2017

Determination of the Shape of a Flattening Filter Free (FFF) Radiation Beam When Modified by a Physical Wedge

Kalel Alsaeed
Wright State University

DETERMINATION OF THE SHAPE OF A FLATTENING FILTER FREE (FFF) RADIATION BEAM WHEN MODIFIED BY A PHYSICAL WEDGE

A thesis submitted in partial fulfillment of the

requirements for the degree of

Master of Science

By

KALEL ALSAEED

Bach., University of Tabuk, Saudi Arabia, 2010

2017

Wright State University

WRIGHT STATE UNIVERSITY

GRADUATE SCHOOL

November 21, 2017

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Kalel Alsaeed ENTITLED Determination of the Shape of a Flattening Filter Free (FFF) Radiation Beam BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

Brent D. Foy, Ph.D.
Thesis Director

Jason A. Deibel, Ph.D.
Department Chair

Committee on
Final Examination

Brent D. Foy, Ph.D.

Michael Gossman, M.S.,
DABR, FAAPM

Sarah F. Tebbens, Ph.D.

Barry Milligan, Ph.D.
Interim Dean of the Graduate School

ABSTRACT

Alsaeed, Kalel. M.S. Department of Physics, Wright State University, 2017.
Determination of the Shape of a Flattening Filter Free (FFF) Radiation Beam When Modified by a Physical Wedge.

The determination of a flattening filter free (FFF) beam profile when the collimator is intentionally modified to incorporate a physical wedge. Specifically, radiation beam profiles change shape when a metallic wedge is placed in the path of the beam. Examination of this unknown is necessary to ascertain whether a physical wedge is clinically beneficial for applications involving FFF beams. The aim of this study is to determine if the radiation profile of a flattening filter free beam having a physical wedge is comparable to a beam with a flattening filter, with the same wedge inserted. This research involves measurement of relative dose along the wedged plane. A commercially available particle accelerator was used for this study, which was capable of producing 6 MV bremsstrahlung x-rays. Only beams operating at 6 MV were considered for the investigation. The results indicate that Wedged profiles are similar in many respects when a FFF beam uses the same physical wedge designed for flattening filter beams. Differences in wedged profiles between the FFF and FF beams are discuss.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I am grateful to all of those with whom I have had the pleasure to work during this project. Each of the members on my Thesis Committee has provided me with extensive personal and professional guidance and taught me a great deal about both scientific research and life in general. I would especially like to thank Dr. Brent Foy, my adviser, for everything and for showing, me what a good scientist should be. My co-adviser, Michael Gossman has taught me more than I could ever give him credit for here. He has shown me, by example, how to work hard. Finally, I would like to thank the people, who really supported me in many ways, especially my family (my father, my mother, my wife, and my little princess Aleen).

1. INTRODUCTION

Radiation therapy uses high-energy radiation to shrink tumors and destroy cancer cells. The leading type of radiation used for radiation therapy is x-rays. Moreover, one needs to spare nearby healthy tissues. This is done by using multiple beam durations, angles, and profiles during a single treatment. The beam shape can be modified in various ways. Collimators control the 2-D spatial extent of the beam, while physical wedges of a material placed in the beam path can alter the dose within the irradiated region, making some locations receive more dose than others. A traditional linac uses a flattening filter (FF) in photon mode. The FF is placed between the main collimator and the monitor chamber and its main role is to make the photon beam dose distribution uniform at reference depth. The flat dose profiles correspond to an equal dose variation across the beam, which is ideally suited for treatment planning.

Flattening filter free (FFF) radiation beams are currently available with modern linear accelerators. These radiation beams have known clinical advantages. One of these benefits is the reduction of time of treatment.[1] This is important for all patients, but especially for cases involving higher doses such as used for some stereotactic radiosurgery procedures, as well as intensity modulated radiation therapy (IMRT) or volumetric modulated arc therapy (MVAT) procedures.

The principal reason for reduction in beam-on time is fundamentally a matter of how the beam exits the collimator. Traditionally, a beam passes through the flattening filter before exiting. Since many such filters are made of a high atomic number material like tungsten, a significant loss of intensity occurs through interactions with it in place. Conversely, for flattening filter free beams, the lack of this absorber in the beam path results in a greater intensity of radiation exiting the collimator. Therefore, there is simply more radiation exiting the machine when the FFF modality is chosen. In that regard, FFF beams are rapidly being introduced into clinical treatments. [1]

To ensure practical clinical implementation, FFF beams are required to be accurately characterized, addressing potential differences in the time for treatment delivery and quality of the plan. The fact about the FFF is that the photon beam attenuates with the material more than the FF because it has lower average photon energy (Robinson, 2012). However, the presence of these low energy photons in FFF beams means that the dose rate is higher. However, it is justifiable to hypothesize that plan quality for treatments involving FFF beams may be relatively comparable, especially given the known advance in using FFF beams with modulated delivery techniques. Here, I investigate one of the important unknowns; whether or not physical wedges, when used in conjunction with FFF beams, produce changes in dose profiles that are consistent with the in wedged field linear profile of the wedge when used with FF beams.

2. BACKGROUND

2.1 Radiation Basics

2.1.1 Types of Radiation

Radiation for therapy is divided into two types, particulate and electromagnetic. Particulate radiation travels as particles of matter, and it includes Alpha particles and beta particles. Electromagnetic radiation is simply packets of energy traveling through space, and this radiation includes radio waves, microwaves, infrared, visible, x-ray, and gamma rays. Radiation therapy can use all of these types, but the most conventional modality is the use of x-rays produced in a Linear Accelerator. Electron beams, gamma rays, and x-rays are types of radiation that are commonly used in radiation therapy. Both types of radiation can be ionizing and thus can produce biological effects. One measure of the strength of biological effects is absorbed dose, defined as the energy absorbed by an irradiated material per unit mass. [1,2]

X-rays and gamma rays can be obtained from natural sources including radioactive elements as well as from cosmic rays reaching the earth's surface from space. Some radiation types can be made artificially. X-rays and gamma rays are both used in power plants, in industry for food irradiation, for cancer treatment, for medical imaging in smaller amounts, and in airport security scanners. Both are simply energy packets classified as photons, with neither charge nor mass or weight. Generally, photons travel through space or vacuum at a velocity of about 186,282 miles per second. This velocity remains constant no matter what the electromagnetic wavelength is. However, through any media other than a vacuum this velocity is reduced.[3]

Particulate radiation involves radiation of fast- moving particles with a defined mass, the most common of which are beta, alpha, neutron, protons, and electrons. Some research involves the use of ions as an incident radiation type. Particles are very small, invisible to the eye, and travel nearly at relativistic speeds. Particles may be created deliberately in equipment such as particle accelerators, or they may be dislodged spontaneously from radioactive materials. Alpha particles and beta particles are often emitted from radioactive materials, while the beams of ions, neutrons, mesons, protons, electrons and even whole molecules or atoms can be generated in nuclear reactors, accelerators, or cyclotrons. Alpha and beta particles are emissions generally used in radiobiological research environments to yield a dose to cell cultures or specimens in a Petri dish.

2.1.2 Radiation Units

The Roentgen is a unit for measuring radiation exposure (X), defined as the amount of ionization created in air from radiation generated by incident photons. One Roentgen produces precisely 2.58×10^{-4} C/kg of air.[1]

The concept of dose refers to the amount of energy absorbed by a material, in this case biological tissue. The primary unit of measure for radiation dose is the Gray (Gy) which is defined as 1 J per kg. The rad is a somewhat less used measurement of dose, and its abbreviation arises from "radiation absorbed dose." In relation, 1 Gray is equal to 100 rads. The rad exists in literature traditionally, although clinicians for medical consistency have more recently adopted the Gray.[1]

The conversion from exposure to dose is found by making use of the value f_{med} (cGy/R), such that $D = X * f_{med}$. The conversion factor is dependent on the average energy of the photon beam, and close to unity for higher energies in water or materials with similar density.

2.1.3 Effect of radiation on biological tissue

Ionizing radiation is a radiation that can disrupt the atoms or molecules within the body. The Photoelectric Effect, Compton Effect, and pair production processes are ionizing photon interactions. When a photon interacts with matter it can produce high-speed electrons if the incident beam has sufficient energy to overcome the binding energy of the electron. These high-speed electrons can interact with DNA either directly or indirectly. In the direct mechanism, the electron itself damages the bonds in DNA. In the indirect mechanism, the high-speed electron interacts with some other molecule first, most likely water. This will create a free radical which then can travel to the DNA and damage the DNA. The indirect mechanism is much more common than the direct mechanism. By damaging DNA, either by physical knock-out interactions or by enabling free radicals to unnecessarily bond to the DNA, radiation prohibits either reproduction or normal functionality of the cell, ultimately resulting in cell death. It is principal by which clinicians attempt to control radiation. In order to irradiate cancer cells or even tumors, while sparing normal health tissue from harmful effects When the radiation is passed through the cancer cells in the human body, the ionization of the molecules can lead to the breakage of genes leading to cell death, consequently treating the cancer .The strength of the biological affect is related to the absorbed dose, defined as the energy absorbed by an irradiated material per unit mass.[1,4]

Generally, radiation of different types and energies deliver a different amount of energy to tissues at different depths. The higher the energy, the further the radiation can travel before suffering enough interactions that they are either transformed or completely absorbed. This is an important thing to consider when dealing with the human body. It is necessary to be able to choose the most appropriate radiation type and energy for it, in order to achieve the desired dose of radiation at a specific depth in the human bod.

