Review of the literature shows that a number of solid tissue equivalent materials have been developed over the past couple of decades and their properties thoroughly understood. These materials were used by many physicists in the field of radiotherapy not only to design and construct phantoms that could evaluate a radiation beam and its properties, but also to cross check on the various treatment procedures before they are implemented on the patient. These planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy the given requirements for quality is termed as ‘Quality assurance’\(^1\). First part of this section discusses briefly about quality assurance in radiotherapy and how it can be quantified and reported, its importance in radiotherapy and various quality assurance procedures carried out on various radiotherapy machines.

Quality assurance of radiotherapy machines, which are designed to be a source of radiation, requires tools that could detect radiation, quantify it and give a meaningful result. Devices or materials that fit into the above criteria are called radiation dosimeters. An overview of certain selected radiation dosimeters which will be used in this work is considered in the second part of this section.

Having defined the objective of this work as the design and fabrication of a quality assurance phantom, the last part of this section discusses on phantoms, its design terms and material selection criteria.


Quality Assurance (QA)

“Every cancer patient deserves to receive the best possible management to achieve cure, long-term tumor control or palliation”: This is the major goal of cancer management\(^2\). The implementation of modern technologies in radiotherapy can lead to continuous improvement in the outcome of treatment with respect to a high tumor control probability and low rate of complications in normal tissue. On the other hand, because of its complexity, radiation treatment is subject to various sources of uncertainties at different steps of radiotherapy chain, from dose prescription to dose delivery. In addition to inherent uncertainties in planning and carrying out of treatment, there is a possibility of errors, including human mistakes and equipment related problems, which can occur during the process of treatment. It is a known fact that many patients receive less than optimal radiation treatments, some being treated inadequately, with the increased probability of a lower cure rate and/or of severe complications. The risk of inadequate radiation treatment and radiation accidents can be minimized through the systematic execution of a comprehensive Quality Assurance (QA) programme, which involves programmes for quality management and periodic quality control of equipment.

Quality Assurance (QA) is defined as all those planned and systematic actions, necessary to provide adequate confidence that a product or service will satisfy given requirements for quality (ISO 9000:1994). It covers all relevant procedures, activities and actions and therefore all groups of staff involved in the process under consideration.

The regulatory process, through which the actual quality performance is measured, compared with existing standards, and finally the actions necessary to keep or regain conformance with the standards (ISO 9000: 1994), is termed as Quality Control (QC). QC is one part of overall QA.
It is concerned with operational techniques and activities used to check that quality requirements are met and to adjust and correct performance, if the requirements are found not to have been met.

Radiotherapy demands high accuracy so as to produce the desired result of tumour control rates as high as possible and at the same time to maintain complication rates within acceptable levels. The QA procedures in radio-therapy are to reduce uncertainties and errors in dosimetry, treatment planning, equipment performance and treatment delivery, thereby reducing the overall uncertainty in the treatment delivery. Quality Assurance in Radiotherapy will ensure consistency of the medical prescription and safe fulfillment of that prescription. This regards, dose to the target volume together with minimal dose to normal tissue, minimal exposure of personnel, and adequate patient monitoring aimed at determining the end result of treatment\(^3\) (WHO 1988). Since QA in radiotherapy is concerned with all aspects of the radiotherapy and since quality activities are interdependent it should involve all groups of staff in a co-operative approach.

QA not only reduces the likelihood of accidents and errors occurring, it also increases the probability that they will be recognized and rectified sooner, if they do occur, thereby reducing their consequences for patient treatment. More over it allows a reliable inter-comparison of results among different radiotherapy centers, ensuring a more uniform and accurate dosimetry and treatment delivery. This is necessary for clinical trials and also for sharing clinical radiotherapy experience and transferring it between centers. Quality assurance programs providing accuracy and consistency help to exploit fully improved technology and more complex treatments in modern radiotherapy.

Quality assurance from the patient safety point of view is to ensure that exposure of normal tissue during radiotherapy be kept As Low
As Reasonably Achievable (ALARA) consistent with delivering the required dose to the planning target volume. This forms part of the objective of the radiation treatment itself. The measures to ensure quality of a radiotherapy treatment inherently provide for patient safety and for the avoidance of accidental exposure. Therefore patient safety is automatically integrated with the quality assurance of the radiotherapy treatments.

The clinical requirements for accuracy are based on evidence from dose-response (dose-effect) curves for tumour control probability (TCP) and normal tissue complication probability (NTCP). Both of these need careful consideration in designing radiotherapy treatments for good clinical outcome. The steepness of a given TCP or NTCP curve against dose defines the change in response expected for a given change in delivered dose (figure 2.1). Thus, uncertainties in delivered dose translate into either reductions in TCP or increases in NTCP, both of which worsen the clinical outcome. The accuracy requirements are defined by the most critical curves,

![Figure 2.1. The principle of therapeutic ratio.
Curve A represents the TCP, Curve B the probability of complications.](image)

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i.e., very steeply responding tumours and normal tissues.

