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Fabrication and Characterization of Beam Quality Phantom for External Beam Radiotherapy

M. Boopathi[1,2], D. Khanna[1], P. Venkatraman[3,5*], Joshua Sahay[4], C S Sureka[5], Varshini Raju[6], Lalit Mohan Aggarwal[3] , Sunil Choudhary[3]

1. Department of Physics, School of Engineering and Technology, Karunya Institute of Technology and Science, Coimbatore, Tamilnadu.
2. Dharan Cancer Specialty Center Pvt Ltd, Salem, Tamilnadu, India
3. Department of Radiotherapy and Radiation Medicine, Banaras Hindu University, Varanasi-221005, India.
4. HCG Cancer Hospital - (Mansarovar, Jaipur), India.
5. Department of Medical Physics, Bharathiar University, Coimbatore- 641046, Tamilnadu, India.
6. Department of Medical Physics, PSG IMSR & Hospitals, Coimbatore - Tamil Nadu – India.

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ABSTRACT

Introduction: Radiation dose measurement plays a major role in Radiation Dosimetry. Effective dose delivery to the patient is ensured with the recommendation of some protocol called Quality assurance (QA). It is necessary to confirm that the beam that is used for treatment is a good quality beam and it is given by beam quality factor TPR 20/10 which is one of the QA protocols.

Material and Methods: In the present $TPR_{20,10}$ phantom both depth (20 and 10 cm) doses can be measured at the same procedure without changing any setup. As the reference condition is maintained, the Gelatin-based phantom is kept for irradiation in the Siemens Linear Accelerator (LINAC) machine. Initially Source Axis Distance (SAD) of 100 cm from the surface and 10×10 cm^2 of field size. The measurement is taken by ion chamber at 10 and 20 cm depth in gantry angles 90° and 270° And the ratio of these values is taken and compared with the measurements of the water-based TPR phantom.

Results: The values for the $TPR_{20,10}$ ratio for the Gelatin and water phantom are measured using the above method and the values are tabulated and compared. Likewise, the output measurements are done and tabulated for comparison. These measurements are carried out for several days to check the repeatability, and reproducibility of the phantom. Also, the measured set of values was analyzed using mean, median, standard deviation, etc.

Conclusion: The fabricated phantom had good outcomes in its response. And the result projects that the phantom can be a better alternative for the other phantom materials and gelatin has more advantages over water, we conclude that gel can be used for better dosimetric procedures.

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Introduction

Over the period of time, radiotherapy had consistently proven to be one of the best modalities in the treatment of cancer [1]. There have been a lot of studies carried out to improve the quality of the treatment [2]. As we know photon beams have characteristics of changing their quality and quantity as they travel through a medium. To study these changes phantoms have been used from early times to now [13]. Patients have been replaced by phantoms to study the beams to have a greater understanding of beam interactions in the medium. Phantom is a material that will absorb and scatter photons like normal tissues. And it will also be similar to the electron density of the tissue. Water is considered to be a tissue equivalent with similar properties as tissues [4-6]. Large selections of phantoms are available from different vendors. In our study, we have fabricated a phantom with the gelatin material. It is shown that gelatin has favorable advantages compared to other types of phantom materials. Its tissue equivalence, high spatial resolution, and lack of energy dependence, more accurate and inexpensive are well-known advantages. Considering all these advantages we fabricated Gelatin phantom for the purpose of Tissue Phantom Ratio (TPR20,10) beam quality check [7-11].