It is important for people to know that ionizing radiation is very dangerous, since it has sufficient energy to cause severe damage to living tissues and cells in the human body. Despite the benefits of radiotherapy, there is always the dangerous possibility that the radiation will also harm nearby healthy tissues. Furthermore, tumors, or the cancerous cells, are unique and distinctive in their response to radiation. This makes cancer cells sometimes resistant or sometimes very sensitive to the radiations and drugs used for their treatment. In the circumstance of any therapy, be it radiation or drug-based, the goal is always to eliminate as many of the cancerous cells as possible.[5]

2.2 Radiation Therapy

2.2.1 Overview

Only a radiation oncologist prescribes radiation treatment for patients. Afterward various tests and images, such as CT and MRI, are performed so that the physician can establish the tumor sizes, involved lymph nodes or metastasis, kind of disease, staging and classification, radiation may be necessary. Treatment may include any combination of radiation, surgery, or chemotherapy. When radiation is essential, the radiation oncologist provides minimum dosage limits for the tumor and maximum dosage limits for nearby healthy tissue. At times, partial volumetric limits are appropriate in order to assist in the production of an ideal computerized plan.[4,5]

The medical physicist then creates a treatment plan to deliver the prescribed doses. They do this using advanced technology called a treatment planning system (TPS). The TPS is a software that makes use physical radiation measurements from the Linac, along with calibration data, and beam geometry, to deduce a computerized rendering of expected dose distributions on patient-specific CT anatomy.

It is here that variations in the intended treatment plan are considered, iteratively changing the aperture beam shape, energy, distance, depth and angular incidence in order to determine the best plan for use on the real machine.

2.2.2 Typical treatment course

Generally, EBRT delivers x-rays of relatively high frequencies and energies to the cancerous cells using an apparatus referred to as a linear accelerator (Linac). By using this machine, the radiation beam can be emitted from any arbitrary angle and be reshaped to suit the tumor contours in the body. The device can rotate around the body while targeting the radiation beam directly to the region of the tumor or cancerous cells according to the plan previously generated on computer. Safely using the Linac requires a board certified medical physicist to calibrated the machine and insure technical specifications are met prior to delivery.[3]

The total number of treatments a patient may require is dependent on the type and stage of the cancer. Some other important factors the oncologist needs to consider during the treatment are how invasive the cancer is, other treatments the patients may be undergoing, and the general health of the patients.

During the process of treatment using EBRT, the patients are required to lie flat on the treatment table and stay motionless throughout the duration of the therapy. No-one is allowed to be present in the room with the patient during treatment. However, staff communicate with and monitor the patient via an intercom and camera system positioned outside the room at a console. EBRT at each daily session may last for a period of between two and ten weeks. Typically, the patients should be scheduled to receive continuous treatment, preferably once a day for five consecutive days in a week, normally from

Monday to Friday. Each of the treatments would only last a few minutes, and is typically done as an outpatient procedure. [4]

However, it takes some time for the radiotherapist to have their apparatus set up to begin the treatment. With set-up and imaging requiring 5-10 minutes to verify positioning, and with a few minutes for treatment to complete, the machine can treat as many as 4 patients per hour. [3]

For the treatment to begin, the patient will need to lie down flat directly below the gantry of the machine. Before proceeding with treatment, the radiation therapist must ensure the safety of the patient by having individual blocks or shields between the radiation device and other healthy body parts. This will provide protection to the other parts of the body from being damaged by the powerful and dangerous radiation. The patient should also be instructed to minimize motion and remain throughout the treatment session.[5]

Once the machine is completely set and ready to begin the treatment, the therapist will have to leave the room and operate the device while checking on the patient on a regular basis. The therapist must, however, control and monitor the movement of the machine on a regular basis to ensure the device is operating properly as is expected. If the patient is worried about any machine behavior, he or she should be able to inform the radiotherapist as soon as possible. Moreover, the patients should also feel free to speak directly to the therapist in case they begin feeling scared or sick. It is possible to stop the machine at any stage of the treatment.[6]

2.3 Linear Accelerator

2.3.1 Basics

The linear accelerator generates and transmits high-energy rays and directs them to the tumor tissue and a particular area of adjacent tissue. Different types of these machines produce various kinds of energy. The main benefit of Linac that it has been using high dose rate and uniform dose. Before particle accelerators were used, machines containing radioactive material were most common. Up until the 1980s, cobalt-60 tele therapy irradiators were prevalent. The limitation of the machine was a specific (1.2 MeV) photon energy with no option to change it.[2] The energy of the photon was based on the average gamma emission from the cobalt-60 source. Another limitation was dose-rate, directly proportional to the activity of the source sealed in the machine. Through the past years, medical linacs have evolved, and used for their e variable energy range and higher dose-rates, not to mention the possibility of using electrons as an incident particulate beam alternatively, making these modern machines very developed in contrast with others. Photon energies specifically range from 4-23 MV in a Linac. Some are used to treat tumors found on the external body surface. Others are concerned with the treatment of tumors located deep within the body. X-rays are the most widely used sources of high-energy radiation.[1]

2.3.2 Collimator

Main aim of radiotherapy treatment is the irradiation of the cancer area target while reducing absorbed dose in surrounding tissues. Shaping the beam is a significant method of minimizing dose in healthy tissue**.** Collimators shape the beam of radiation coming from the aperture of linear accelerators.[7]

The linear accelerator possesses three types of collimators: primary, secondary, and a multileaf collimator.[1] The primary collimator is the first set of lead blocks that the beam passes through first in the gantry head. There are two sets of jaws that move in the opposite directions, which are called the secondary collimators. These two pairs of jawscan close or open to increase or decrease the size of the treatment area. Below both of these is generally what is known as a multileaf collimator (MLC) see (Fig 1). Like jaws, the MLC is usually made from tungsten, a known high Z material. It typically has 80 to 120 small long rectangular shaped leaves that interdigitate, each moving separately, but in only one plane.[8] It is here that a more fine-tuned shape can be obtained mechanically, and it is the final component of the aperture to define the shape of the incident beam. In order to be effective in blocking x-ray radiation outside of the open area of the beam, jaws and the MLC were designed to have a thickness of roughly 7 cm thick tungsten.[7]

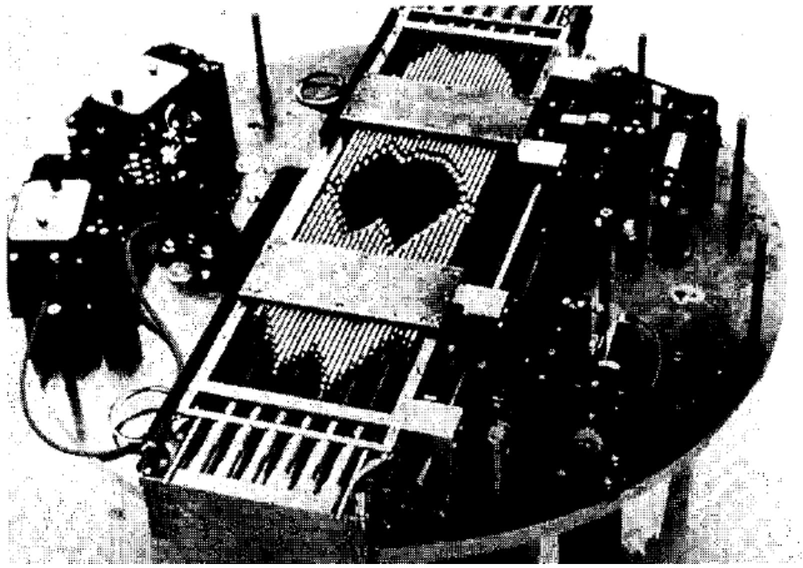

Figure 1. Multileaf collimator attached to accelerator [1].

2.4 Flattening Filters (FF) and Flattening Filter Free (FFF) Beams

The main goal for flattening filters is to make the incoming beam profile, which is centrally peaked, become flatter in cross section. This is why the flattening filter is shaped like an inverted Gaussian curve. The filter is located just above the set of collimators, such that the beam would have to pass through this filter first (Fig 2). The internal ion chamber monitors beam intensity and assists the medical physicist in insuring the same beam output for each mode as calibrated.[9]

After using FF for more than 30 years as a standard element of treatment in the medical fields, the use of flattening filter free beams (FFF) is increasing. Without a flattening filter, the Gaussian curve-shaped beam exits the machine and is director toward the patient. The lack of a flattening filter in the way allows for a greater amount of intensity to exit, but the shape of the beam is no longer flat. [10]

The three significant benefits for FFF are increasing the dose rate per pulse, reducing the energy variation across the beam, and reducing the leakage of radiation. The dose rate can increase more than 800 MU/min between FFF (1,400 MU/min) and FF (600 MU/min) beams.[11] The increased dose rate allows for less time in treatment. The faster we can irradiate the patient, the more quickly we can get them on their way home.[1]