With consideration of the available evidence on clinical data, various recommendations have been made about required accuracy in radiotherapy:

The ICRU\(^4\) reviewed TCP data and concluded that an uncertainty of 5\% is acceptable in the delivery of absorbed dose to the target volume. This has been widely quoted as a standard; however, it was not stated explicitly what confidence level this represented. It is generally interpreted as 1.5 SD or 2 SD and this assumption has been broadly supported by more recent publications. Mijnheer et al.\(^5\), considering NTCP, and Brahme et al.\(^6\), considering the effect of dose variations on TCP, recommend an uncertainty of 3 to 3.5\% (1SD), (i.e., 6\% or 7\% at the 95\% CL). The smallest of these numbers (6\% at the 95\% CL) might be applicable to the simplest situations, with the minimum number of parameters involved, while the larger figure (7\%) is more realistic for practical clinical radiotherapy when more complex treatment situations and patient factors are considered.

Various national as well as international organizations and publications have recommended structure and management of quality assurance programme for radiotherapy\(^7\) (e.g., WHO (1988); AAPM (1994); ESTRO (1995); COIN (1999); IPEM (1998); IEC (1989); Van Dyk and Purdy (1999); McKenzie et al. (2003)). Realization of a treatment objective with an acceptable uncertainty can be obtained only by reducing the uncertainties at each step of the treatment process. One important area that needs to be quality assured is in the delivery stage of radiation, i.e. the treatment machines. As per the above recommendation, the medical physicist or radiation oncology physicist or radiotherapy physicist or clinical physicist is in many countries certified by a recognized national board and is responsible for specification, acceptance, commissioning, calibration and QA of all radiotherapy equipment. Their duty also include measurement of radiation beam data, calculation procedures for determination and verification of patient
doses, manage the physics content of treatment planning and patient
treatment plans, supervising the therapy equipment maintenance for its
safety and performance and establish and review QA procedures. They are
also responsible for radiation safety and radiation protection in the
radiotherapy centre.

The structure of an equipment QA programme starts from preparation of
initial specification, acceptance testing and commissioning for clinical use,
including calibration where applicable. At the conclusion of the
commissioning measurements, before the equipment is put into clinical use,
quality control tests should be established and a formal QC programme
initiated which will continue for the entire clinical lifetime of the equipment.
The functional performance of radiotherapy equipment can change suddenly
due to electronic malfunction, component failure or mechanical breakdown,
or can change slowly due to deterioration and aging of the components.
Additional QC tests need to be conducted after any significant repair,
intervention or adjustment or when there is any indication of changes in
performance as observed during use or during the planned preventive
maintenance or the routine QC programmes. Planned preventive
maintenance program schedules in accordance with manufacturer’s
recommendations need to be followed. These are intended to make it
possible to achieve an overall dosimetric uncertainty of ±5% and an overall
spatial uncertainty of ±5 mm which are generally perceived as clinically
acceptable and technically achievable. Further improvements are
possible, only with significant technical innovations and increased cost.
Radiotherapy Equipments and its Quality Assurance

1. **Brachytherapy Machines and its QA programme**

   Brachytherapy is the use of encapsulated radioactive sources to deliver radiation dose within a distance of a few centimeters by surface, intracavitary, interstitial or intraluminal applications. Brachytherapy has potential spatial and temporal advantages over external beam therapy\(^{11}\) (Barendsen, 1982; Turesson, 1990). The use of remote afterloading machines permits sources of increased strength to be utilized in order that treatment times can be reduced. Use of remote afterloading machines have led to the concept of low, medium and high dose-rate (respectively LDR, MDR and HDR) brachytherapy. The ICRU\(^{12}\) (1985) Report No. 38 advocates high dose-rate as exceeding 0.2 Gy per minute and low dose-rates between 0.4 and 2.0 Gy per hour. The aim of giving a brachytherapy treatment is not only delivery of the requisite dose to the tissue volume but also the control of dose outside the tissue volume being irradiated. The most commonly used sources in a remote afterloading machine are Ir-192 and Co-60. Movement of source in these machines is controlled by stepper motors. Figure 2.2 shows a HDR brachytherapy machine which uses Iridium 192 radioisotope. Realization of a treatment plan depends on the accuracy with which source can be positioned by the remote afterloader as per the treatment plan. The accuracy of dose prediction by the treatment planning system strongly depends on the accuracy with which the source strength is measured and the value entered into the TPS. One goal of QA is to achieve a desired level of accuracy and precision in the delivery of dose. In the case of brachytherapy, an uncertainty of ±15% in the delivery of prescribed dose is a more realistic value and larger uncertainties may be present in certain procedures\(^{13}\). Starting with source calibration to checking for uniformity in distribution of radioactivity in the encapsulated source, quality assurance of a brachytherapy machine has been addressed in various literatures\(^{14}\). (AAPM, 1984; Williamson, 1983; Williamson et al., 1985; Nath et al., 1990; Weaver et al., 1990b).
2. **Radiotherapy Simulator and its QA programme**

Radiotherapy Treatment simulators replicate the movements of an isocentric Teletherapy treatment machines and are also fitted with identical beam and distance indicators (figure 2.3). Hence, all measurements that concern these aspects of Teletherapy machines also apply to the simulator and should be quality-controlled in a similar manner. It should be noted that, if mechanical/geometric parameters are out of tolerance on the simulator, this will affect treatments of all patients, whichever treatment machine they are subsequently treated on. In addition, the performance of the imaging components on the simulator is of equal importance to its satisfactory operation. For this reason, the quality control on simulators requires critical measurements of the imaging system. The imaging system consists of a diagnostic x-ray tube, an imager with manual and automatic kV-mA facilities and an imaging chain that may include digital image capture. Typical QA procedures for a conventional simulator with test frequencies and action levels need to be prepared for each department with guidelines from agencies like IPEM\(^\text{15}\) (1999) and AAPM\(^\text{16}\) (1994).