"Quality Assurance" refers to the deliberate and methodical steps required to instill sufficient confidence that a product or service will meet the prescribed quality standards. It will ensure consistency of the radiation dose prescription to the patient and safe fulfillment in radiotherapy treatment. Tissue Phantom Ratio (TPR20,10) is one of the dose delivery validation methods, which ensures the beam quality. TPR20,10 represents the ratio between the absorbed doses at depths of 20 cm and 10 cm within a water phantom. These measurements are conducted under

**Corresponding Author:* Email: venkat00108@gmail.com

consistent conditions, maintaining a fixed source-chamber distance of 100 cm, and employing a field size of 10 cm x 10 cm at the chamber's plane. The most significant characteristic of the beam quality index TPR20,10 is that the incident beam is independent of electron contamination. It also describes approximately, the exponential decrease of a photon depth-dose curve beyond the depth of maximum dose, which gives the measure of effective attenuation coefficient of depth-dose. The use of displacement correction factor for two depths is not needed for the chambers as the measurement is based on the ratio of two depths. Furthermore, TPR20,10 has an advantage in that in most clinical setups we encounter systematic errors in positioning the chamber at each depth which do not affect the measurement results, as the error will occur similarly in both positions of measurements resulting in no error in the measurements. A special water phantom is available for this measurement purpose alone. In which both the depth dose can be measured at the same time without changing the phantom positions. So, this is commercially available as a water phantom [12-22]. Our idea is to fabricate the same phantom with the gel material. And also make use of the advantageous applications of Gel dosimetry.

Materials and Methods

Linear Accelerator

A linear accelerator (LINAC) is a device that accelerates charged particles such as electrons to high energies through a linear tube using high-frequency electromagnetic waves. It is most commonly used for external beam radiation therapy. These treatments can destroy the cancer cells while sparing the surrounding normal tissue. LINAC has a wide variety of techniques like conventional technique, Intensity-Modulated Radiation Therapy (IMRT), Volumetric Modulated Arc Therapy (VMAT), Image Guided Radiation Therapy (IGRT), Stereotactic Radiosurgery (SRS), and Stereotactic Body Radiotherapy (SBRT).

The linear accelerator uses equipment called "wave guide", which accelerates the electron using microwave technology (similar to that used for radar). These accelerated electrons are then allowed to collide with heavy metals which in turn produces the high energy X-rays. These X-rays are shaped into a customized beam as they exit the machine to treat a patient's tumor. This beam customization is usually done by a multi-leaf collimator that is amalgamated into the head of the machine [23-26]. The patient is made to lie on a moveable treatment couch which has freedom of movement in directions including up, down, right, left, in and out, and using lasers it is made sure that the patient is in the proper position. Another important part of the accelerator is called gantry which helps in delivering radiation beams in all 360º around the patient. The oncologist prescribes treatment volume and dosage to the patient which is then determined by the medical physicist for how long a radiation beam to be delivered to achieve the prescribed dose. Then the treatment is carried out by the radiation therapist who operates the linear accelerator and gives the radiation treatment to the patients as it is prescribed and planned [27-30].

Gelatin

Gelatin is extracted from the collagen found in the pigs, cattle, and other animals from their skin, bones, and connective tissue [31]. Sometimes collagen from fish bones is also used. When bone and connective tissue are boiled in water these proteins dissolve out in the water. The dissolved collagen is extracted into the stock and cooled which is then hydrolyzed to form gelatin. Pure Gelatin is nothing but a protein, but contains nine of ten essential amino acids which is why it can be called a complete protein and also it contains no carbohydrates or fats. Gelatin is used for a large variety of purposes and is usually sold in sheets, granules, or powder. Gelatin powder in a one-ounce packet contains approximately 23 calories and six grams of protein. Gelatin has a tendency to form cross-links in the denatured collagen chains under specified conditions which is the reason for gelatin has a low dissolution rate which stabilizes the gel network and prevents dissolution. The raw material of gelatin is shown in figure 1.