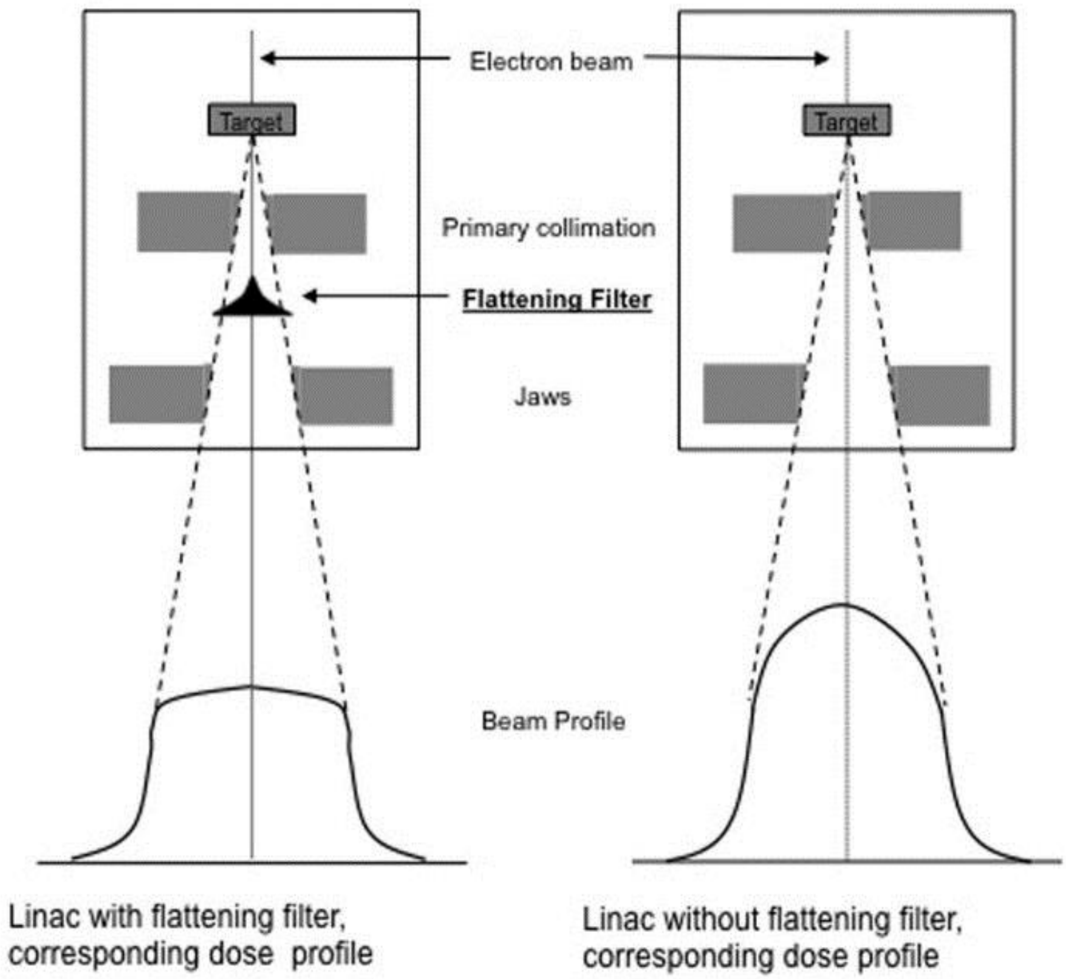

Figure 2. Schematic image of linac gantry along with FF and FFF beam profiles.[12]

2.5 Physical and dynamic wedges

The wedges are stainless steel beam modifying devices that can manually be placed in the path of the beam, residing just below the jaws and MLC. The wedge gets its name from the inclined plane shape it possesses, having a thicker end (heel) and a much thinner end (toe). An ability to change the intensity along a single direction is the main reason for the use of wedges. The wedges are put in the beam path before running the machine to start treating patients.[1]

Physical wedges are used to create an angle in the isodose profile (Fig. 3). They are used to tailor the dose so that greater accuracy can be obtained to achieve desired doses to tumors and reduced doses to surrounding healthy tissue. In practice, they are most useful for tumors within 10 cm of the skin surface.[1] In addition, wedge filters can be applied to smooth out the isodose regions for the beam of protons striking on the flat body surface of the patient lying under slightly tilted incidences of the beam. In other words, if a beam must be directed to a part of the body that is already angled, like a breast, then a flat dose distribution may still be achievable if the beam were angled to compensate for that.[13]

The use of a physical wedge filter lowers the beam intensity, and therefore prolongs treatment time. Sometimes, the physical wedge filter changes the quality of the x-ray beam, which would subsequently result in hardening of the x-ray beam at certain energies, especially between 6-10 MV, and the softening of the x-ray beam at energies slightly above 15 MV.[9] Such effects will generally influence the dose deposition at a specific depth. Each of these influences should be properly considered in the planning process.

The wedge angle is the angle of the isodose curve at a certain water depth, usually, 10 cm, and is tilted at the center of the axis of the beam compared to the normal incidences of the beam at whatever angle the wedge was specified for in manufacturing. Four angles of wedges are commonly used: 15°, 30°, 45°, and 60°. [1]

A wedge effect can also be created by dynamically moving the collimator jaws. This is called a dynamic wedge. At a particular beam angle, the collimator can gradually move in or out to create a wedge effect so that one part of the beam profile receives a greater dose than others.[1]

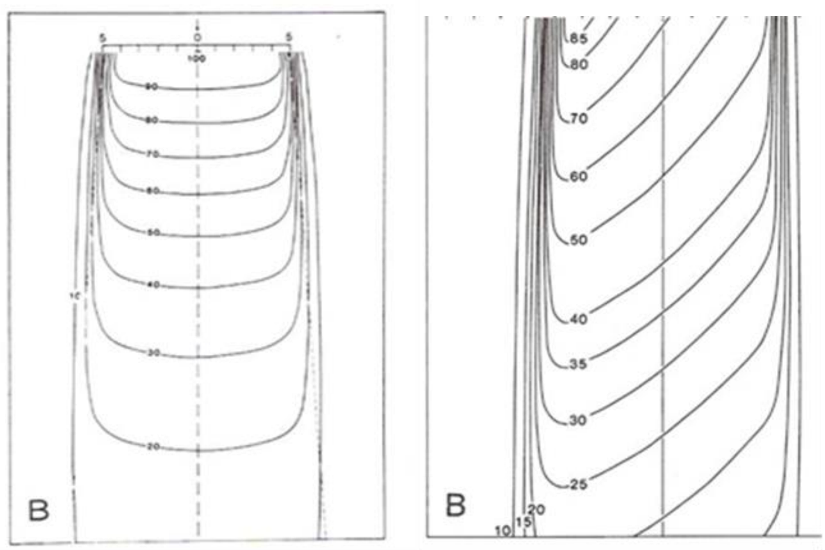

Figure 3. Normal isodose curve and wedged beam isodose curve with wedge in beam. [1]

2.6 Previous Research on the Effect of Metal in an FFF Beam

When a photon passes through a material, the attenuation interaction that occurs depends on the energy of the photon and type and thickness of the material. The attenuation coefficient defends as the beam that is absorbed or scattered per unit thickness.[14] A previous study explores some key relationships between FF and FFF beams, attenuation by metal filters, and dosimetry under various conditions.[15] While the Robinson study does not explicitly use wedges, the results have implications for the current research with wedges because both the Robinson study and the work of this thesis deal with metal in the beam path for FF and FFF beams. All of the differences between FF and FFF beams revealed in the Robinson study can be explained by considering the fact that FFF beams contain a much higher percentage of low energy photons, since the flattening filter isn't present to reduce the number of low energy photons. One experiment shows that the effective attenuation coefficient for brass is higher for FFF beams than for FF beams (Fig. 1a).[15] This is due to the fact that low energy photons are attenuated more strongly than high energy photons.

The Robinson study also reveals that the effective attenuation coefficient of brass depends on the depth within a water phantom at which the attenuation calculation is performed. Obviously, the properties of the brass don not change with phantom depth. But this experimental measurement is affected because the water phantom itself hardens the beam, more so for greater depth. This in turn makes the brass attenuation appear to be less effective because only high energy photons penetrate deeply into the material. Thus, when one is trying to design a wedge which produces a beam profile with an isodose line at a specific angle to the beam (for example, 30^{o}), one needs to consider that the attenuation due to the metal wedge has a variable effect for different depths.

Another part of the Robinson study explored off axis attenuation by a uniform thickness of brass (Fig. 4).[15] When normalized to attenuation on-axis, attenuation by the FFF beam decreased less than the FF beam as one moves farther off axis. Again, this is due to the second beam hardening effect present in FF beams which occurs at the flattering filter, and this beam hardening is non-uniform across the profile.

Finally, Robinson showed that the diode sensitivity for ARCCHECK varies with brass thickness, and this varying effect is obvious for the FFF beam because of the higher incidence of the low energy photons (Fig. 2b).[15] Due to sensitivity of ARCCHECK with varying brass thickness, the expectation for this study is that we may find our measurements are affected by diode sensitivity in addition to wedge attenuation.

Several other studies about the properties of FFF beams have been investigated. The incorporation of a FFF into clinical treatments is continuing to mature. Different energies such as 6 and 10 MV evaluate the characteristics of FFF beam. It reported that using the FFF decreases the head scatter, which is ratio of doses measured in a phantom between different collimator settings and a reference collimator setting. Scatter radiation must be modeled in the treatment planning system.[16]

According to various studies, the increase in the physical wedge thickness increases the beam hardening. The material of the wedge and energy are the major factors for the effect of the beam hardening. [17]

These studies indicate that along with dose distribution changes and dose-rate changes, using FFF beams with a physical wedge will also alter the spectrum of photon energies that irradiate the patient. All of these variables must be considered in the computerized dose modeling system.

3. MATERIALS AND METHODS

3.1.1Linear Accelerator

The linear accelerator used was the TrueBeam® model from Varian Medical Systems, Inc. ® (Palo Alto, CA) see (Fig 4). It has a multileaf collimator with 120 leafs at 2.5 mm per leaf width. Some other significant features for the TrueBeam® are:

- Photon energies for flattening filter (FF) (6,10, and 15) MV
- Photon energies for flattening filter free (FFF) (6 and 10) MV
- Electron energies (6, 9, 12, 16, and 20) MeV

Figure 4. The TrueBeam® linac with the ArcCHECK® residing on the exam bed

3.1.2 Wedges

The TrueBeam linear accelerator can accommodate physical wedges, and these wedges have angles of 15°, 30°, 45° and 60° see (Fig5and 6). The wedges used in this study are made from lead. The field size for 15°, 30°, 45°, and 60° wedges is 10 x 10 cm^2 . The base of the physical wedges is placed 59.8 cm above the target. However, the wedges that used in this study are made from lead. The field size for 15°, 30°, 45°, and 60° wedges is

10 x 10 cm^2. The base of the physical wedges is placed 59.8 cm above the target.