3. **Treatment Planning systems and its QA programme**

As an integral part of the radiotherapy process, the Treatment Planning System (TPS) provides computer predictions of the dose distributions that can be achieved both in the target volume and also in normal tissue. As this information is used to provide guidance to the clinician on the best treatment for an individual patient, these systems are critical to the treatment process and hence their performance must be assured to work accurately and effectively. A TPS along with Vidar Film Scanner and Digitizer Table as input devices is shown in figure 2.4.

A major aspect of the acceptance and commissioning of the system is to test its fundamental performance and gain an understanding of
the algorithms used for the dose prediction. This provides the knowledge on the limitations of the system and this understanding should be gained by comparison with experimental measurements in phantoms for test cases of varying complexity\textsuperscript{17}. Some information on this should also be obtainable from the manufacturer, from the literature and from users groups.

Following software upgrades a more limited acceptance and commissioning programme should be undertaken. The extent of this will depend upon the extent of changes made to the system. However, it is prudent to take a cautious approach in order to ensure that the performance of the system remains satisfactory. Testing should not be deferred simply to reduce the time to make the new software clinical.

Generic tolerances have often been quoted as 2\% for isodose distributions where dose gradients are not steep and 2 mm where dose gradients are steep. These may typically be applied to single field or single source isodose distributions. However, these will not necessarily be applicable in less simple situations. A similar generic tolerance of 2\% is often quoted on MU calculations for linear accelerators, which again may need careful consideration in complex situations. Discussion of the acceptable tolerances for different situations is given by Van Dyk et al\textsuperscript{18} and ESTRO\textsuperscript{19}.

Acceptance, commissioning and QC recommendations are published by AAPM\textsuperscript{20}, IPEM\textsuperscript{21} and IPEM81\textsuperscript{22}. The exact requirements will depend on the level of complexity of the system and of the treatment planning techniques used clinically. Any uncertainty concerning the operation or output of a treatment planning system should be tested by comparing the performance of the treatment planning system with measurements in suitable phantoms.
4. Cobalt-60 and Linear Accelerator (LA) Teletherapy Machine and its QA Programme

Treatment machines incorporating X-rays or γ-ray sources for use in external beam radiotherapy are called Teletherapy machines. The structure of the machine that holds the source of radiation, the collimating devices to limit the area of the incident beam and radiation beam modifying devices is called ‘Gantry’. The Gantry is mounted isocentrically, allowing the beam to rotate about the patient at a fixed Source to Axis Distance (SAD). Teletherapy machines having a radioactive material (Cobalt-60), as the source of radiation are called Telecobalt machines (figure 2.5). To have X-ray as the source of radiation, Teletherapy machines use Linear Acceleration Principle to accelerate electrons which in turn are used for the production of bremsstrahlung X-ray (figure 2.6).

Teletherapy machines, whether it is Cobalt-60 isotope based or linear accelerator, plays its role in the last stage in the radiotherapy delivery process. Errors at this stage will mean wastage of a team’s effort in achieving a therapeutic goal. A QA programme for a cobalt-60 teletherapy machine and linear accelerator with recommended test procedures, test frequencies and action levels is given by different agencies. These could be adopted as such into practice or fine tuned to the needs of your centre. There is considerable variation in the practice of quality control on a Co-60 machine and that of linear accelerators because of the levels of complexity of the two machines. The safe operation of computer controlled radiation machines requires extensive and repetitive checking of interlock chains. AAPM Reports describe special testing requirements for computer controlled accelerators. The three major publications on the quality assurance programme of a linear accelerator are IEC, IPEM 81 and AAPM.
Figure 2.2 HDR Machine

Figure 2.3 Radiotherapy Simulator

Figure 2.4 Treatment Planning System

Figure 2.5 Cobalt 60 Teletherapy Machine

Figure 2.6 High Energy Linear Accelerator
5. Intensity Modulated Radiotherapy Procedure and its QA programme

Intensity-modulated radiation therapy (IMRT) represents a fundamentally new approach to the planning and delivery of radiation therapy (RT). This technique of treatment planning and radiation delivery helps not only to conform the radiation dose to the tumor volume but also helps in the ‘conformal avoidance’ of the critical structures near to the tumor. IMRT process starts off with immobilizing the patient in the treatment posture. CT scan of the region to be treated is taken with the immobilization in place. Tumor region to be treated (PTV) and critical organs that need to be spared (OAR) are delineated on the CT scan images using dedicated contouring software. The images are then transferred to the inverse treatment planning software. Radiation beams are directed to the PTV from different gantry angles. Dose prescriptions are made for the PTV and OAR. This prescription includes the dose to be delivered to the PTV, the max dose to the OAR, volumes of tissue that can receive max dose etc. The inverse planning software then runs an optimization to arrive at the correct weightage of radiation dose that need to be delivered from each gantry angle. To arrive at an optimal plan that is close to the prescription, the radiation beam from each gantry angle is split into number of segments that conform to the PTV and at the same time provide conformal avoidance to the OAR. Hence the resultant dose distribution is the superposition of segments from each gantry angle. Once an acceptable plan is reached, it is evaluated for the accuracy of the inverse planning software in calculating the dose distribution. In addition to that, it is also evaluated for the accelerator’s accuracy to execute the planned segments to realize the planned dose distribution.

