Code of practice for x-ray therapy linear accelerators*

Part I: Information for radiation oncologists and hospital administrators

The successful treatment of cancer by radiation incorporates a skillful balance between the maximum probability of cure and the minimum probability of radiation-induced complications. It is now well documented that precisely administered radiation treatments are a requisite to achieving that balance and, therefore, are essential for radiation therapy with curative intent.

The use of megavoltage radiation in external beam therapy is one major step toward this goal of precision. However, the use of megavoltage radiation does remove or greatly modify many of the visible biological indicators previously used by the radiation therapist to evaluate the progress of the treatment and to avoid complications. Therefore, the radiation therapist must obtain a precise knowledge of the radiation dose distributed throughout the irradiated volume of the patient prior to initiating treatments. This knowledge must not only include the dose to the tumor itself but also the dose to normal organs or radiation-sensitive structures in the irradiated volume. This knowledge is based on physical information regarding the radiation beam to be used, on how this beam is altered as it passes through the various tissues of the body, and, finally, on how several beams are to be utilized to achieve the desired dose distribution in the patient. This information is all at a much higher level of sophistication than that practiced for orthovoltage therapy. If the advantages of megavoltage radiation therapy are to be realized, then the decision to purchase must be accompanied by the decision to carry out the required physical measurements (Appendix I) with the assistance of a qualified radiological physicist (Appendix II). This radiological physicist shall plan and survey the installation in order that it comply with the various State and Federal laws as well as the recommendations of such bodies as the Federal Radiation Council and the National Council on Radiation Protection. The physicist shall certify that the therapy equipment is performing according to specifications after it is installed, generate the data necessary for the practice of high-quality radiation therapy, and outline a procedure to be used daily to determine that the machine is operating under the conditions for which the data were obtained. It must be emphasized that the practices of output calibrations once a year and dose distributions measured on other equipment are totally inadequate and not accepted as good practice.

It is necessary that the qualified radiological physicist have the appropriate equipment and instrumentation to perform the required measurements. It is also highly desirable that he have access to computer facilities so that meaningful physical evaluation of complex treatment plans proposed by the radiologist may be rapidly performed prior to the initiation of therapy.

In summary, the decision to provide a community with megavoltage radiation therapy facilities not only involves a decision to enlist the services of a radiation oncologist, purchase and house the therapy equipment, and arrange for its continued maintenance, but also to provide for the support of the qualified radiological physicist who has access to the appropriate equipment and facility.

Part II: Installation and performance measurements for x-ray linacs

I. INTRODUCTION

This is Part II of a document prepared on behalf of the American Association of Physicists in Medicine as a guideline for the physical aspects of the installation and continuing use of megavoltage linear accelerators. It is intended to apply primarily to accelerators of 10-MeV energy or less. Part I indicated the objectives of this document and emphasized the importance of the services of a qualified radiological physicist to a hospital contemplating use of such an accelerator. Part II is intended as a more specific guideline for the radiological physicist with respect to tests to be carried out at the time of installation of megavoltage accelerators as well as tests and measurements carried out regularly to ensure continuing accuracy of performance. This document is necessarily brief, and primary reliance must be placed on the training and experience of the physicist. References are made to dosimetry documents prepared previously by the AAPM and other groups. Any questions on this document should be referred to the Chairman of the Task Group of the AAPM Scientific Committee responsible for its preparation.

II. INSTRUMENTATION

A. Survey meters

Two types of survey meters are required:

An ionization-chamber-type survey instrument having multiple ranges from 0 to not more than 5 mR/h full scale

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to 0 to 50 R/h full scale. This need may be met by one single instrument or by a combination of several having linear or logarithmic scales. Instrumentation with the capability of measuring exposure as well as exposure rate is useful for measurement of leakage radiation around the x-ray head. The construction should be such that the calibration factors do not change more than 5% with orientation or for a change in photon energy from ^{137}Cs to ^{60}Co gamma radiation.

A rapid response Geiger or scintillation-type survey meter whose purpose is to search for anomalous leaks of radiation into occupiable space. Such leaks may be due to structural defects, unbacked junction boxes in the walls, inadequate caulking of lead glass windows, defects in overlaps between lead doors and leaded jambs, etc.