.

Figure 5. Physical wedges used in this study (original by author)

Figure 6. Physical wedges of the angle of 30º and 45º used in this study (original by author)

3.1.3 Dosimetry

The (Sun Nuclear Corporation, Melbourne, FL, USA) Model ArcCHECK® is a tube-like water equivalent kind of phantom with a three-dimensional array of 1,386 diodes homogeneously arranged throughout a 21 x 21 cm^2 field. Each are organized in a unique spiral pattern around a 15-cm dimeter cylinder (Fig 7). A computer is connected to the ArcCHECK® outside of the room so that it could receive the information from the ArcCHECK®. The measured dose delivery was evaluated by using associated SNC Patient Software ® Version 6.7.3. The software permits the measurement of a beam with a prespecified beam-on time to be saved with a measured amount of dose from each diode. To begin setup, a digital level was used to ensure that the ArcCHECK was aligned at exactly 0 degrees between the ArcCHECK and the treatment couch.

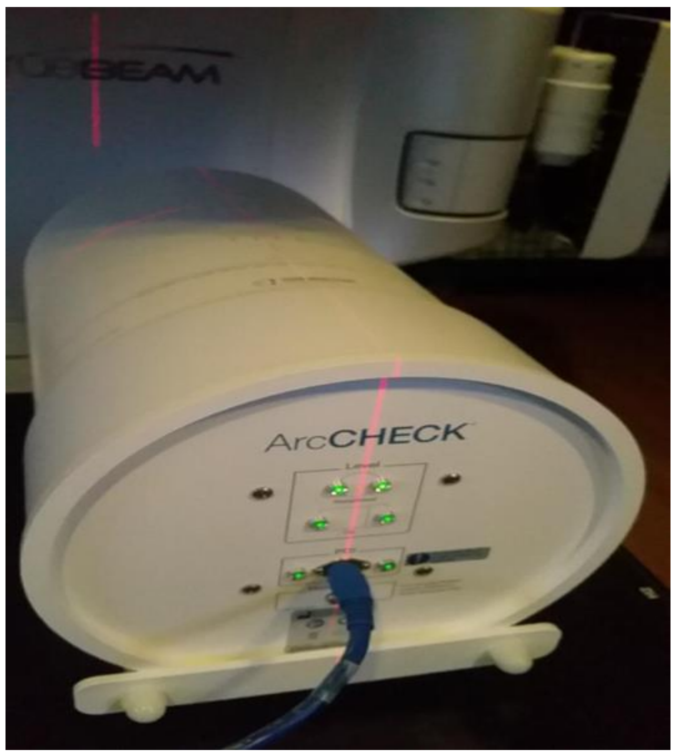

Figure 7. The ArcCHECH® connected with laser sensor to assure positioning at the target point of the TrueBeam. (original by author)

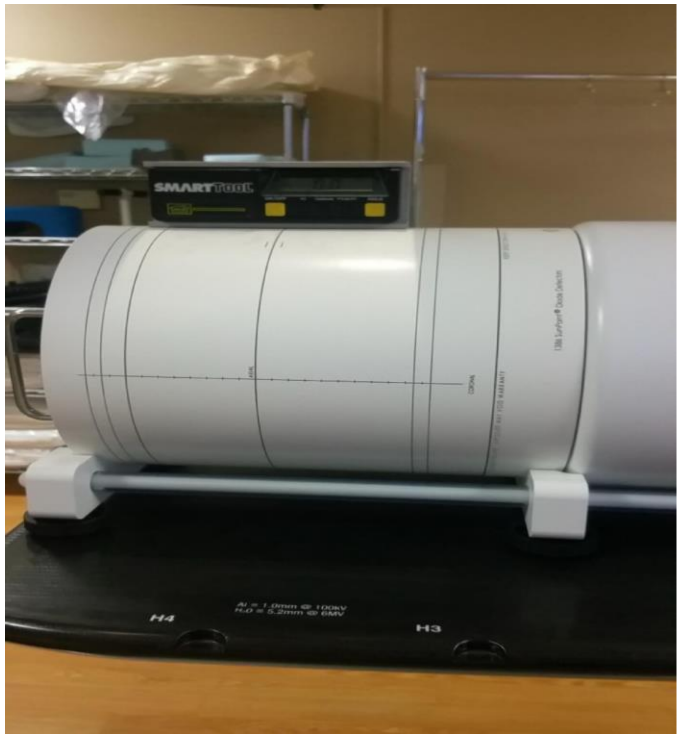

Figure 8. The smart tool positioned above the ArcCHECK®

at 0° as desired (original by author)

An in-room laser was used to assist in alignment to the middle of the ArcCHECK® cross-hairs see (Fig 8).

3.1.4 Modeling

Before calculating the percent of changing in attention values at selected location in the wedge, it should be known that each beam consists of a range of photon energies. Energy has different attenuation coefficient values for low and high energies. To model these energy differences, we will simplify the situation and consider that the photon beam consists of only 2 energies for the 6 MV beam. The energy photon that used to calculate attenuation were 4 Mev for high-energy and 1 Mev for low-energy. 0.475 cm^{-1} and 0.805 cm^{-1} are the attenuation coefficient values for high and low energies respectively, which are used to find the percent of changing in attenuation at selected region on the wedge for FF and FFF. [18] The density of lead (11.34 g/cm^3) was used to calculate linear attenuation coefficient from the mass attenuation coefficient for both energies. [18] Table 1 shows the values of attenuation coefficient. A 30-degree wedge was chosen for this calculation. The three locations selected on the wedge were heel, on axis, and toe. 1.2 cm, 1 cm, and0.8 cm are the thickness of three locations on 30-degree wedge. The normalization was done by taking the total energy for each location (low and high energy) multiply by 100 and division the outcome by the total attenuation for the central axis. The following definition for intensity attenuation was used to calculate the predicted doses:

$$I = I_0 e^{-\mu x}$$

Where **I**, is the intensity of photons transmitted, $\mathbf{I_0}$ is the initial intensity of photons, **μ** is the linear attenuation coefficient, and **x** is thickness.

Table 1. The attenuation coefficient values in Lead for high and low energy

Energy	Mev	μ/ ρ	μ
LE	1	$7.1x10^{-2}$ g/cm^2	0.805 cm^{-1}
HE	4	$4.19x10^{-2}$ g/cm^2	0.475 cm^{-1}

3.2 Study protocol

All available wedges (15^o, 30^o, 45^o, and 60^o) were investigated for both FF and FFF in a 6MV photon beam. The depth and the field size were kept constant at 10 cm and 10x10 cm^2 respectively. After mounting the physical wedges (15^o, 30^o, 45^o, and 60^o) manually, and consecutively one at a time, to the machine, and the experiment was run twice for each wedge, one for FF and the other for FFF. Within the 10x10cm^2 field, a profile of dose was obtained perpendicular to the long axis the couch length.

Measurements were taken without any wedge present at all. Four points were marked for each side as measurement point as (-A, -B, -C, - D), and (A, B, C, D), located at 1.5 cm, 2.5 cm, 3.5cm, and 4.5 cm respectively off the central axis. Since each wedge was inserted with the beam on for the same amount of time, and since the thicker the wedge, the more different the intensity is, then every wedge causes a different dose. Therefore, in order to plot them on the same graph with analyzable scaling, normalized to make the center of the beam arbitrarily 100% intensity, to make it easier to explain. The measured data consists of a text file with dose entries for each of the diodes present on the detector array. By making use of a commercially available software spreadsheet, direct comparisons can be made between 6 MV FF and 6 MV-FFF measured doses.

3.3 Analysis

For each point off-axis, the percent change in intensity between the intensity when the wedge was in place and in the absence of the wedge (open field) was calculated. The formula for this is:

$$I\ Change\ = \frac{I_{wa,loc}(\%) - I_{open,loc}(\%)}{I_{open,loc}(\%)}$$

Where *I* refers to the dose, $I_{wa,loc}$ refers to the dose using a particular wedge angle at a particular location, and $I_{open,loc}$ refers to the dose in the open field (no wedge) at the same location. This calculation was performed for both FF and FFF beams.

4. RESULT AND DISCUSSION

Comparison of FF and FFF beams without wedges

Measurements were taken without a wedge present with the central axis dose normalized at 100 %. What I found is that the total dose for the FFF beam decreased in both sides (toe and heel) compared to the FF beam. The primary result of this outcome measurement is shown in **Figure 9**.

Table 2 presents a summary of the data shown in Fig. 4.1 and gives numerical values for the specified locations. The intensity values are symmetric about the central axis, and the maximum change between FFF and FF beams was a reduction of -10.7% for the FFF beam at locations –D and -10.1 for +D.