Traditional method followed in treatment verification is by testing individual portals and using superposition to determine the accuracy of a complex dose distribution. IMRT-generated dose distributions often
have complex shapes with high gradient regions surrounding critical patient structures. Analysis of discrepancies between measured and calculated doses by single-point measurements in high-gradient regions will be complicated by positioning uncertainties. The use of single-point detectors is usually limited by these practical considerations to the measurement of only a few points within low-gradient regions. There are no single planar detectors capable of providing sufficiently accurate dosimetry to use as the sole source of verification for IMRT treatments. The most common planar dosimeter is film, in spite of its poor reproducibility and energy dependency. Although film may not provide absolute dose measurements, it is capable of providing relative dose measurements that enable the precise determination of the location of high dose-gradient regions. Radiographic film doesn’t exhibit significant energy response and have problems regarding uniform sensitivity. The process of IMRT plan verification can be summarized as follows:

a. Create treatment plan based on patient scans.

b. Configure the IMRT verification Phantom on the CT couch in a reproducible manner.

c. CT scan the phantom with the selected chamber in place.

d. Transfer the CT phantom scans into the treatment planning system.

e. Transpose treatment plan onto CT phantom scans.

f. Place the phantom, with ion chamber, film, or any detector that can give a meaningful response, on the accelerator treatment couch.

g. Treat the phantom as the treatment plan indicates.

h. Examine the output of the ion chamber (absolute dose) and film (relative or fluence dose), and compare them to the treatment plan.
Radiation Dosimeters

Evaluation of a treatment machine or a treatment process requires devices that can quantify the parameter under evaluation. If radiation at a point or region is the parameter under study, then appropriate radiation dosimeters need to be employed. Radiation dosimetry deals with methods for quantitative determination of energy deposited in a given medium by a radiation source. A radiation dosimeter is a device, instrument or system that measures or evaluates, either directly or indirectly, the radiation quantities which can be absorbed dose and/or relative quantities of ionizing radiation. A dosimeter along with its reader is referred to as a dosimetric system.

A device to function as a radiation dosimeter, it should satisfy certain criteria such as its accuracy and precision, linearity, dose or dose-rate dependence, energy response, directional dependence and special resolution. Not all dosimeters can satisfy all characteristics. The choice of a radiation dosimeter and a reader must therefore be made judiciously, taking into account requirements of the measurement situation.

One of the most important tool for conducting a quality assurance programme is a good radiation dosimeter that will help to evaluate the specific process or device. Radiation dosimeters used in the present study are (1) Film dosimeter, (2) Thermo Luminescent Dosimeter (TLD), (3) Ionimetry dosimeter and (4) Chemical dosimeter.

1. Film Dosimeter

In film dosimeters, film serves as a radiation detector, a relative dosimeter, a display device and an archival medium. Film gives excellent 2-D spatial resolution and, in a single exposure, provides information about the
spatial distribution of radiation in the area of interest or the attenuation of radiation by intervening objects.

Unexposed X ray film consists of a base of thin plastic with a radiation sensitive emulsion coated uniformly on one or both sides of the base. Result of radiation interaction forms a latent image in the film. This image becomes visible and permanent subsequent to processing.

Radiation interaction causes film opacity, and light transmission is a function of the film opacity. This is measured in terms of optical density (OD) with devices called densitometers. The OD is defined as

\[
\text{OD} = \log_{10} \left( \frac{I_0}{I} \right)
\]

and is a function of dose. \(I_0\) is the initial light intensity and \(I\) is the intensity transmitted through the film. The useful dose range of film is limited and the energy dependence is pronounced for lower energy photons. The response of the film depends on several parameters, which are difficult to control. Consistent processing of the film is a unique challenge in this regard.

Typically, films are used for qualitative dosimetry, but with proper calibration, careful use and analysis, film can also be used for dose evaluation. Various types of film are available for radiotherapy work (e.g. direct exposure non-screen films for field size verification, phosphor screen films used with simulators, metallic screen films used in portal imaging and Extended Dose Range (EDR) film for therapy verification). Unexposed film would exhibit a background OD called the fog density (\(\text{OD}_f\)). The density due to radiation exposure, called the net OD, can be obtained from the measured density by subtracting the fog density. OD readers include film densitometers, laser densitometers and automatic film scanners.
Ideally, the relationship between the dose and OD should be linear, but this is not always the case. Some emulsions are linear, some are linear over a limited dose range and others are non-linear. The dose versus OD curve, known as the sensitometric curve (also known as the characteristic or H&D curve, in honor of Hurter and Driffield) must therefore be established for each film before using it for dosimetry work. H&D curve for a radiographic film is shown in figure 2.7.

