**

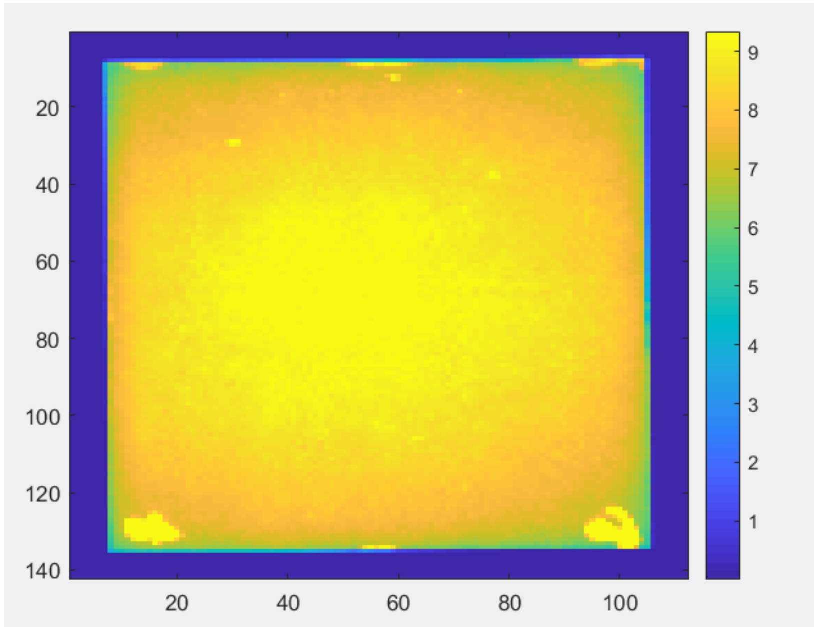

Figure 4-48: Dose calibration for film number 1

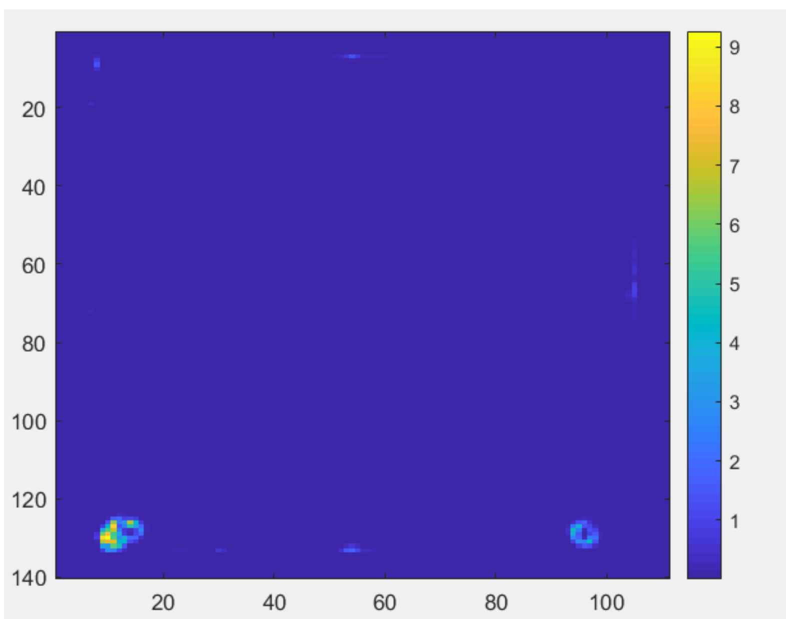

Figure 4-49: Dose calibration for film number 6

5 Discussion

5.1. Phantoms design and 3D printing

The phantoms were designed in order to fasten the procedure of setting up the montage for direct dose measuring using or not the applicator.
During the printing process several calibrations of the printed needed to be performed in order to avoid whipping and with it uncertainties generation due to the positioning of the source or the depth and thickness of the gap determined.
As the printing process was performed in 2 stages (one in spring and the other one in summer) temperatures of the nozzle needed to be adjusted during the second part in order for the PLA not to be burned.
The pieces were printed successfully and the quality was acceptable in most of them except with the piece corresponding to the direct dose measurement setup where, in order to print the structure supporting material was printed in the hole corresponding to the applicator and when this was removed the surface was uneven.
In the design process some of the dimensions in the film guide did not satisfy the requirements to fix to the proper position the film within the montage, so it was not possible to use it later. Nevertheless, the fitted guide will diminish the setup time for further evaluations (the new values for the hole of the guide should correspond to 35 x 45 mm, due to the configuration of the printer 0.5 mm addition in a measurement would correspond to 1 mm and the gap is too big, so the image would get lost)

5.2. Gafchromic film handling

The Gafchromic films should be cut with a very sharp cutter element and quickly, otherwise the borders will crack and the further evaluation will be worsen as well as the presence of marker marks.