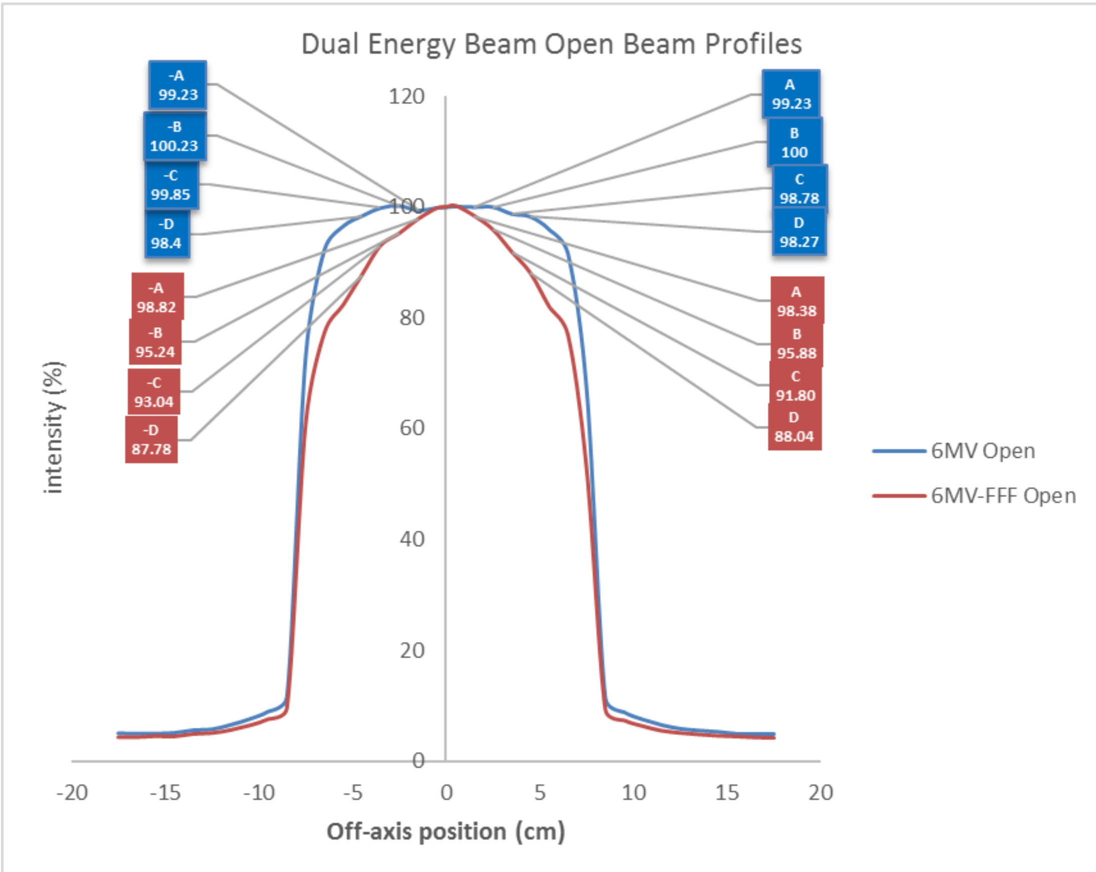

Figure 9. The difference between open FF and FFF.

Table 2. The intensity (%) difference in

intensity between open FF and FFF beams

Off-axis (cm)	-D	-C	-B	-A	0	A	B	C	D
6MV	98.4	99.85	100.2	99.2	100	99.2	100	98.7	98.2
6MV-FFF	87.7	93	95.2	98.8	100	98.3	95.8	91.8	88.04
Difference (%)	-10.7	-6.8	-5.0	-0.4	0.0	-0.9	-4.2	-6.9	-10.1

Intensity data using wedges

15° Wedge data

Figure 10 presents the profile in the presence and absence of the 15^{o} wedge for the FFF beam and FF beam. **Table 3** presents the data for the 15^{o} for both the FF and FFF beams at specific locations. **Table 3** and **Fig. 11** also represent the percentage in different behavior of both the FF and FFF beams with the wedge. One can see that the percentage change is very similar when using the FFF beam with a wedge compared to the FF beam. However, the attenuation due to the wedge in the FFF beam was slightly less at the extreme heel and extreme toe locations (-D, +C, +D), and slightly greater at one other location (-A). Both beams have approximately the same percentage change between locations (+A, +B, +C).

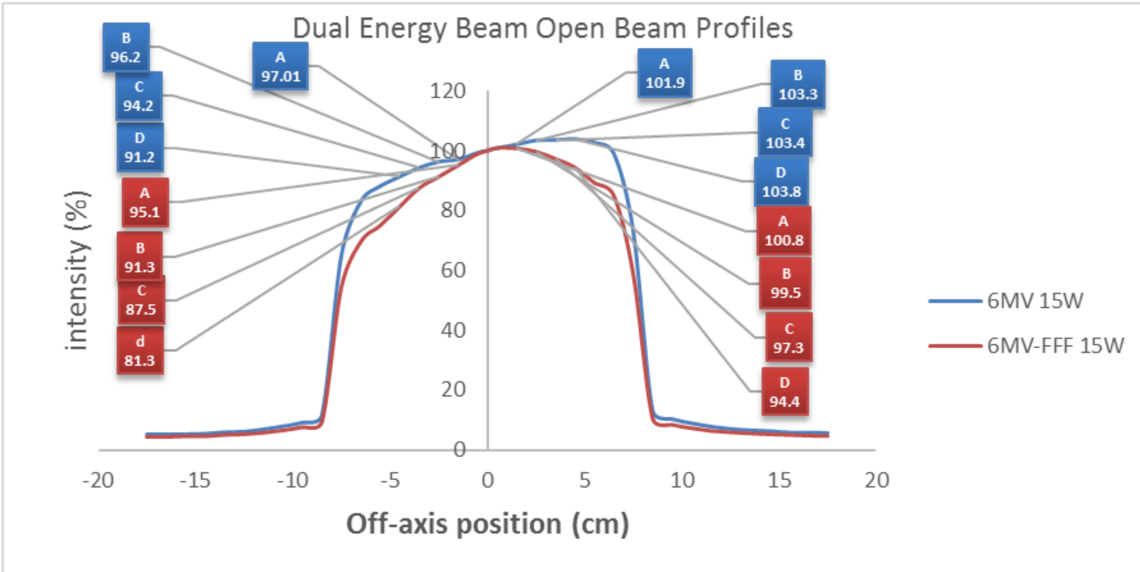

Figure 10. Dose distribution for a 15° wedge in FFF and FF beam.

Table 3. Intensity values and percent changes at select locations for the 15º wedge for FF and FFF beams

Off-axis (cm)	- D	- C	- B	- A	0	A	B	C	D
FF (%)	98.4	99.85	100.2	99.2	100	99.2	100	98.7	98.2
FFF (%)	87.7	93	95.2	98.8	100	98.3	95.8	91.8	88.04
FF 15W (%)	91.2	94.2	96.2	97.01	100	101.9	103.3	103.4	103.8
FFF 15W (%)	81.3	87.5	91.3	95.1	100	100.8	99.5	97.3	94.4
I Change FF (%)	-7.2	-5.6	-4.0	-2.1	0	2.7	2.2	4.7	5.6
I Change FFF (%)	-6.4	-5.5	-3.9	-3.7	0	2.5	2	5.5	6.3

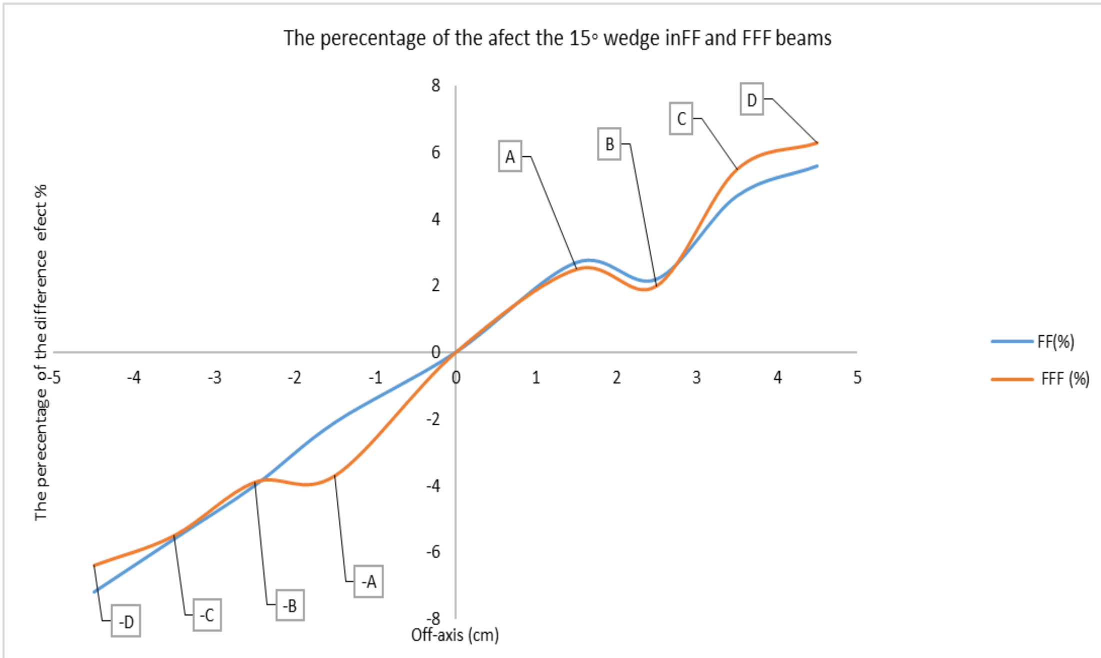

Figure 11. The percentages of the effect of the 15◦ wedge in FF and FFF beams

.

30° Wedge data

The **Figures 12 and 13**, and **Table 4** illustrate the difference between FF & FFF in 30^o Wedge. It is obvious to see that the use of the wedge with the FFF and the FF beam have almost the same effect for all points. Again, in the extreme heel and toe locations, the attenuation due to the wedge for FFF beams was slightly less than for FF beams, and again at location –A, the effect of the wedge was greater for FFF beams. The combined effect, when looking at the locations from –A to +D, is to suggest that the slope is greater for the FFF beam than the FF beam, indicating that the effective wedge angle won't match 30^o precisely.