![Figure 2.7 Sensitometric (characteristic H&D) curve for a radiographic film.](image)

The curve has four regions: (1) fog, at low or zero exposures; (2) toe; (3) a linear portion at intermediate exposures; and (4) shoulder and saturation at high exposures. The linear portion is referred to as optimum measurement conditions, the toe is the region of underexposure and the shoulder is the region of overexposure.

Important parameters of film response to radiation are gamma, latitude and speed. The slope of the straight line portion of the H&D curve is called the gamma of the film. The exposure should be chosen to make all parts of the radiograph lie on the linear portion of the H&D curve, to ensure the same contrast for all ODs. The latitude is defined as the range of exposures over which the ODs will lie in the linear region. The speed of a
film is determined by giving the exposure required to produce an OD which is 1.0 greater than the OD of fog.

Typical applications of a radiographic film in radiotherapy are qualitative and quantitative measurements, including electron beam dosimetry, quality control of radiotherapy machines (e.g. congruence of light and radiation fields and the determination of the position of a collimator axis), verification of treatment techniques in various phantoms and portal imaging.

Radiochromic film is a type of film used in radiotherapy dosimetry. The most commonly used is a GafChromic film which contains a special dye that is polymerized upon exposure to radiation. It is a colorless film with a nearly tissue equivalent composition (9.0% hydrogen, 60.6% carbon, 11.2% nitrogen and 19.2% oxygen) that develops a blue color upon radiation exposure. Radiochromic film is self-developing and eliminates the need for darkroom facilities. Since radiochromic film is grain-less, it has a very high resolution and can be used in high dose gradient regions for dosimetry (e.g. measurements of dose distributions in stereotactic fields and in the vicinity of brachytherapy sources). Disadvantages of radiochromic films are that they are generally less sensitive than radiographic films and require higher doses. Also dose response non-linearity should be corrected for the upper dose region.

2. **Thermoluminescent dosimeter (TLD)**

Thermoluminescent dosimeter systems (TLD) use certain substance after being doped with suitable impurities that will exhibit thermally activated phosphorescence (Thermoluminescence). In these substances, energy from radiation is absorbed which in turn will raise the energy level of some of its electrons. Though most of the electrons return back to their ground state spontaneously, a few are trapped in the impurity
level. On heating, these trapped electrons are taken to a higher energy level from which they return to the ground state with the emission of visible light.

TLDs are available in various forms (e.g. powder, chips, rods and ribbons). Most commonly used TLDs in medical applications are LiF:Mg,Ti, LiF:Mg,Cu,P and Li2B4O7:Mn for their tissue equivalence. Other TLDs, used because of their high sensitivity, are CaSO4:Dy, Al2O3:C and CaF2:Mn. Before they are used, TLDs need to be annealed to erase the residual signal. Well established and reproducible annealing cycles, including the heating and cooling rates, should be used. A basic TLD reader system consists of a planchet for placing and heating the TLD, a photo multiplier tube (PMT) to detect the thermoluminescence light emission and convert it into an electrical signal linearly proportional to the detected photon fluence and an electrometer for recording the PMT signal as a charge or current. The thermoluminescence intensity emission is a function of the TLD temperature T. If the emitted light is plotted against the crystal temperature, one obtains a curve called the TLD glow curve (figure 2.8). The peaks in the glow curve may be correlated with trap depths responsible for thermoluminescence emission.

![Figure 2.8 Thermogram (glow curve) of LiF:Mg,Ti measured with a TLD reader at a low heating rate](image-url)
The above graph shows dosimetric peak of the LiF:Mg,Ti glow curve between 180°C and 260°C. The peak temperature is high enough so as not to be affected by room temperature.

The total thermoluminescence signal emitted (i.e. the area under the appropriate portion of the glow curve) can be correlated to dose through proper calibration. The thermoluminescence dose response is linear over a wide range of doses used in radiotherapy, although it increases in the higher dose region, exhibiting supralinear behavior before it saturates at even higher doses. TLDs need to be calibrated before they are used (thus they serve as relative dosimeters). To derive the absorbed dose from the thermoluminescence reading, a few correction factors have to be applied such as those for energy, fading and dose response non-linearity. Typical applications of TLDs in radiotherapy are: in vivo dosimetry on patients, dosimetry audits (such as the IAEA–World Health Organization (WHO) TLD postal dose audit programme), and radiation fluence mapping of an incident beam.

3. **Ionometric Dosimeters**

Ionometrics Dosimetric Systems uses Ionization chambers to collect the charges produced by ionization and an electrometer to measure the collected charge. These systems are used in radiotherapy to determine radiation dose. Ionization chambers come in various shapes and sizes depending upon the specific requirements, but generally they all have common properties. An ionization chamber is basically a gas filled cavity surrounded by a conductive outer wall and having a central collecting electrode.