Both types of survey meters shall be calibrated against a certified cesium, cobalt, or radium source within three months prior to use for purposes of survey.

B. Calibration dosimeters

The primary calibration of megavoltage therapy equipment should be made with an ionization chamber bearing calibrations for ^{60}Co gamma rays traceable to the National Bureau of Standards (NBS) through no more than one exchange. Alternatively, it may be calibrated by a Regional Calibration Laboratory (RCL). A calibration certificate should be obtained which includes chamber calibration factors, a specification of the voltage sensitivity, linearity of response, electrical leakage, size of irradiation field at calibration, stem leakage effects, and presence of openings to the atmosphere. Measurements should be made at 5-cm depth in a primary tissue-equivalent phantom (see Sec. V.C) and corrected for spectral differences by use of the appropriate C_λ factor.[1] Check measurements which are normalized to such a primary calibration may be made under more varied conditions suitable to the phenomena under study (e.g., "in air" for study of variations in output with angle of the gantry, "in a finite size" phantom for daily checks, etc.).

The changes in instrument calibration produced by the trauma of frequent use and transportation dictate that at least two ionometric dosimeters should be available together with an isotopic calibration source. One dosimeter should be of a design suitable for a local standard. Ideally, it would be reserved solely for that role. Under certain circumstances it may be used for the relatively infrequent initial, primary, reference calibration of a machine; otherwise, a third instrument similar to this first must be available for this purpose. The second ionometric dosimeter may be of less restrictive design and may be used as the field instrument for ongoing calibration of equipment subsequent to the initial reference calibration. It should be subject to frequent calibration checks against the local standard.

1. *Dosimeter suitable for a local standard and for initial or reference calibrations*

A direct-reading, integrating dosimeter is preferred as a local standard. If multirange, the instrument should be calibrated on all ranges. The linearity of response between indicated instrument reading and ^{60}Co gamma-ray exposure should be within $\pm 1\%$. The design should be such that it is inherently capable of being calibrated to within $\pm 0.5\%$ of a national standard for ^{60}Co gamma radiation after correction for linearity of indicated response. The full-scale deflection should be in the range of therapy exposures. The ion-chamber wall should be of sufficient thickness, either inherently or by means of an added plastic cap, to provide electronic equilibrium for ^{60}Co gamma rays. If fitted with a cap, that cap must be considered an integral part of the instrument for all measurements utilizing the ^{60}Co gamma-ray calibration factor. The collection efficiency of the chamber should be determined for conditions of instrument intercomparison. If the intercomparison with field instruments is performed in a ^{60}Co gamma-ray beam, the collection efficiency should be determined under conditions of maximum dose rate to be used in standardization. If the beam is of a pulsing nature, the collection efficiency should be determined under conditions of maximum dose-rate and dose per pulse. If the design of the instrument permits controlled variation of the collection voltage on the ionization chamber, the saturation current or quantity of charge collected per unit time should be determined for positive and negative polarity and the mean value taken. The saturation current may be obtained by placing the collecting voltage at +50, +100, +150, +250, +500 V, or any other increment suitable to the chamber and recording the observed ionization current for each voltage with a constant exposure rate. The resulting data may be plotted against the reciprocal of the square of the voltage. Extrapolation of this curve to 0 on the $1/V^2$ axis yields the true saturation current as the intercept on the current axis. The design of the instrument may not permit controlled variation of the collection voltage for experimental determination of collection efficiency. The collection efficiency under the conditions of use outlined above may be computed using the method of Boag.[2] Limited information on the values of the constants entering the calculation make it advisable to operate the chamber under conditions where 99% collection efficiency may be expected from such calculations so that the correction is small. The interval between return to an RCL for recalibration should not exceed two years if the dosimeter is dedicated as a local standard and routinely compared to an isotopic standard. The instrument stability should be such that changes in calibration factor in excess of 1% are not observed between calibrations by an RCL.

If an isotopic source suitable for constancy check is available, one instrument may be used for primary calibrations in addition to its use as a local standard for comparison with other dosimeters. If no suitable source is available, one instrument should be used solely for comparison with other dosimeters and a second equivalent calibrated dosimeter should be obtained for initial primary reference calibrations.