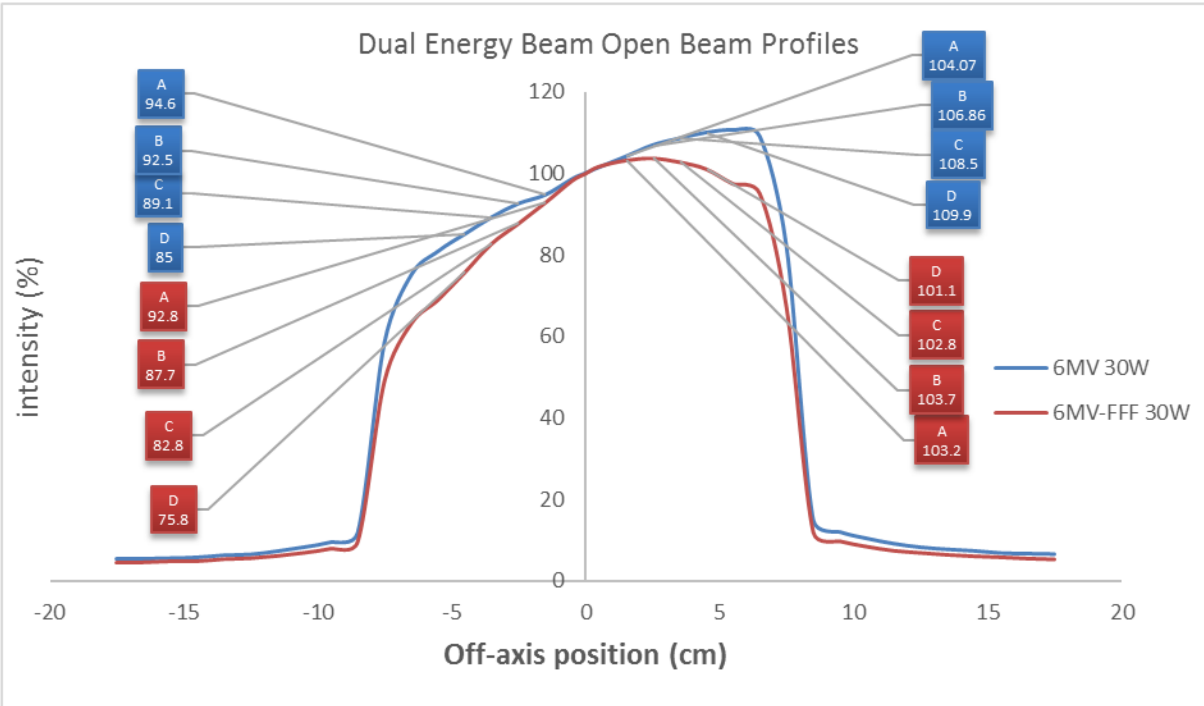

Figure 12. Dose distribution for a 30° wedge in FFF and FF beam.

Table 4. Intensity change at select locations for the 30° wedge for FF and FFF beams

Off-axis (cm)	**- D**	**- C**	**- B**	**- A**	**0**	**A**	**B**	**C**	**D**
FF (%)	98.4	99.85	100.2	99.2	100	99.2	100	98.7	98.2
FFF (%)	87.7	93.0	95.2	98.8	100	98.3	95.8	91.8	88.0
FF 30W (%)	85.0	89.1	92.5	94.6	100	104.0	106.8	108.5	109.9
FFF 30W (%)	75.8	82.8	87.7	92.8	100	103.2	103.7	102.8	101.1
I Change FF (%)	-13.4	-10.7	-7.7	-4.6	0	4.8	6.8	9.8	11.7
I Change FFF (%)	-11.9	-10.2	-7.5	-6	0	5.4	7.9	11.0	13.1

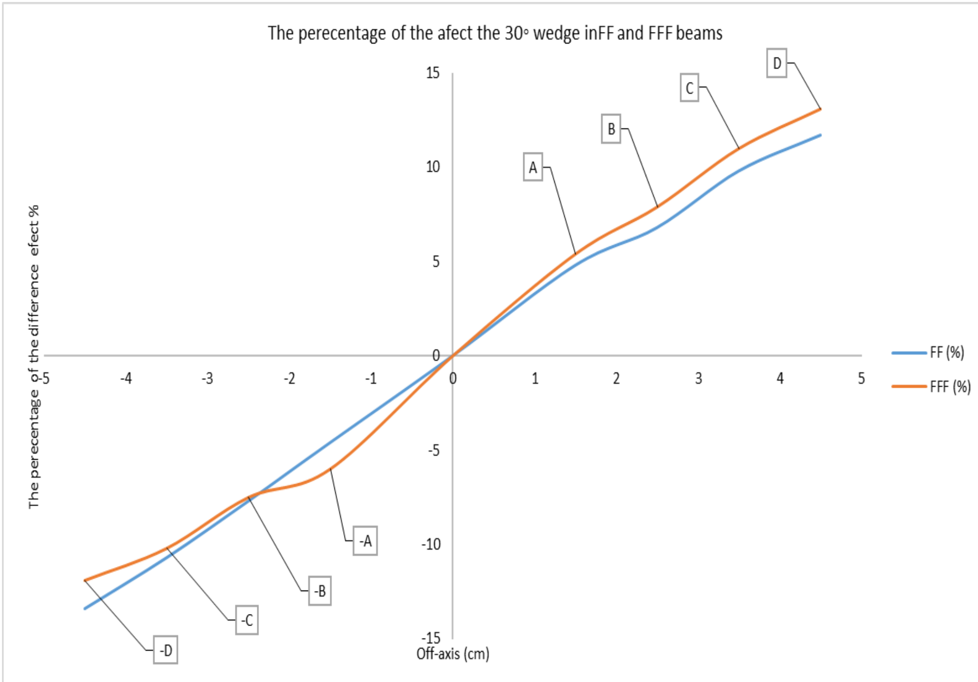

Figure 13. The percentages of the effect of the 30◦ wedge in FF and FFF beams.

45° Wedge data

As the previous figures, **Figures 14, 15**, and **Table 5** have the little differences of changing in the intensity of both beams. One can see that the use of the wedge with the FFF beam and the FF beam results the same behavior for both beams. In point –D, it shows the largest difference between FF and FFF by 2.3%. Additionally, the FFF beam is higher than FF beam in all point accept between -2 cm and -1 cm.

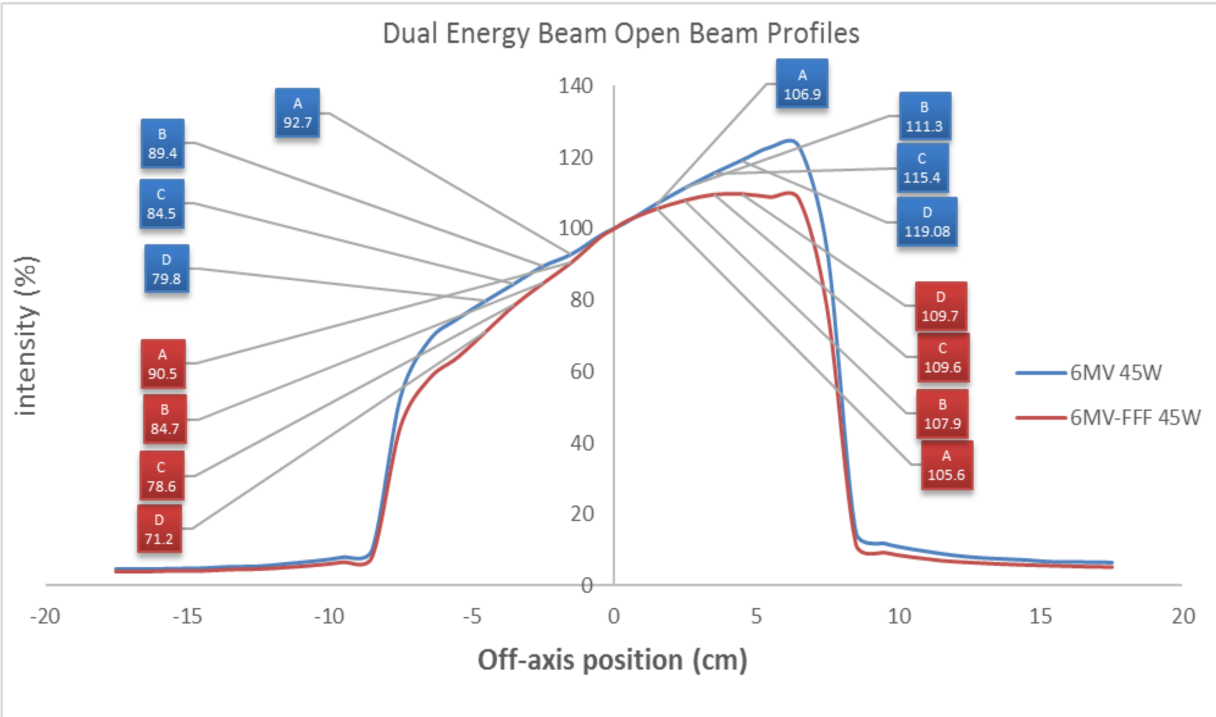

Figure 14. Dose distribution for a 45° wedge in FFF and FF beam.