Design of a Farmer type cylindrical ionization chamber is shown in figure 2.9. The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing
voltage is applied to the chamber. A guard electrode is usually provided in the chamber to further reduce chamber leakage. The guard electrode intercepts the leakage current and allows it to flow to ground, bypassing the collecting electrode. It also ensures improved field uniformity in the active or sensitive volume of the chamber, with resulting advantages in charge collection. Measurements with open air ionization chambers require temperature and pressure correction to account for the change in the mass of air in the chamber volume, which changes with the ambient temperature and pressure. Electrometers are devices for measuring small currents, of the order of $10^{-9}$A or less. An electrometer is used in conjunction with an ionization chamber to measure the chamber current or charge over a fixed time interval.

Cylindrical ionisation chamber is very convenient for measurement of radiation qualities as it is robust and simple to use for measurements in a water phantom. The chamber cavity volume is between $0.1 \text{ cm}^3$ and $1 \text{ cm}^3$. This size range is a compromise between the need for sufficient sensitivity and the ability to measure dose at a point. These requirements are met in cylindrical chambers with an air cavity of internal diameter not greater than around 7 mm and an internal length not greater than around 25 mm. In use, the chamber must be aligned in such a way that the radiation fluence is approximately uniform over the cross-section of the chamber cavity. The cavity length therefore sets a lower limit on the size of the field in which measurements may be made.

![Figure 2.9 Design of a cylindrical Farmer type ionization chamber.](image-url)
A parallel-plate ionization chamber consists of two plane walls, one serving as an entry window which is the polarizing electrode and the other as the back wall which is the collecting electrode, as well as a guard ring system. The back wall is usually a block of conducting plastic or a non-conducting material (usually Perspex or polystyrene) with a thin conducting layer of graphite forming the collecting electrode and the guard ring system on top. The parallel-plate chamber is recommended for dosimetry of electron beams with energies below 10 MeV. It is also used for surface dose and depth dose measurements in the buildup region of megavoltage photon beams.

4. Chemical Dosimetry

Chemical Dosimetry uses methods to measure chemical change produced in a certain medium due to absorption of radiation dose in that medium. The amount of this chemical change can be used to measure radiation dose. It is useful in the determination of absorbed dose and also the relative absorbed dose values in a given location in a phantom with respect to the absorbed dose at a standard position. Chemical dosimetry is a good technique because an aqueous chemical dosimeter in a plastic container closely approximates the density and atomic composition of biological materials. Also liquid chemical dosimeter is very useful since the liquid can fill any shape to measure average absorbed dose in that volume. The concentration of the product ‘X’ formed during radiolysis is determined using an analytical instrument like a spectrophotometer. This is converted to dose using ‘G’ value, defined as the number of molecules, ions, atoms or free radicals formed or destroyed for each 100 eV of energy absorbed by the system. $G(\text{Fe}^3\text{+})$ indicates the no of ferric ions formed /100eV. Most G values lie between 0.1 - 15/100eV.

Commonly used chemical dosimeter in radiotherapy are Fricke Dosimeter, FBX Dosimeter, Ceric-Cerous Dosimeter etc
In our work a low level sensitive and accurate dosimeter containing ferrous sulphate, benzoic acid (BA) and xylene orange (XO) in acidic aerated aqueous solution, now known as FBX dosimeter, can be used. This was developed by Gupta\textsuperscript{28}. In this dosimeter, benzoic acid increases the chain length for ferrous ion oxidation and the chain is controlled by XO making the system accurate and reproducible. The G (Fe\textsuperscript{3+}) value is $55.9 \times 10^{-7}$ Mol/J. In addition, XO forms a complex with ferric ions which is used for spectrophotometric measurements. The ferrous sulphate, BA and XO dosimeter is capable of measuring doses in the range 0.1 to 50 Gy. The dose absorbance relationship of the dosimeter is non-linear. However, when reciprocal of absorbance is plotted against reciprocal of dose, a linear relationship is obtained. From that an empirical formula to calculate absorbed dose is obtained:

$$\text{Dose (Gy)} = 0.179/ \left( (1/\text{Fe}^{3+}) - 0.003 \right)$$

Here concentration of Fe\textsuperscript{3+} ion is expressed in $\mu$ mol/litre.

Response of the system is independent of photon energy in the range 33 keV to 42 MeV. G(Fe\textsuperscript{3+}) value is stable in the temperature range 15\textdegree C to 45\textdegree C. The molar absorption coefficient value is also independent of changes in temperature, in the same range. Fresh solutions should be prepared just before use when only occasional dosimetry work is done. Solutions once prepared can be used for up to 15 days. It is advisable to measure irradiated solutions within a day of completion of irradiation though FBX dosimeter has a post irradiation stability of three days. The pre and post irradiation effects in FBX system mainly arise due to thermal oxidation of ferrous ions in it.

**Phantoms**

The methodology of applying a dosimeter to determine the radiation parameters as per an accepted protocol or a customized setup that can be justifiable is called radiation dosimetry. The objective of radiotherapy
being to deliver the required dose to the planning target volume (PTV), patient safety also need to be ensured by controlling the exposure to the normal tissue during radiotherapy keeping it as low as reasonably achievable (ALARA). This can only be realized by following a strict disciplinary approach to the processes attached to the delivery of radiation. So a demand for quality control in radiotherapy is higher than many other disciplines of medicine. In order to perform evaluation of the radiation machine or a treatment procedure, appropriate dosimeter in a known environment that simulate radiation interaction as that of body tissue, but in a controlled setup is required. These substitutes are termed as phantoms and have been in use since the beginning of radiotherapy.