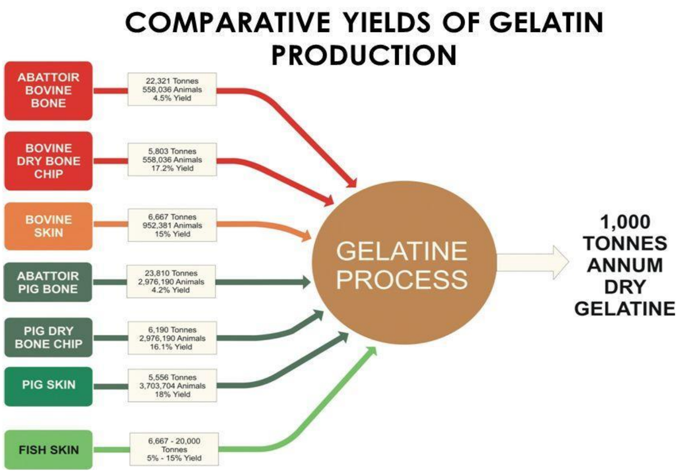


Figure 1. shows the comparative yields of gelatin production

Figure 2. Composition of different type of raw material for preparation of Gelatin

The Manufacturing Process

Inspection and cutting

The animal parts like bones, tissues, and skins are inspected for quality and loaded into chopping machines which cut them into small pieces about (12.7cm) in diameter.

Degreasing and roasting

The chopped animal parts are then treated under high-pressure water sprays to remove debris. The fat content is reduced to about 2% by soaking them in. They are then decreased by soaking them in hot water and are roasted for about 30 minutes at 200º F.

Acid and alkaline treatment

The Degreased and roasted animal part is then soaked for five days in lime or some other type of acid or alkali to remove the minerals and bacteria and also this releases collagen shown in figure 2.

Boiling

In this process, the pieces of bone, tissue, and skin are boiled in distilled water by loaded into large aluminum extractors. Liquid in gelatin is drained off from a tube running from the extractor. To sterilize the liquid the flash-heating is done at about 375° F (140° C) for approximately four seconds.

Evaporating and grinding

Bits of bone, tissue or skin which are still attached to the extractor, is separated by filters. After filtering these liquids are piped into evaporators to separate the liquid from the solid gelatin. Then the gelatin is pressed into sheets as it passes through machines and grinds into fine powders depending on the final application.

Flavoring and coloring

In the case of gelatin to be used in the food industry adding of sweeteners, flavorings, and coloring's is at this point. The additive amounts are Pre-set and thoroughly mixed into the powdered gelatin. The chemical structure of gelatin shown in figure 3.

Preparation of Gelatin phantom

Gelatin is first dissolved in normal water in the ratio of 500g of gelatin to 1 liter of water. It is stirred well and dissolved completely. The dissolved gelatin is made to boom by keeping the liquid in the refrigerator for about two hours shown in figure 4 and 5. They create connections through crosslinks with collagen molecules. Again, the boomed Gelatin is to be cooked (i.e. Kept in a water bath to increase the temperature gradually, then it is made to heat on the stove). Temperature must be maintained below 45^0 C to avoid any overcooking. At that time, the boomed Gelatin changes its state to liquid due to the breakage of cross-linked bonds. Then it is kept cool down for a few hours. Once it is cooled down it is again kept in the refrigerator for a booming process for about 12 hours. And the temperature is maintained at 36° C. Then it can be taken out and used for our purpose. It has the property of melting, when it is kept above the temperature of 36° C. Hence, they should be maintained in a specified temperature. One can also make the gel to have a stable state by adding suitable chemicals to make it a stable state.