To be useful for primary calibration, the ion chamber internal diameter should not exceed 1 cm nor the length 2 cm since displacement and field uniformity corrections will be excessive.[3] The collection efficiency of the chamber

under conditions of maximum dose rate and dose per pulse should exceed 99% as determined above.

Stem effects should be minimized (e.g., by a guarded signal conductor design) and should be quantitatively known. The effects of rf interference should be minimized by external earthed sheaths and modifications to the electrometer circuits where appropriate. If the chambers are not hermetically sealed, the reading must be corrected for deviation of ambient temperature and pressure from those pertaining to the calibration. If the chambers are to be subject to sudden changes in either parameter, the rate of equilibration, and therefore the time to reach room temperature and pressure, should be known.

To make these corrections, it is desirable that a thermometer and high quality aneroid barometer calibrated against a standard mercury barometer be available to measure the atmospheric temperature and pressure relevant to the calibration conditions. If an aneroid barometer is transported by air, the calibration may be lost by the pointer being driven against the stops and the calibration should be checked against the elevation barometric pressure as recorded at the airport before leaving for the therapy installation which may be at a different altitude. If the instrument is to be transported between treatment centers for initial reference calibrations, it should be hand-carried and placed on the floor of an automobile or in the passenger cabin space in an aircraft. This practice will minimize possible modifications to the calibration factor caused by mechanical changes and by significant temperature and pressure variations. It may be shipped to an RCL for calibration but should be returned by courier after calibration.

The instrument, if widely transported, should be submitted for recalibration by an RCL annually when all features of the certification will be reviewed. Instruments used locally and compared with isotopic standards routinely need only be returned to an RCL every two years for recertification.

2. Routine field instrument used for ongoing calibrations of equipment subsequent to the initial reference calibration

This instrument will be of maximum use if it is multirange and multipurpose so that large and small doses and dose rates can be conveniently measured in one to two minutes. If an integrating survey meter is not available (Sec. II.A) then an auxilliary ion chamber large enough to serve the same purpose for exposures as low as one thousandth of primary beam intensity should be available. The considerations of chamber size, low collection efficiency, stem effects, and rf pickup, enumerated under Sec. II.B.1, are relevant. Linearity of response should be $\pm 1\%$ over the working range. The spread of repeated readings in a ^{60}Co gamma-ray beam should not exceed $\pm 1.5\%$ and the long-term calibration stability should be such that changes in calibration factors do not exceed $\pm 2\%$ between comparisons with the local standard. Field instruments should be calibrated by an RCL at purchase and immediately compared to the local standard. If an isotopic source is available for local intercomparisons, the instruments do not need to be returned to an RCL until a deviation in calibration factor in excess of 2% is observed. If no isotopic source is available they should be returned to an RCL at least every two years.

C. Care and maintenance

Instructions given in the manufacturer's handbook should be followed. In the event of defective performance, do not attempt local repairs. When not in use, the instrument should be kept in an appropriately sealed carrying case, glass jar, or polyethylene bag. In moist environments these should contain dessicants, which should be maintained in active condition. It is recommended that the dosimeter be assessed for constancy of performance on a routine basis by comparison with a local isotope standard with reproducible geometry. Such standards are usually available from the manufacturer of the instrument.

III. RADIATION PROTECTION SURVEY

A. Surveyor safety

Check that the radiation ON warning lights and door interlocks of the treatment room have been installed and that they and the EMERGENCY OFF buttons are operative. To ensure that subsequent survey measurements are meaningful, make a preliminary measurement of the output of the machine. This may conveniently be made "in air" at the isocenter with a field instrument which has been fitted with a cap of sufficient thickness to provide electronic equilibrium. If the delivered dose rate at the isocenter is within $\pm 5\%$ of specification, it may be considered that the linac is operating satisfactorily for purposes of survey. This limit is chosen to account for measurement errors and errors due to misalignment between the center of the x-ray beam and isocenter of up to 1 cm.