International Commission on Radiation Units and Measurements (ICRU Report 44, 1989) defines any material that stimulates a body tissue in its interaction with ionization radiation as a tissue substitute. Specific radiation interaction coefficients such as linear attenuation co-efficient and/or stopping power, are usually considered to equate two materials. A structure that contains one or more tissue substitutes which is used to stimulate radiation interaction in the body is termed as phantom. A phantom may stimulate a volume of body tissue considering anatomical structures, shape and spatial mass density distribution.

Phantoms are used widely in radiotherapy, radiological imaging, nuclear medicine, radiation protection and radiobiology. The major application is in radiation dosimetry. Other application includes its use in the calibration of radiation detector systems, assessment of image quality and in the calibration of quantitative information derived from digital images. Consequently, phantoms may be broadly categorized according to their primary function as Dosimetric phantoms, Calibration phantoms and Imaging phantoms.
A Dosimetric phantom is used for the measurement of absorbed dose in a specific geometry. The absorbed dose may be measured at a depth within the irradiated phantom. Such a phantom may also be used solely as a radiation scatterer so that the absorbed dose may be measured at a point external to the phantom. Standard Dosimetric phantoms have well defined geometry and physical dimensions with close tolerances. Uncertainties in the depth of radiation detector may lead to large errors in the measured absorbed dose\(^{31}\).

A calibration phantom may be used for establishing the response of radiation detection and for correcting quantitative information derived from digital images. Active calibration phantom contain known quantities of specified radionuclide. Inactive calibration phantoms are used for their radiation interaction properties. Calibration phantoms, both active and inactive must have their dimensions within strict tolerance, especially if they are being used solely as inactive attenuators.

An imaging phantom is used for the assessment of image quality. As in the case of a calibration phantom, it may be active or inactive. An imaging phantom may have objects of specific dimensions that act as reference points in the image. In ICRU 44\(^{29}\), it was stated that in an imaging phantom, the threshold visibility of small embedded test pieces depended upon a number of factors. They include the shape, size and attenuation properties of the bulk material in which they are embedded. Phantoms used for evaluating high resolution systems, close tolerances on the physical dimensions of these test pieces is essential.

Within each of these functional categories, there are types or designs of phantom and computational models called body, standard or reference.
A body phantom has the shape and composition of a human body or part of it. A body phantom is generally composed of various tissue substitutes simulating the human body or part of the body with respect to its size, shape, spatial distribution, mass density and radiation interaction. These phantoms are referred to as anthropomorphic phantoms.

The standard phantom was introduced in ICRU Report 10\textsuperscript{d}\textsuperscript{32} and defined in ICRU Report 23\textsuperscript{33} for radiotherapy dosimetry. It was a cubic water phantom of at least 30cm on a side and was recommended for absorbed dose determination. Different standard phantoms have been recommended for determining the absorbed dose with photons, electron beams and other radiation beams\textsuperscript{34} (ICRU 35). A heterogeneous phantom consists of a number of tissue substitutes\textsuperscript{1} but there is only one tissue substitute present in a homogenous one.

**History of Phantom Development**

Since the introduction of tissue substitutes at the beginning of last century, phantoms in one form or the other have been used extensively in experimental radiation dosimetry. By necessity, these phantoms have been fabricated from existing tissue substitutes. Therefore the types and availability of suitable material have strongly influenced the categories of phantoms in common use. Following the pioneering work of Kienbock\textsuperscript{35}, Szilard\textsuperscript{36}, Salmoud\textsuperscript{37}, Baumeister\textsuperscript{38} and others, water and wax were established as muscle or soft tissue substitutes. Consequently, during the 1920’s, experimental studies were based on tanks of water and blocks of wax\textsuperscript{39}.

The concept of ‘Reference Man’ was introduced by ICRP in 1975 to represent a large population\textsuperscript{40}. He has been defined as being between 20-30 years of age, living in a climate with average temperature from 10\ruler{\textdegree}C to 20\ruler{\textdegree}C and a Western European or North American in habitat and custom. 1988 the Eastern countries jointly produced a “Reference Asian Man'.
Radiation related requirements for Phantom

The composition and/or shape of any phantom adopted for radiation dosimetry or other radiation measurements derive from the accuracy required.

“Available evidence for certain type of tumors points to the need for an accuracy of ±5% in the delivery of an absorbed dose to a target volume if the eradication of the primary tumour is sought”- ICRU$^{41}$.

Any phantom used for radiation dosimetry or other radiation measurements, must fulfill certain requirements.

1. The geometry of the complete phantom, its internal and external physical dimensions must conform to the limits required by the application.
2. Tissue substitutes used for the construction of a phantom must have either known elemental composition and mass densities or known measured radiation absorption and scattering properties for the type and energy of radiation under consideration. In addition, the tissue substitutes must not introduce error in absorbed dose estimation or radiation attenuations, greater than those permitted by the applications.
3. Any machined or fabricated cavities for radiation detection must be at the required, specified depth, within the uncertainty permitted for the planned measurements.