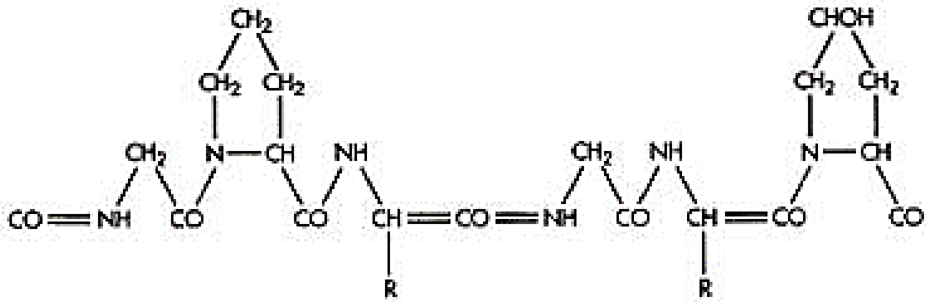


Figure 3. The chemical structure of gelatin

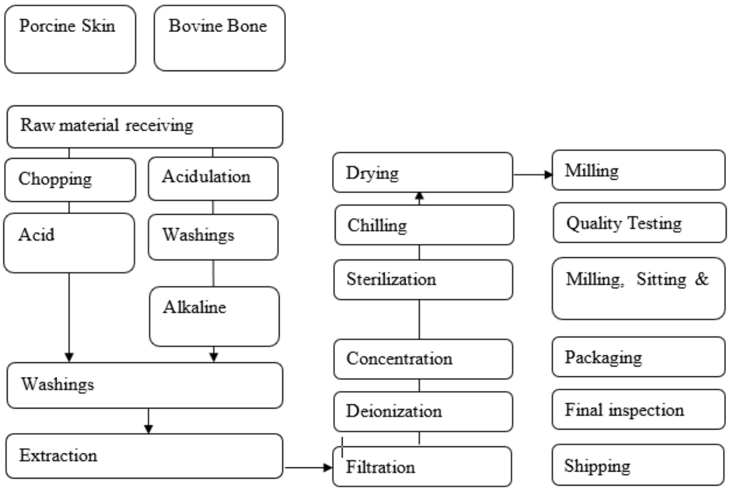


Figure 4. Shows that the flowchart of raw Gelatin material processing

Figure 5. Gelatin in the form of gel

Fabrication of $TPR_{20,10}$ phantom

Two types of phantoms were fabricated. One is filling the gel material with commercially available $TPR_{20,10}$ phantom (which has acrylic body thickness of 1 cm) instead of water shown in figure 6 a and b. And another phantom fabricated on our own having an outer layer of acrylic material with 5mm thickness. Phantom box has a dimension of length of 30 cm and breadth of 17 cm. The total field size in the sides of the phantom is 17×17 cm^2. A hole was made 10 cm at length in the phantom at one end. So that the distance between the surface and the hole will be 20 cm from the other side. This is the specialty of $TPR_{20,10}$ Phantom, where we can take the reading at a single setting. Chamber is inserted in the hollow surface which is made by a plastic tube to prevent the chamber from having contact with the gel material. Horizontal and vertical Lines were drawn on the outer body of the phantom for laser matching purposes. In the same way we used commercially available phantom by draining out water and filling with gel material and measurements were taken by following the same procedure. We also took reading using slab phantom which is a PMMA material for comparison purposes [32].

Measurement of $TPR_{20,10}$ procedures

The fabricated phantom is kept horizontally on the couch as a source axis distance (SAD) setup of 100 cm from linac. In the console field size is set to 5×5, 10×10, 15×15 cm^2 for consecutive trials and MU is set to 100. The absorbed dose is measured at 20 and 10 cm depth by keeping gantry angles 90^o and 270^o. The ratio is calculated by the obtained values. These procedures are repeated for many trials to see the consistency and the reproducibility of the phantom for measured values. Likewise, the output of the machine is also calculated by keeping the constraints in reference condition. All these readings are taken in consecutive days and the values are noted for further analysis. This method is used for both commercially available phantom and our own phantom is shown in figure 7 a and b.

While measuring with slab phantom, a different method was followed. Slap phantoms were arranged and measurements were taken in 20 and 10 cm depth while the gantry is in 0^o. Phantom setup has been changed each time to measure to 20 and 10 cm in depth.

We also took a CT scan of the phantom by placing the phantom over the Normal CT couch and an image was taken. This was done simply to compare the CT numbers of tissues and the gelatin material.