With the radiation beam in the most frequently used position and incident on a scattering medium of sufficient size, determine if the exposure to the operator is likely to exceed permitted limits during the survey using the maximum collimator aperture, with consideration given to arbitrary collimator rotation angles, and the x-ray machine operating at its maximum practical working dose rate. If the exposure rate is satisfactory, proceed with the radiation measurements with the x-ray unit operating as above. If not satisfactory, and the installation complies with the drawings and original assumptions of the design, reduce the beam intensity or otherwise maintain operator exposures below the recommended levels and proceed with a view to determining the source of excess exposure. All measurements shall be made from outside the room.

B. Head leakage

1. Anomalous leaks

The purpose of this test is to locate the zones of highest exposure from leakage radiation for subsequent quantitation. With the primary beam blocked by the collimator shutters or shutters supplemented by lead blocks, enclose the head with "ready-pack" film. Choose the slowest avail-

able film so that optimal exposure conditions can be utilized. The film is easier to handle if no cassette is used. If the film is maintained in contact with the head, the accelerator housing will provide sufficient build-up material for the purpose in hand. The films should overlap by at least one inch and be coded (e.g., by pin pricks) to permit keying of the spatial position of the film relative to the treatment head. Provide a sufficiently long exposure to produce an optical film density of approximately unity in the hot areas. This may be approximated by computation from the expected output of the machine and the geometry but should be expected to require several trial exposures of film in one typical position. With type M film and automatic processing, an integrated dose setting of approximately 1000 rads is found to be satisfactory.

2. *Determination of absolute leakage*

Using suitably calibrated ion chambers of appropriate wall thickness and sensitivity range, measure the "in-air" dose or dose rate 1 m from the target in any "hot areas" as demonstrated by the films. If the dose rate over these hot areas exceeds the permitted limit of 0.1%[5] of the useful beam around the main x-ray housing and fixed primary collimator, their elimination is the responsibility of the equipment manufacturer.

Measure the dose rate in areas shielded by the movable collimators. Leakage radiation at 1 m from the target should not exceed 2% of the maximum useful beam at 1 m and *shall* not exceed 5%.[5]

C. Occupiable space outside the treatment room

The radiation survey should be performed under conditions that are likely to give the highest exposure at the point of interest, i.e., without scattering phantom for primary barriers but with a phantom for secondary barriers. This phantom should produce maximum scatter; it should be 10 cm larger than the beam on all sides. The pattern of dose as a function of machine orientation should be established in areas likely to experience exposures above background caused by operation of the linear accelerator.

To conduct the survey, first establish a 3×3 ft matrix for observation points, using chalk or strips of masking tape on relevant wall, floor, and ceiling surfaces. Measurements may be made 1 ft away from each surface. Record the dose rates at these points as obtained from an ionization-chamber survey instrument while operating the x-ray generator at a constant, safe dose rate (Sec. III.A). Search areas between matrix points for anomalous leaks using equipment with a rapid response. This process is facilitated if the instrument has an aural as well as visual indication of radiation response. Special attention should be paid to areas adjacent to inset junction boxes, windows, conduits, pipes, ventilation ducts, door frames, and transoms.

The expected weekly exposures can be computed from these data together with the expected workload and use factor of the treatment unit and the occupancy of the adjoining spaces. A signed, written report and statement shall be prepared as to the compliance of the installation with the appropriate radiation control regulations.[4,5] This report should contain an evaluation of the expected weekly exposures, measured leakage radiation data, tests of interlocks, observations of warning lights, checks of emergency switches, and copies of posted notices.

IV. OPERATIONAL PERFORMANCE AT INITIAL INSTALLATION

It is essential that the sequence of checks and adjustments be performed in the order indicated.

A. Mechanical alignment of the collimator jaws on the axis of rotation of the collimator

The mechanical closure of the collimator jaws on the mechanical axis of rotation of the collimator should be tested first and, if necessary, adjusted. This is accomplished using a downward-directed beam with the aid of a straight, pointed rod of small diameter and sufficient length to be grasped by all four collimator jaws so as to extend beyond the jaws to the isocenter. Close down both pairs of jaws so that the rod is firmly held. This may require the rod to be accurately tapered for some units. Place a white card perpendicular to the end of this rod, taping it to the couch or other support. The collimator assembly should now be rotated and the pattern traced by the moving point inspected to detect any departure from co-linearity and, therefore, misalignment between the jaw closure positions and collimator rotational axis. If misalignment exceeds 0.5 mm, adjust the jaw closures according to the manufacturer's instructions. Mark the aligned jaw closures and collimator rotation axis on the white card. This will serve as the reference point for the checks that follow.