5.3. Measurements obtainment

5.3.1. With the bare source

The use of the phantom facilitated the assembly and disassembly of the whole setup when varying the depth, nevertheless, the high of the source had an uncertainty of 1 mm because, it was fixed visually as the printed tool which was designed in order to establish a limit to the insert of the tip was folded due to the force applied by the source.
Measuring DDC allowed to determine the dose rate for each calibration curve and improving the time of calculating the time of radiation at a determined high in order to obtain an specific dose.

5.3.2. With the applicator

Scattering effects showed in measurements showed that it was better to perform the measurements with the applicator without using the montage, however distance between the center of the chamber, the positioning of the film and the center of the applicator were introduced because there was not a proper guide to fix in the same position the whole structure.
For this case it it necessary to redesign the holder in order to speed up the process.

5.4. HVD and HVT

It is possible to identify that the attenuation of the beam increases in an air media faster than in a water media. Also, when comparing the attenuation of the beam between the higher and the lower energy on the source it is possible to observe that the beam requires more thickness in the material to goal its half value of dose.

5.5. Digitization of the images

The congruence of orientation within the images in the scanning bed was key to obtain uniform results. Factors such as foldings, cracks and marker marks in the border of the film were identified for damaging the quality of the image and further results were altered.
By the moment the optima orientation direction of the package of films over the scanner should be vertical as the orientation of the individual films (if the orientation is horizontal the size of the bounding box will not be enough to cover the whole film and the evaluation process would not be able to be performed). It is important when placing the films over the scanning bed, to leave a considering space (about 1 mm to 2 mm) between each films to ease the individual cutting of them in the dosimetric evaluation.

5.6. Dosimetric evaluation

During the evaluation process, errors in scanning and Gafchromic film handling affected the cutting of the films and the curvature edges detection that is the reason why the bounding box included 6 pixels of the background per dimension, the laplacian filter was applied in order to strengthen the contrast of the edges and several thresholding values were taken into consideration in order to identify the peaks of the edges.
At the moment of generating a calibration curve it can be seen that the best channels to identify the changes of the dose corresponds to the green and the red ones; The blue channel captures considerable quantities of noise and that is the reason why changes are not very evident during the calibration curve.
Several functions were tried in order to obtain an adequate fitting function between the normalized density pixel values and the dose values but the best result was given by a rational function of second grade in the numerator and a first grade in the denominator

6 Conclusions and further recommendations

6.1. Conclusions

The development of dosimetric evaluation robust technique was completed successfully. It was possible to perform a proper design of phantoms for direct measurements with the bare source but the results obtained from the design of the phantom needed for the measurements with the applicator were unsatisfactory as well as the guide which purpose was to fix the film in a proper position in the center of the slabs for all the measurements, nevertheless this results did not stopped the measuring process and the correspondent measurements could be performed doing a manual positioning of the setup.

The evaluation of the films was satisfactory, the Gafchromic films could be cut in the optimal size; most of the resulting films of the evaluation package selected passed the dosimetric evaluation and a corresponding dose calibration could be applied to the whole set. The set of films which could not be evaluated corresponded to films with marks or cracks in the borders, or horizontal positioned films in the scanner.

At the moment of performing the measurements, results were altered because of the presence of the Gafchromic film over the ionization chamber, that is the reason why for each measurement the procedure had to be repeated two times, one with the ionization chamber and the second time with the Gafhromic film being irradiated.

The use of a rational function with a higher degree in the numerator allowed to obtain better results when creating a fitting curve for the dose values and the normalized values of pixel density.

Due to time inconveniences and location of the equipment it was not possible to repeat measurements, improve the phantoms or adapting the code as desired; making improvements to the protocol should be performed in order to make it more robust in the detection of the coordinate plane, the accurate cutting of the images with the bounding box and the fitting of the curve to the points within the calibration curve.

The multichannel dose calibration is optimal for performing a dose calibration of the images due to the variances presented within each color channel. However for a further work, as the red and green channel demonstrated to have the most higher response, a multichannel dose calibration with them should be performed and evaluated in order to check if there is a significant improvement in the results.

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