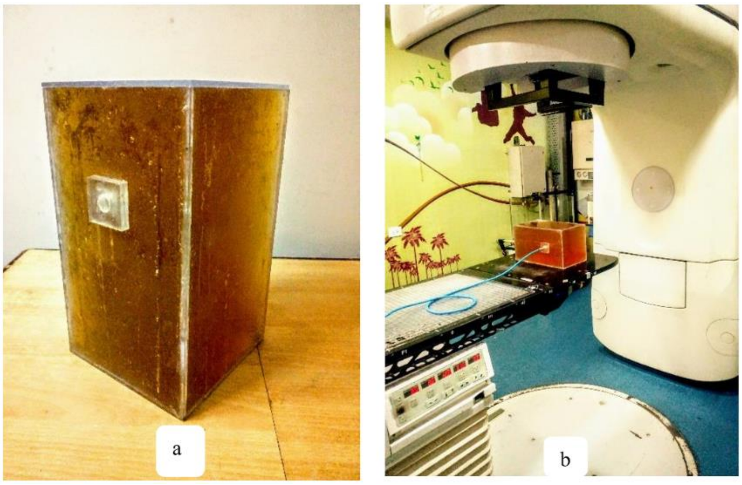
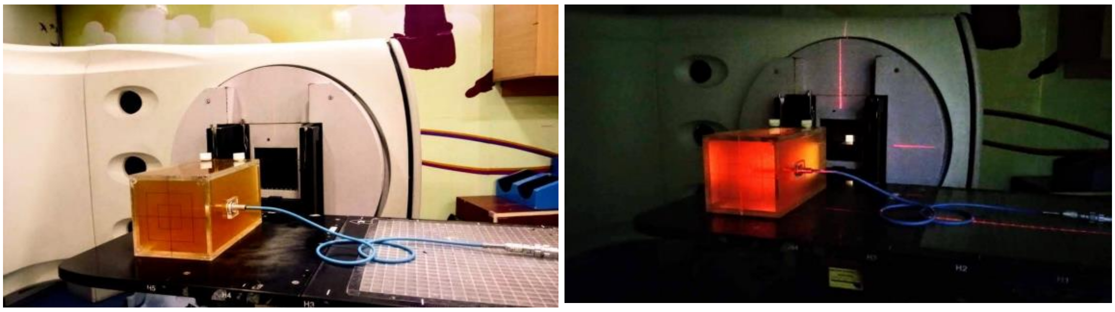


Figure 6. a) Indigenously fabricated $TPR_{20,10}$ phantom b) Experimental setup for $TPR_{20,10}$ measurement



(a) (b)

Figure 7. a) Experimental setup of phantom for the dose measurements b) Shows that the setting of phantom by matching laser light

Accuracy

Accuracy is the most intuitive performance measure and it is simply a ratio of correctly predicted observation to the total observations.

$$Accuracy = \frac{TP+TN}{TP+FP+TN+FN} \quad (1)$$

Precision

Precision is the ratio of correctly predicted positive observations to the total predicted positive observations (TP- True Positive, TN- True Negative).

$$Precision = \frac{TP}{TP+FP} \quad (2)$$

Results

Siemens LINAC machine is used to irradiate the phantom to measure the beam quality and output in the fabricated Gelatin phantom. Many trials were made every day with the same setup of the phantom. We did a beam quality check for 6 MV energy, reference conditions like field size 10X10 cm^2 at SAD 100 cm are maintained. For 6 MV, with our phantom the range of $TPR_{20,10}$ was 0.64 ± 3%. We also did a comparison study with other available phantoms like slab phantom, water phantom and hospital water phantom replaced with Gelatin. PTW 0.66cc Farmer chamber is used for measurements [31, 32].

Based on these, 4 sets of phantoms based on water, gelatin, slab, and our own fabricated phantom were measured one by one with the same setup for all phantoms. The measurements were repeated three times in order to enhance the precision and reliability of the data. This practice aids in reducing random variations and identifying potential systematic errors, ultimately contributing to more accurate and consistent results. The mean, range, variance, standard deviation, accuracy, precision, and error by water, slab, gelatin, and our own fabricated gelatin phantom were compared and shown in Table 1.

All the measurements were repeated 3 times that showed the reproducibility of 4.89, and 7.613 with an accuracy of 0.1%. Further, its repeatability was tested over a period of one month that showed 0.01, and 0.005 variations among the results in Tables 2,3 and 4.