B. Coincidence of the mechanical axis of the collimator assembly, the central axis of the light beam, and the cross hairs

With the white card perpendicular to the rotation axis of the collimator, remove rod and turn on the field light. Adjust the collimator to yield a rectangular field smaller than the card. Note the collimator rotation angle on the degree scale. Mark (a) the edges of the light field, (b) the intersection of the diagonal, and (c) the position of the image of the cross hairs. Points (b) and (c) should coincide. Rotate through 180° and check for coincidence of the new position of the edges of the light and the cross-hair intersection of the diagonals with the previous positions as marked on the card. If all are in alignment, proceed to IV.C. If significant misalignment exists, the field-light edges will appear displaced and not coincident for 180° rotation of the collimator. In this case, adjust the position of the field-light bulb for correct alignment, i.e., coincidence. Since field-light positioning will move the image of the cross hairs, it must precede adjustment of the cross-hair position which is the final adjustment. The cross hairs are adjusted to provide images that are parallel to the jaws and intersecting at the point marked on the white card. The mechanical adjustment check is important and must be per-

formed accurately and prior to the measurements that follow.

C. Coincidence of the light beam with the useful x-ray beam

This may be divided into two parts:

(i) Are the light and x-ray beams symmetrically related to one another for all orientations of the collimator assembly and of the gantry; i.e., is the target (or focal spot) coincident with the effective position of the light source and the geometric back projection of the collimator axis?

(ii) Are the dimensions of the light beam, the settings of the collimator dials, and the formally defined x-ray beam sizes coincident at the reference distances; i.e., is the light source at the correct optical distance from the collimating aperture and are the collimator dials correctly inscribed?

The reference distance may be the source-to-skin distance or the source-to-axis distance. The boundaries of the field are defined geometrically by lines from the center of the front face of the source, which intersect the inner edges of the collimator. The divergent field so defined will coincide approximately with 50% of the central dose rate in air and, in practice, with the 50% isodose curve at the depth of maximum electron buildup in the phantom. This has the advantage that the light localizer size may be observed on the skin and measured with fewer artifacts from electron contamination by a detector with an electronic equilibrium wall "in air" or at depth of electronic equilibrium in a phanton. Field size is also defined in Sec. X.A.

1. *Symmetry of light and x-ray beam*

Three methods of checking the symmetry of the light and x-ray beams are:

(*a*) *X-ray film method.* Open the radiation field to a rectangular field of the size of interest. A rectangular field is recommended to reduce confusion between sets of collimator jaws. Place a film wrapped in a light-tight envelope (or use ready pack) in the light beam at the proposed treatment distance (SSD or SAD) and perpendicular to the central axis of the beam. Place a small lead marker at the precise center of the field as delineated by the light and cross-hair image (see Sec. IV.B). Several alternative methods of marking the light beam are available, e.g., use of rectangular lead plates or disks to mark the middle of the edges of the field or the corners of the field or a ballpoint pen may be used to mark the film directly through the envelope. The corners may be marked by use of a needle to pierce through the envelope and film base. Cover with sufficient material to produce electronic equilibrium. Make an exposure sufficient to yield an optical density on the film in its linear range, usually between one and two. Rotate the collimator through 90°. Move the film so that a fresh area is exposed or use a second film. Replace the markers and buildup material and make a second exposure. Process the film.

Visual inspection, aided by a ruler, of the x-ray-beam image and light-beam fiduciary marks will determine if the light and x-ray fields are symmetrically related and if the symmetry is retained on rotation of the collimator. The process should be repeated at 0°, 90°, 180°, and 270° angulations of the gantry.

(*b*) *Ionization chamber method.* A small ionization chamber with a buildup cap, 6 mm i.d. or less in the dimension perpendicular to the field edge, is fixed rigidly to the diaphragm system by clamps firmly attached to the accessory holder and located 20 cm or so below the collimator jaws so that it is in the penumbra. This is achieved by taking a reading on the ionization chamber with the jaws fully open and then closing the jaws until the reading on the dosimeter is half its initial value. Several identical exposures are made and the average reading noted. The diaphragm system with the ionization chamber attached is then carefully rotated through 180° without disturbing the jaw setting. A further series of readings is taken and the average noted. If the focal spot is symmetrically positioned on the central axis these two averages will be identical within 2%–3%. The method may be employed using square fields on units in which the rotation of the collimator is restricted to 90°, but this is less satisfactory.