The first two requirements given above ensure that the radiation interaction within the irradiated phantom match to the required accuracy with those interactions that would occur in a corresponding body section of the same geometry and physical dimensions. Consequently, the radiation absorption and scattering that occur within the irradiated phantom, together with any associated absorbed-dose determination, would be within
the required accuracy. These requirements apply to the three functional groups of phantoms (dosimetric, calibration and imaging) and the three types of phantoms (body, standard and reference).

Non-radiation requirements of Phantom

In a homogenous phantom the inhomogeneities due to poor dispersion of fillers or unintentional porosity in solid tissue substitutes must not introduce uncertainties in excess of 1% in radiation transmission or adsorbed dose estimations. Absorption of water by the material should not introduce any inhomogeneity. Also the material must be free from contamination with high Z materials. Minimal water loss should be ensured if the phantom material is an aqueous solution or water based gel. Liquids and gels must be contained in vessels of adequate wall thickness to avoid leakage and which will not chemically react. A suitable bacteriostat (e.g. Sodium Azide) should be used in them to inhibit fungal growth. Inhomogeneities due to trapped air in phantoms containing liquids must be minimized.

All tissue substitutes should be inert and stable and plastics containing volatile plasticizers should be avoided. If more than one tissue substitute is used in a phantom, no chemical reaction should take place between them. Material should not degrade under repeated irradiation and should maintain dimensional tolerances. Phantoms should have sufficient mechanical strength to withstand routine handling and should not deform irreversibly.

General Properties of a Phantom

What ever be the type of phantom, Body, Standard or reference, they follow some general properties.

i. Body phantom must take into account both external and internal dimensions of the body it represents. Physical dimensions of the structures should be as per the stated values.
ii. A standard phantom by definition has a well defined geometry. The external cross section of the phantom is usually larger than the specified radiation beam area so that a margin of at least 5cm is present around the primary beam at measured depth. Acceptable uncertainties in the external dimensions of the phantom are less stringent than those applied to the depth of radiation detector.

iii. Reference phantoms have simple well defined geometry. Dimensional tolerance should be stated in the description of the phantom.

Standard dosimetry phantoms are used in radiotherapy to compare irradiation under standard conditions. They provide volume of tissue substitute for the measurement of absorbed dose and are large enough to ensure that essentially the full contributions of the absorbed dose from scattered radiation is received at the point of measurement. Water and other tissue substitute such as polystyrene, acrylic and WTI are commonly used because of their acceptable and reproducible composition and availability with necessary purity for radiation dosimetry. Standard phantoms for photon radiotherapy are defined in ICRU Report 23 as a homogenous phantom of 30cm x 30cm x 20 cm deep. The physical dimensions of the phantom are such that they leaves a margin of 5cm around the primary photon beam. The standard phantom for electron therapy is defined in ICRU Report 35 as a 30cm cube. The total depth should be 5cm greater than the practical range. Water and other solid phantoms can be used for electron beam.

**Safety requirements of a phantom**

All phantoms must be safe to use in normal practice and must not present user with an undue hazard.

i. They should be made of non-toxic materials (solids, liquid and gels) that are non-carcinogenic and hypo-allergic. Corrosive and volatile materials should be avoided. Materials giving off hazardous quantities of toxic
gases must be avoided if appropriate safety enclosures are not available. Adequate ventilation must be provided if volatile products have to be used.

ii. The phantom design should be such that Sharp edges/ corners should be avoided in a solid phantom⁴³.

iii. Excessive use of silicon grease on the surface of a solid phantom to enhance appearance should not affect safe handling.

iv. A phantom with a mass of over 10kg should be provided with the means of moving it safely from place to place and should be placed on strong support when in use.

v. A phantom that contain liquid and gel must be leak proof.

vi. The incorporation of a radioactive material into a calibration or imaging phantom must be strictly controlled by a competent, authorized person. All statutory requirements with regard to surface absorbed dose rate, surface contamination levels, hazard warning notices etc must be observed. All contained radioactivity, whether solid, liquid or gel must be in leak proof container. Fragile, friable products should not be used to contain radioactive materials. Safe, secure storage is essential and use of double containment with absorbent packing, during storage, is strongly recommended.

vii. All necessary fire precautions must be enforced if flammable products are used as phantom material.

An ideal quality assurance tool is one which could help to realize a quality assurance program objective. In radiotherapy this is achieved with the combination of a tissue equivalent phantom with a proper radiation dosimeter. In the present work a tissue equivalent phantom with the objective of doing quality assurance in radiotherapy machines and procedures is designed as per the guidelines.
Reference:


9 International Commission on Radiation Units and Measurements, Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma rays in Radiotherapy Procedures. ICRU Report No. 24; Bethesda, MD. ICRU 1976.


17 ESTRO. Quality Assurance of Treatment Planning Systems Practical Examples For Non-Imrt Photon Beams, 2004; Brussels.


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36 Szliard B. On the absolute measurement of the X-rays and gamma rays. Arch Roentgen Ray 1914; 19: pp 3.


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