Table 1. $TPR_{20,10}$ measurement for different phantoms like water, Gelatin and slab phantom

Phantom	Depth (cm)	R_1 (nC)	R_2 (nC)	R_3 (nC)	Range	Mean	SD*	Ratio
Water	20	10.1	10.1	10.1	10.1	10.1	0	0.67
	10	15.1	15	15.1	15 – 15.1	15.06	0.047	
Gelatin Hospital	20	9.9	10	10	9.9 – 10	9.96	0.047	0.66
	10	15	15.1	15.1	15 – 15.1	15.06	0.047	
Slab	20	9.9	9.8	9.8	9.8 – 9.9	9.83	0.047	0.66
	10	14.9	14.9	14.8	14.8 – 14.9	14.86	0.047	
Gelatin Indigenous phantom	20	9.78	9.78	9.78	9.78	9.78	0	0.64
	10	15.23	15.23	15.22	15.22 -15.23	15.226	0.004	

*Standard Deviation
- Gelatin Hospital phantom means instead of water it is filled with gelatin in TPR 20, 10 phantoms.
- Gelatin Indigenous phantom, in this case, we have to use gelatin and acrylic as the outer layer of phantom.

Table 2. Measured reproducibility of the indigenous gelatin phantom

Phantom	Depth (cm)	R_1 (nC)	R_2 (nC)	R_3 (nC)	Mean	Reproducibility
Gelatin Our product	20	9.78	9.78	9.78	9.78	4.89
	10	15.23	15.23	15.22	15.226	7.613

Table 3. Measured Repeatability of the indigenous gelatin phantom

Gelatin (Our product)	Depth (cm)	R_1 (nC)	R_2 (nC)	R_3 (nC)	Mean	Repeatability
(Day 1)	20	9.78	9.78	9.78	9.78	0.01
	10	15.23	15.23	15.22	15.226	0.005
(Day 2)	20	9.76	9.76	9.76	9.76	0.01
	10	15.21	15.21	15.22	15.215	0.005

Table 4. Measured range, mean, variance, standard deviation precision and accuracy for different phantoms used in the study

Phantom	Water Commercial product		Gelatin Commercial product		Slab		Gelatin Indigenous phantom	
	20 cm	10 cm	20 cm	10 cm	20 cm	10 cm	20 cm	10 cm
Range	10.1	15 -15.1	9.9 – 10	15 –15.1	9.8 – 9.9	14.8 – 14.9	9.44 – 9.45	14.81 -14.83
Mean value	10.1	15.06	9.96	15.06	9.83	14.86	9.44	14.83
Variance	0	0.002	0.002	0.002	0.002	0.002	0	2.22
Standard deviation	0	0.047	0.047	0.047	0.047	0.047	0	0.0047
Accuracy	0	0.1	0.1	0.1	0.1	0.1	0	0.1
Precision	0.990	0.996	1.004	0.996	1.017	1.009	1.022	0.985
Error	0.01		0		0		0.02	

Table 5. Comparison of output measurements for water phantom and slab for different field sizes

Field size	Water phantom				O/P	Slab phantom				O/P
	R_1	R_2	R_3	Avg		R_1	R_2	R_3	Avg	
5 x 5	11.11	11.12	11.12	11.115	92.87	10.92	10.92	10.93	10.925	91.28
10 x 10	12.54	12.54	12.54	12.54	99.47	12.34	12.34	12.34	12.34	97.88
15 x 15	13.33	13.34	13.33	13.335	103.16	13.14	13.14	13.14	13.14	101.65

O/P = Output factor

Table 6. Represents output measurement of indigenous phantom and commercially available phantom for different field sizes