(*c*) *Linographic paper method.* Type 1895 Kodak linographic paper exhibits responses to ionizing radiation and visible light that are effectively opposite in blackening effect. Furthermore, the sensitivity of the paper to visible light is such that it may be handled in subdued light (1–2 fc) from incandescent lamps without imaging. If the paper receives a x-ray dose of 250 rad and is then subject to 150–200 fc from a fluorescent lamp (such as a desk light) for one minute, a dark image of the irradiated field develops. Then, if without moving the paper it is illuminated by the localizing light for two minutes, only the differences between the two fields will show as light or dark areas.[6] Misalignment may be observed by inspection.

The test should be applied for orthogonal placements of the collimator and quadrature angulations of the gantry as indicated above.

Misalignment between the center of the light and x-ray beams should not exceed 1.5 mm at the reference distance. As the concentricity of the light and collimator system has already been verified, misalignment between light and x-ray-beam edges or center implies that the x-ray beam is not centered on the rotational axis of the collimator. This misalignment should not move with the shadow of the collimator jaws as they are rotated. If it does follow the jaws, recheck for axial alignment of lights and collimators and for mechanical alignment; e.g., do the jaws close symmetrically through all field sizes?

2. *Coincidence of light field, collimator dial settings, and x-ray beam sizes at the SAD or SSD distance*

(a) *Film method.* The films developed under IV.C.1(a) above may be scanned with a film densitometer to determine the location of the edge of the x-ray field as defined by the 50% level of the central area density (excluding the spot caused by the marker). Repeat for small, medium, and large fields. The distance from the center of the field to each

edge in each orientation of the collimator may now be measured.

The distances from the center to each side, as indicated by the 50% levels of central film density, should be equal, and the total distance between opposite sides should agree with the dimensions as indicated by the light beam and collimator dial to within 1.5 mm. If the light beam and radiation field are in agreement, then the collimator dials should be adjusted to agree with the light and radiation beams.

(b) *On-line scanning method.* If a small detector and scanning mechanism are available, the detector can be scanned across the beam in a water phantom at a depth corresponding to the maximum dose. The signal from the detector may be fed out to an *X-Y* plotter. The light-beam dimensions can be measured and the position of the cross hairs indicated by a photon-absorbing marker, such as a piece of lead, to provide a beam-center fiduciary mark. The data may be reviewed as described under the film method. It should be noted that the detector must be sufficiently small so that the dose gradient across it in the penumbra is not greater than 30% or the geometric center and the center of sensitivity will not be coincident.[3]

D. Determination of the mechanical isocenter

If not supplied, a graticule should be fitted in the light-localizer optics or a cross hair should be fitted at the collimator exit. Their images should be aligned with the mechanical center of the collimator system, the light localizer beam, and the x-ray beam as outlined above.

The approximate location of the isocenter may be determined by orienting the gantry in two successive positions at right angles to each other (e.g., 0° and 90°) and finding the intersection of the central ray (by graticule or cross-hair image) from each orientation. By using a needle point in a vise mounted on the treatment table at this approximate location, the lateral and vertical isocenter projections may be refined by locating a fixed point in space equidistant from the head at 90°, 270°, 0°, and 180°. If a piece of paper is wrapped around a length of square-section bar stock centered on the isocenter with its long axis along the gantry axis and with two of its faces vertical and two horizontal, the position of the image of the cross hairs on the paper may be marked with the beam vertically up and down (0° and 180°) and right and left horizontal (90° and 270°). When the paper is opened out it can be seen whether the image of the cross hairs representing the mechanical center of the beam passes through an isocenter or not. If the mechanical center of the beam passes through an isocenter, then all four images will be on a straight line parallel to the top edge of the paper, and they will be equidistant from the corner of the bar stock as indicated by fold marks on the paper. The range of movement of the mechanical center of the beam may be readily obtained from the displacement of the images. It should not move outside a sphere 2 mm in diameter. An alternative procedure utilizes a mechanical pointer grasped in the jaws of the collimator and of such a length that its end coincides with the approximate position of the isocenter. The pointer should terminate in a scribe or other recording device so that the excursion of the end of the rod may be registered as the head is rotated. It should be noted that measurements are required in at least two planes and the tolerances demand care in setting up the recording device.