Table 5. Intensity change at select locations for the 45° wedge for FF and FFF beams

Off-axis (cm)	- D	- C	- B	- A	0	A	B	C	D
FF (%)	98.4	99.85	100.2	99.2	100	99.2	100	98.7	98.2
FFF (%)	87.7	93.0	95.2	98.8	100	98.3	95.8	91.8	88.0
FF 45W (%)	79.8	84.5	89.4	92.7	100	106.9	111.3	115.4	119.0
FFF 45W (%)	71.2	78.6	84.7	90.5	100	105.6	107.9	109.6	109.7
I Change FF (%)	-18.6	-15.3	-10.8	-6.5	0	7.7	11.3	16.7	20.8
I Change FFF (%)	-16.5	-14.4	-10.5	-8.3	0	7.3	12.1	17.8	21.7

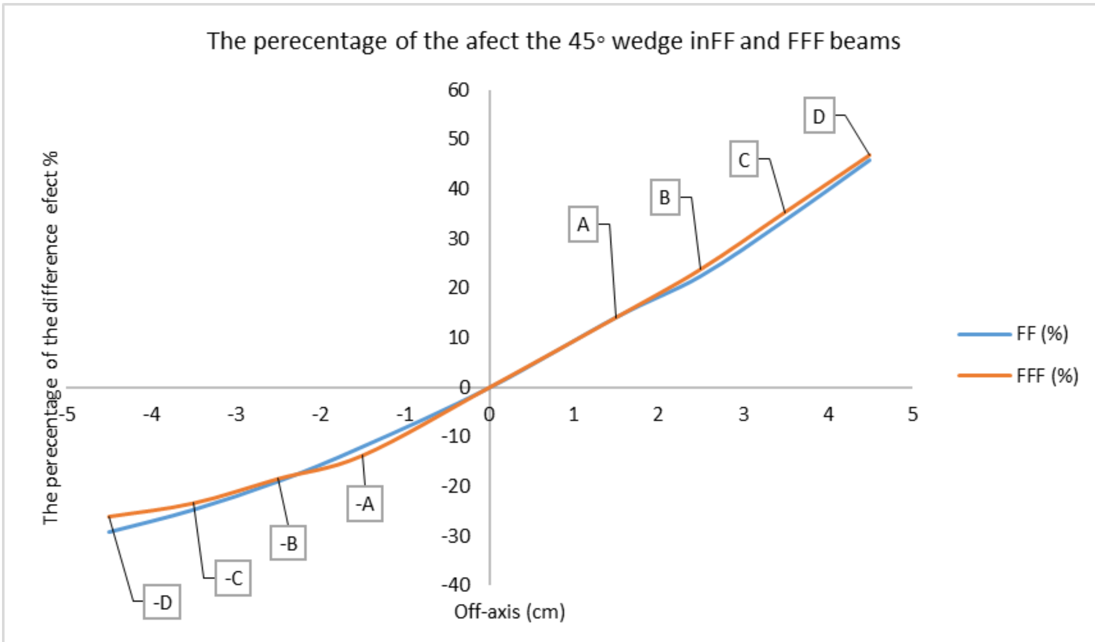

Figure 15. The percentages of the effect of the 45◦ wedge in FF and FFF beams.

60° Wedge data

Figure 16, **17**, and **Table 6** for 60^{o} wedge show the same results that shown in figure 4.2.3b. In point –D, it shows a difference between FF and FFF by 3.1%. Additionally, the FFF beam is higher than FF beam in all point accept between -2 cm and -0.5 cm. One can see that the use of the wedge with the FFF beam compared to the FF beam results in a slight increasing in the percent intensity change on the toe side of the wedge for all locations. However, there was considerable agreement between the FF and FFF profiles for the 60^{o} wedge. As with the 45^{o} wedge, the FF beam shows a percentage change at location -D.

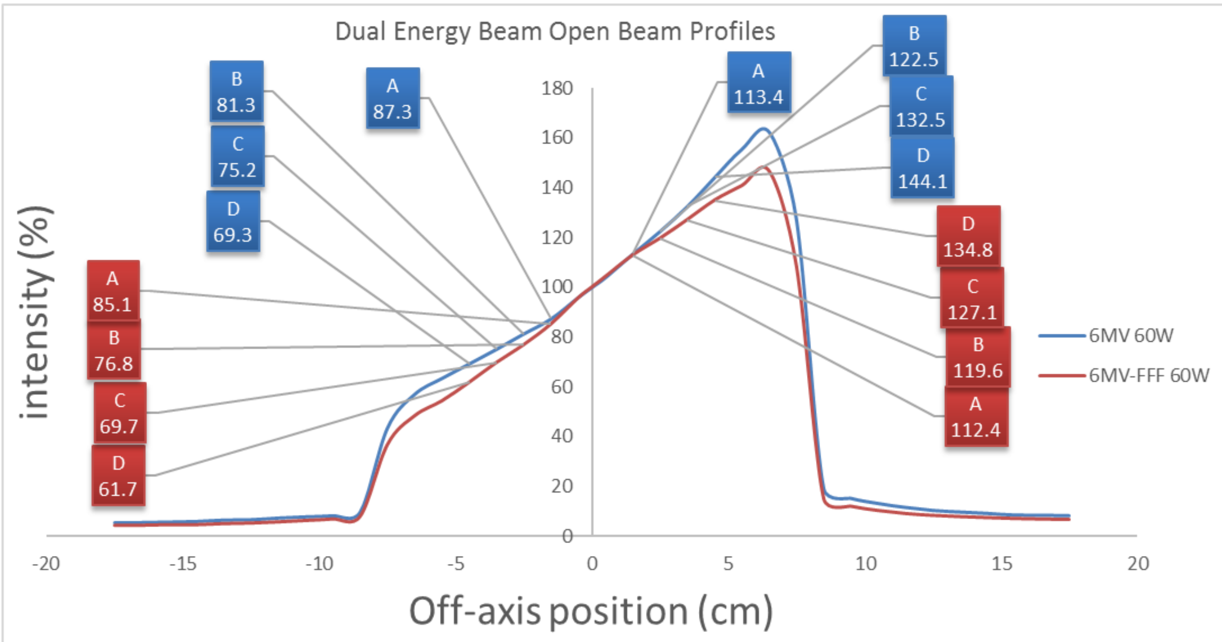

Figure 16. Dose distribution for a 60° wedge in FFF and FF beam.

Table 6. Intensity change at select locations for the 60° wedge for FF and FFF beams

Off-axis (cm)	**- D**	**- C**	**- B**	**- A**	**0**	**A**	**B**	**C**	**D**
FF (%)	98.4	99.85	100.2	99.2	100	99.2	100	98.7	98.2
FFF (%)	87.7	93.0	95.2	98.8	100	98.3	95.8	91.8	88.0
FF 60W (%)	69.3	75.2	81.3	87.3	100	113.4	122.5	132.5	144.1
FFF 60W (%)	61.7	69.7	76.8	85.1	100	112.4	119.6	127.1	134.8
I Change FF (%)	-29.1	-24.6	-18.9	-11.9	0	14.2	22.5	33.8	45.9
I Change FFF (%)	-26.0	-23.3	-18.4	-13.7	0	14.1	23.8	35.3	46.8

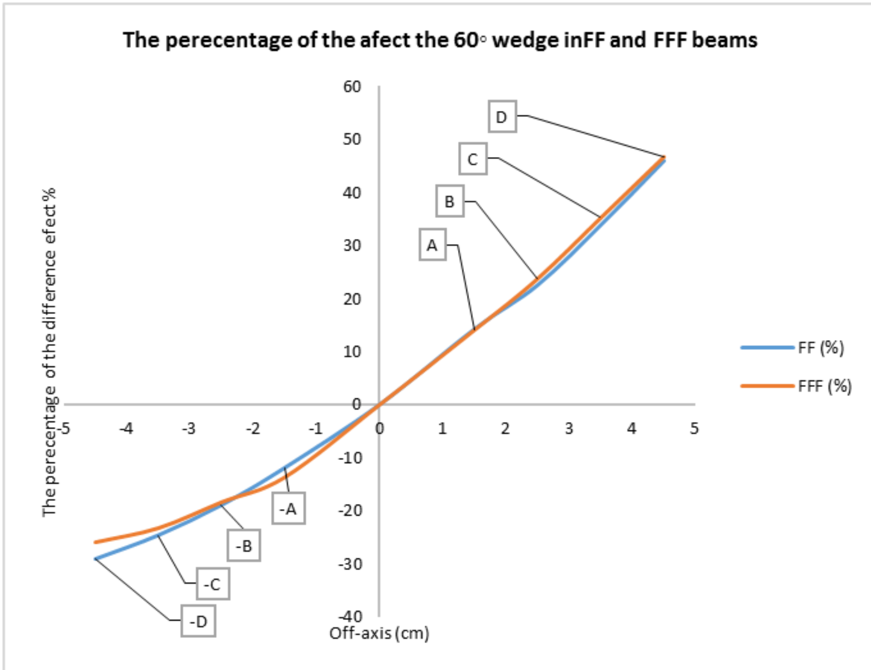

Figure 17. The percentages of the effect of the 60◦ wedge in FF and FFF beams.

Theoretical Calculation of Wedge Attenuation in FFF and FF Beams

Table 7 and **Table 8** illustrate different values for the transmitted beam for three different locations on the wedge for both beams. From the following tables, it is clear to see that the largest value of the transmitted beam occurred in the Toe region of the wedge with the FFF beam compared to FF. On the other hand, the smallest value reported in the Toe region with the FF beam by 96.8.

Table 7. Theoretical Calculation of Beam Profile in Presence of Flattening Filter Free Table.

Location	Energy	Linac Output	After Wedge	Normalized	I Change (%)
Heel	HE	46.5	26.3		
	LE	46.5	17.7		
	Total	93	44	82.2	-11.6
On-Axis	HE	50	31.1		
	LE	50	22.4		
	Total	100	53.5	100	0
Toe	HE	45.9	31.4		
	LE	45.9	24.1		
	Total	91.8	55.5	103.7	13

Table 8. Theoretical Calculation of Beam Profile in Presence of Flattening Table.