Field size	Gelatin (Indigenous phantom)				O/P	Gelatin (commercially available phantom)				O/P
	R_1	R_2	R_3	Avg		R_1	R_2	R_3	Avg	
5 x 5	10.88	10.85	10.86	10.86	90.74	11.12	11.12	11.13	11.125	92.95
10 x 10	12.74	12.73	12.73	12.73	100.97	12.58	12.58	12.57	12.58	99.78
15 x 15	13.23	13.26	13.28	13.256	102.55	13.34	13.34	13.34	13.34	103.2

For water, gelatin, slab and our own fabricated phantom, the means at 20 cm are 10.1, 9.96, 9.83, 9.44, and at 10 cm are 15.06, 15.06, 14.86, 14.83 respectively and the ranges of the phantom at (20 cm) are 10.1, 9.9-10, 9.8-9.9, 9.44-9.45 and at (10 cm) are 15-15.1, 15-15.1, 14.8-14.9, 14.81-14.83 respectively. Then, the variances of the phantom at (20 cm) are 0, 0.002, 0.002, 0 and at 10 cm are 0.002, 0.002, 0, 2.22 respectively. Similarly, the standard deviations at (20 cm) are 0, 0.047, 0.047, 0.047, and for (10 cm) are 0.047, 0.047, 0, and 0.0047 respectively. Similarly, the accuracy of the phantoms at (20 cm) are 0, 0.1, 0.1, 0.1, 0, and at (10cm) are 0.1, 0.1, 0.1, 0.1 respectively. The precision of the phantoms at (20 cm) is 0.990, 1004, 1.017, 1.022 and at (10 cm) are 0.996, 0.996, 1.009, 0.985 respectively. Error of the phantom measurements are 0.01, 0, 0, 0.02 respectively higher than that of remaining phantoms.

To calculate the output the parameters below are used,

$$Output = \frac{D_{(w,Q)}}{PDD} \times 100 \quad (3)$$

Where,

$D_{(W,Q)} = M_Q * K_{(q,q_o)} * N_{(D,w)}$

$M_Q = M * K_{TP} * K_{pol} * K_s$

M_Q = Reading of a dosimeter at quality Q, corrected for influence quantities other than beam quality.

K_{TP} = Factor to correct the response of an ionization chamber for the effect of the difference that may exist between the standard reference temperature and pressure specified by the standards laboratory and the temperature and pressure of the chamber in the user facility under different environmental conditions.

K_{POL}= Factor to correct the response of an ionization chamber for the effect of a change in polarity of the polarizing voltage applied to the chamber.

K_s = Factor to correct the response of an ionization chamber for the lack of complete charge collection

$K_{q,q0}$ = Factor to correct for the difference between the response of an ionization chamber in the reference beam quality Qo used for calibrating the chamber and in the actual user beam quality Q. The subscript Qo is omitted when the reference quality is 60Co gamma radiation (i.e. the reduced notation kQ always corresponds to the reference quality 60Co)

N_{DW} = Absorbed dose to air chamber factor of an ionization chamber.

Machine setup values:

Prescribed dose = 100 mu

$N_{(D,W)}$ = 5.402 Gy/C

K_Q = 0.99025

K_{TP} = 0.995

PPD at 10 cm = 63.7 (5x5), 67.1 (10x10), 68.8 (15x15)

In table 5 and 6, Output consistency test is also carried out with our Gelatin phantom and another available phantom. From the above table 6, the output consistency can be studied. It shows that there is not much variation in each phantom, yet the measured values are well within the agreement. This shows that the phantom we fabricated has the ability to produce consistent output measurement. We also did the study for different field sizes like 5x5, 10x10, and 15x15 cm^2. It's recommended that the output should be measured for 10x10 cm^2 field size alone.

In Table 7, We took a CT image of our phantom to compare the CT numbers with the standard values available for different materials. It is noted that as long as the temperature of the phantom is maintained below 36^o C it remains semisolid. There were no physical changes seen after the irradiation of phantom.

Table 7. Comparison of standard CT number of different materials.