If the mechanical isocenter location is satisfactory, proceed to the next step. If not, consult with the installation personnel.

E. Determination of the isocenter of the radiation beam

1. *Collimation*

Rotate the gantry so that the x-ray beam will be perpendicular to the floor and table top. Open the upper jaws of the collimator wide; close the lower jaws to yield a narrow slit of radiation 1 mm or less at the isocenter distance. Place a film flat on the table top. By rotating the collimator, make eight exposures on the same film, sufficient in duration to produce unit film density. Make four of the exposures 45° apart, the fifth exposure 67° from the fourth, and complete four additional exposures at 45° intervals.

Close the upper jaws to a narrow slit, open the lower jaws, and repeat the above sequence on a new film.

On development, lines may be drawn parallel to and centered in the eight images. The intersection of the lines should be contained in a circle *1.5 mm in diameter.* If the result is satisfactory, proceed to the next step.

2. *Treatment table*

It is assumed the table is capable of 180° rotation about the isocenter. Place a film on the table top. Open the upper jaws of the collimator wide and close the lower jaws to yield a narrow slit of radiation 1 mm or less at the isocenter distance. Make seven exposures on the same film rotating the table through 30° between exposures except for the movement between numbers 6 and 7 when the angle should be reduced to 20° to avoid overlap with image number 1. The intersection of the center lines of the images on the developed film should be contained in a circle *1.5 mm in diameter.*

3. *Gantry*

Support a film in a cassette in a vertical plane such that the plane of the film contains the beam central axes for all gantry positions. Reduce the beam to a slit that is horizontal and parallel to the gantry axis of rotation when the gantry is at 90°. Make twelve successive exposures on the same film with the gantry rotated between exposures. Make the first six exposures 30° apart, make the angulation 45° between numbers 6 and 7, and the angulation 30° between the subsequent exposures to avoid overlap. The intersection of the center lines of the beams should be contained within 2 mm.

If the above tests are satisfied, the radiation isocenter of the gantry will be contained within a 2 mm diameter sphere.

F. Timer

The timer on accelerators is a secondary device used for exposure termination in the event of dosimeter failure. It should be tested for machine turnoff against a good wrist watch with a sweep second hand. The time intervals should correspond to typical treatment times.

G. Verification of beam flatness

The manufacturer usually specifies beam flatness in terms of a certain percentage variation about the average dose along the central portion of the longitudinal and transverse axes of the maximum field size at a certain depth. Typical figures are $\pm 3\%$ over the central 80% of the largest field area at the isocenter or the usual TSD plus 10 cm of water or equivalent material in the case of some non-rotational units. Provided the position of the focal spot remains stable relative to the beam-flattening filter, the dose distribution at the specified depth in a water tank may be rapidly explored by use of an ionization chamber, operated in the rate mode, traversed along the longitudinal and transverse axes by means of a lead screw. Assemblies employing solid state detectors are commercially available. Such rapid response devices are particularly valuable in initial alignment of beam-flattening filters. The response of such devices should be assessed by comparison with ionization-chamber systems before they are used for quantitative measurements. If the focal spot is not spatially stable, an average value of dose over a precessing cycle or a time period comparable with treatment times is desired. This may be obtained by use of lithium-fluoride–Teflon disks or a slow film such as imaging film placed in a polystyrene phantom (e.g., the SCRAD phantom[7,8]) so that the plane occupied by the detector passes through the isocenter and is covered by the appropriate thickness of essentially unit density material. This thicknesss should coincide with the depth at which beam flatness is specified.

If the beam is flat within the specified limits, the beam should then be checked for symmetry using the above cross-plot data. Symmetry problems can usually be corrected by re-alignment of the flattening filter or accelerator guide. Energy assessment by central-axis depth-dose measurement follows (see Sec. VI). If the beam flatness does not meet specifications but the beam energy is correct, the manufacturer of the treatment unit should be consulted. If modification of the beam-flattening filter is subsequently necessary, a repetition of all further steps in this manual will be required.