Location	Energy	Linac Output	After FF	After Wedge	Normalized FF	Normalized Wedge	I Change (%)
Heel	HE	46.5	45.2	23.6			
	LE	46.5	43.6	15.0			
	Total	93	88.8	38.6	98.5	88.7	-9.9
On-Axis	HE	50	46.3	26.3			
	LE	50	43.8	17.3			
	Total	100	90.1	43.6	100	100	0
Toe	HE	45.9	44.8	28.2			
	LE	45.9	42.5	20.5			
	Total	91.8	87.3	48.7	96.8	111	14.6

5. DISCUSSION AND CONCLUSION

The expectation for the experiment was that FF and FFF beams should behave differently with physical wedges (15º, 30º, 45º, and 60º), due to the differences in photon spectrum between the two beams. This study investigated the behavior of the FF and FFF beams when the operated with physical wedge. For all wedges at all locations, the difference between FFF and FF beams was less than 5% in terms of the percent reduction in dose. Thus, any differences observed in this work were small. One small but consistent effect noted was a reduced attenuation in the presence of FFF beams at the extreme heel location (-D). Three of the wedge angles (15º, 30º, and 45º) revealed the opposite effect at a location near the central axis but towards the heel side (location -A), namely that the attenuation was slightly greater for the FFF beam.

Possible causes of observed dose intensity differences with physical wedges in FF and FFF beams are beam hardening, wedge angle associated with wedge thickness, field size, and the depth. Since the field size and depth remained unchanged for all wedges, at 10x10 cm^2 size and 10 cm depth, those can be excluded here. The most significant effect of using FFF beams is greater attenuation in all materials because of the greater absorption of in lower energy photons.

The goal of wedge design is to produce an isodose line which makes the stated angle to the beam axis within the tissue. Multiple factors which affect this isodose line are altered when one moves from a FF beam to a FFF beam, due to different levels of beam hardening[17]. Some of these factors include the physical thickness of the wedge metal at different spots in the profile, the depth in the tissue, and the location off-axis. Even the sensitivity of diodes used to measure dose are affected by the photon energy distribution. The use of the FFF beam with wedges designed for FF beams may result in isodose angles that are not exactly the same. A 30-degree wedge might be produce a 33^{o} or 35^{o} isodose angle (hypothetically). Consequently, the wedge design may not be correct based on the FFF beam. Those combinations may make differences in the profile of the beam.

An attempt was made to calculate the differential beam hardening effects of FF and FFF beams when used with a wedge. While this calculation simplified some aspects, such as using only 2 photon energies and ignoring possible variations in detector sensitivity with photon energy, the results show that small dose differences between FF and FFF beams will occur. The fact that only small differences were seen is consistent with the small differences seen experimentally, although the direction of the changes was not always consistent.

Note that determination of the wedge angle should only consider points near the beam axis. 10 cm is the stated width of the beam. However, the profile starts to drop at the penumbra. The cutoff for a consideration of wedge angle should be the first couple centimeters from the central axis. The first two points for each side at +/-2cm are crucial. A better characterization of wedges in FFF beams can enable more accurate treatment plans, and thus allow the advantages of FFF beams, such as shorter treatment times, to be used in cases where wedge use is indicated. The relationship between beam hardening in

FF vs. FFF beams and wedge angles is complex and precise calculations to consider all the effects will be needed to design the proper wedges for use with FFF beams.

6. AUTOBIOGRAPHY

I am a young Saudi Teaching Assistant at The University of Tabuk with a BS degree in Physics from University of Tabuk. It is my objective to continue my education and earn an MS in Physics degree from Wright State University. I chose Wright State for its pioneering scientific programs and biochemistry research, which will help me acquire advanced field-related knowledge and skills. This will give me the opportunity to pursue a PhD degree in Physics and advance in my career as a lecturer and researcher. Thus, I seek admission to the Ph.D. in Physics program at WSU, for it is my belief that if I am successful in joining the program, I will be able to utilize the knowledge, skills and experience I gain at WSU towards the realization of my ambitions.

As an undergraduate attending a demanding and challenging program, I sought to gain relevant exposure to Physics that would satisfy my inquiring mind and assist in focusing my future career and studies on the advancement of the science in my country. Therefore, I attended my courses with focus, tackled my assignments with meticulous attention and participated in laboratory experiments actively and attentively. Additionally, and during my senior year, I presented my graduating paper that discussed the various types and symptoms of heart disease from a biochemistry perspective.

Prior to commencing my studies, I was offered a TA position in the newly established Physics department at the University of Tabuk, which I happily accepted. As a TA at the University of Tabuk, I was assigned to teach several in-class and laboratory-based classes to the undergraduate students in the Physics program, through which I attempted to convey the material to my students in an intriguing and effective manner. However, motivated to further enhance my comprehension of the science and thus improve my teaching effectiveness, I made the decision to pursue an MS in Physics at WSU. I reasoned that by attending such a program, I would be better equipped to research the science at an advanced level and consequently improve the study and education of the science at my university and in my country, where it is still an emerging field of study.

Moreover, through my graduate studies, I look forward to focusing my studies on researching means through which my country may achieve an enhanced utilization of biochemistry sciences and improve the nation's various related industries.

Upon commencing my studies at WSU, I would like to continue my education and pursue a PhD degree in Physics, so I may return to my university as a capable and well educated Physics lecturer and researcher. I believe that if I am successful in such a quest, I will possess the academic and scientific tools to contribute effectively in educating young Saudi men and women in the fundamentals of the science, and consequently contribute to increasing the number of Saudi Physics graduates, while working hard on advancing Physics education and research in Saudi Arabia.

In conclusion, I truly believe that if I am able to continue studying for a Ph.D. in a Physics program either at WSU or another school, I will do my best to honor my commitment to realize my full potential as a WSU graduate and Physics lecturer.

7. REFERENCES

1. Khan FM. *The Physics of Radiation Therapy.* 2003.

2. Indra J. Das CWC, Ronald J. Watts, Anders Ahnesjö, John Gibbons, X. Allen Li, Jessica Lowenstein, Raj K. Mitra, William E. Simon, Timothy C. Zhu. Accelerator beam data commissioning equipment and procedures: Report of the TG-106 of the Therapy Physics Committee of the AAPM. 2008;35(9):4186-4215.

3. Ruben JD, Davis S, Evans C, et al. The Effect of Intensity-Modulated Radiotherapy on Radiation-Induced Second Malignancies. *International Journal of Radiation Oncology • Biology • Physics.* 2008;70(5):1530-1536.

4. Klein EE, Low DA, Meigooni AS, Purdy JA. Dosimetry and clinical implementation of dynamic wedge. *International Journal of Radiation Oncology • Biology • Physics.* 1995;31(3):583-592.

5. Siyong Kim CRL, Timothy C. Zhu,Jatinder R. Palta. Photon beam skin dose analyses for different clinical setups. *Medical Physics.* 1998;25(6):860-866.

6. Sigamani Ashokkumar NANR, Sujit Nath Sinha, Girigesh Yadav, Rajesh Thiyagarajan, Kothanda Raman, Manindra Bhushan Mishra. Comparison of Head Scatter Factor for 6MV and 10MV flattened (FB) and Unflattened (FFF) Photon Beam using indigenously Designed Columnar Mini Phantom. 2014;39(3):184-191.

7. Galvin JM, Chen X-G, Smith RM. Combining multileaf fields to modulate fluence distributions. *International Journal of Radiation Oncology*Biology*Physics.* 1993;27(3):697-705.

8. Anders Gustafsson BKL, Roger Svensson,Anders Brahme. Simultaneous optimization of dynamic multileaf collimation and scanning patterns or compensation filters using a generalized pencil beam algorithmAuthors. *Medical Physics.* 1995;22(7):1141-1156.

9. Mohammed M, Chakir E, Boukhal H, Mroan S, El Bardouni T. Evaluation of the dosimetric characteristics of 6MV flattened and unflattened photon beam. *Journal of King Saud University - Science.* 2017;29(3):371-379.

10. Jason C. The characterization of unflattened photon beams from a 6 MV linear accelerator. *Physics in Medicine & Biology.* 2008;53(7):1933.

11. Dietmar Georg TK, Brendan McClean. Current status and future perspective of flattening filter free photon beams. 2011;38(3):1280-1293.

12. Tina G, Robin H, Zdenka K, Stephen B, Justin BD, Clive B. Radiological characterization and water equivalency of genipin gel for x-ray and electron beam dosimetry. *Physics in Medicine & Biology.* 2011;56(15):4685.

13. Saminathan S, Manickam R, Supe SS. Comparison of dosimetric characteristics of physical and enhanced dynamic wedges. *Reports of Practical Oncology and Radiotherapy.* 2012;17(1):4-12.

14. Pei Y, Lan Z, Wang K, et al. Attenuated Renal Disease Severity Associated with a Missense PKD1 Mutation. *Kidney international.* 2012;81(4):412-417.

15. Robinson J OD, Zhang G, Cashon K, Kozelka J, Hunt D, Walker L, Hoffe S, Shridhar R, Feygelman V. Evaluating dosimetric accuracy of flattening filter free compensator-based IMRT: measurements with diode arrays.. *Medical Physics.* 2012;39(1):342-352.

16. Lei Xing RJH, C. Pelizzari,G. T. Y. Chen. A three-dimensional algorithm for optimizing beam weights and wedge filters. *Medical Physics.* 1998;25(10):1858-1865.

17. Geraily G, Mirzapour M, Mahdavi SR, Allahverdi M, Mostaar A, Masoudifar M. Monte Carlo study on beam hardening effect of physical wedges. *Int-J-Radiat-Res.* 2014;12(3):249-256.

18. Akbal A, Tutkun E, Yılmaz H. Lead exposure is a risk for worsening bone mineral density in middle-aged male workers. *The Aging Male.* 2014;17(3):189-193.