Phantom	CT number
Gelatine	(-20 – 70) Our phantom measures value
Soft tissue	(-40 – 100)
water	0 tolerance (-40 – 40)
Acrylic	110 – 130

Discussion

From Table 1, the ratio of the two depths shows some variation in the values for different type of phantoms namely slab phantom, our product, commercial product, and water phantom. The actual value of the $TPR_{20,10}$ ratio is 0.66 for a 6 MV photon beam and the tolerance can be of ±3%. When we see the result, it is observed that the $TPR_{20,10}$ measurements range from (0.64 – 0.67). Our product shows a ratio of low value compared to that of actual value. This may be due to the properties of gelatin material having different densities compared to that of water. And also because of some uncertainties in the phantom's outer shell fabrication. From Table 1, it is observed that the mean, range, variance, standard deviation, accuracy, precision, and error of the phantom's small variation in our phantom.

From Tables 2 and 3, variations may be due to the change in thickness of acrylic material of 5 mm used for the outer layer, whereas in the already available phantoms, they have used 1 cm of acrylic material. Also, there is inaccuracy in the chamber holder angle, which is slightly inclined. So due to these reasons our phantom marginally has a variation in the $TPR_{20,10}$ measurements. But this variation is not very high, if we could make a phantom more accurate and precise chamber positioning and phantom dimension, we could expect a phantom not to give variation in its reading when compared to that of available phantoms.

In our study, we have taken three field sizes (5×5, 10×10, and 15×15 cm^2). So, there is some discrepancy in the field sizes 5×5 cm^2 and 15×15 cm^2. For 10×10 cm^2 field size, values are within the tolerance limit which shows that the phantom's reproducibility of output measurements has a good agreement. The results are tabulated in the table 6.

Form the measured values CT numbers we can see that the Gelatin has a range of (-20 to 70) which is the actual range of water and soft tissues, that is (-40 to 40) and (-40 to 100) and this shows that the Gelatin we fabricated is a tissue equivalent material. We also compared these measured values with the already available phantom by taking the CT numbers for it. The results showed that there is well agreement with our phantom CT number values.

Based on our analysis we have drawn graphs for range, accuracy, precision, standard deviation, and error. This graph shows the variation in the measurements. These results show that there is a significant variation in the graphical representation of range, accuracy, precision, standard deviation and also in the error. And the reason for this is already discussed in the above chapters. The graph representing error shows the deviation from the standard value of the regular phantoms. Especially our product has a greater deviation in its measurements since they have some inaccuracy in its dimension and as well as in the chamber holder inclined angle. Also, we have compared the values of both $TPR_{20,10}$ and output readings of water phantoms. There is a notable difference in the properties of water and gelatin. So, we consider may also contribute to significant variation in the measurements. When we see the graph for the hospital phantom filled with gel material, we can see that there is no significant deviation of measured values in the phantom shown in figure 8. This is because of the accuracy of the phantom, where there is no setup error and minimum deviation. Since they have the closeness to the reported value which is 0.66. On the other hand, the output measurements were analyzed, they have a good or the Gelatin phantom, and the measured values are well within the tolerance limit.

Conclusion

From early days there has been lots of advancement in the field of dosimetry. As time passed, dose measurements were made simple, more precise, and accurate. In today’s context Gel gel-based phantom plays a major role in the development of dosimetry. From this point of view, we fabricated a Gelatin phantom and studied it with some parameters called $TPR_{20,10}$ (Beam Quality check) and output consistency. Since QA is the basic need of Radiotherapy phantom plays a major role in it. The effectiveness and safety of radiation therapy hinge on the impeccable functioning of equipment, the precise alignment of devices, and the reliability of dosimetry processes. Based on these two parameters, the response of the phantom is analyzed. It is concluded that the fabricated phantom had good results in its response and has good durability. The result projects that the phantom can be a better alternative to the other phantom materials. Gelatin phantom offers convenient dosimetry under a variety of circumstances. Additional advantages include tissue equivalence, high spatial accuracy, good dose precision, and reasonable convenience. Once the Gel dosimetry finds its path in the practice then this would be the greatest tool in radiation dosimetry.

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