Further information on procedures described in this section is available from the Hospital Physicists Association.[9]

V. CALIBRATION OF THE MACHINE

For general properties of the ionometric calibration dosimeters, see Sec. II.B.

A. Instruments

If an integrating dosimeter with a balancing circuit is employed, the electrometer should be continuously balanced during operation. If a condenser-chamber-type instrument is employed, the exposure time should be adjusted so as not to exceed $\frac{2}{3}$-scale reading for comparison with the indicated monitor units. If the instrument is of the type providing a choice of rate or integrated dose, it is recommended that the unit be operated in the integrating mode. Exposure time should be adjusted so as to compare 50% of full scale on an appropriate sensitivity setting with the indicated monitor units. All chambers should have been fitted with caps or sleeves sufficient to produce electron equilibrium for ^{60}Co gamma radiation and to have been calibrated against a standard traceable to NBS for that radiation. In all subsequent manipulation, the additional caps or sleeves must remain in position. The calibration factor for ^{60}Co γ rays will be referred to as N. The collection efficiency of the monitor chamber in the machine must be determined (see Sec. II.B.1) and its linearity over the range of available repetition rates should be checked.

B. Depth of calibration

Experiment shows that measurements in air or at dose maximum are subject to influence by secondary electron contamination or dose gradients.[10] Thus, while in-air or other measurements with standardized walls may be satisfactory for "check" measurements, basic calibration should be performed at depths in a phantom where these effects are not significant. For uniformity of practice, a depth of 5 cm is recommended.

C. Phantoms

Phantoms may be divided into two groups, primary phantoms and secondary phantoms. Primary phantoms are the best match to tissue, they are accurately reproducible from place to place, and basic data generated using them are substantially without dimensional corrections for density effects. Water is the standard material for such a phantom. Using such a primary phantom presents some difficulties and a number of solid secondary phantom materials have been developed.

1. Primary or water phantom

Water is the standard material in which dose is to be determined. An acrylic resin (Perspex or Lucite) tank makes a convenient container. It should be deep enough to provide maximum backscatter and large enough in cross-sectional area to provide 5 cm margin about the largest field size. Typically, this would be $40 \times 40 \times 40$ cm so that the photon beam may be incident on the phantom horizontally or vertically. If the phantom is to be used with the beam horizontal, the anterior side should be provided with a wall 3 mm or less in thickness or, better, a "window" of 3 mm. Under these circumstances, with an acrylic plastic tank, corrections for the difference between water and the wall material may be neglected. It is recommended that the ionization chamber be held in a jig that ensures a reproducible relationship between the center of the chamber and the free surface of the water (or the tank wall if the beam

is horizontal). If it is necessary to fit a waterproof sleeve to the chamber and this is of acrylic plastic such as Lucite, this may form part of the jig. It is desirable that this sleeve not increase the effective wall thickness beyond 5 mm and, therefore, may conveniently be the buildup cap for the ^{60}Co calibration.

2. Secondary phantoms

Secondary phantoms of polystyrene, acrylic plastic, Temex (a tissue equivalent rubber), Mix-D slabs, etc. may be used to supplement the primary water phantoms for the calibration of linear accelerators. The advantages of plastic phantoms are the exact reproducibility of detector positioning, the possibility of making measurements for any beam direction, and the speed and convenience in handling.

In order to use plastic phantoms for dose calibration, the calibration depth must be adjusted so as to be equivalent to the recommended depth in water in g/cm^2. Because of the variation in density of commercially produced plastic, it is desirable that this should be experimentally determined. In order to avoid inverse square law corrections in polystyrene and acrylic plastic phantoms, it is recommended that the same source-detector distance be employed for dose determinations in a plastic phantom as would be used in a primary phantom. A jig may be developed to clamp the phantom reproducibly to the accessory ring to facilitate accurate repetition of the geometry in later measurements.

Conversion of the dose determined in plastic to that which would be measured in water at the equivalent depth requires correction for differences in the mass-energy-absorption coefficients of the plastic and water.[11–13] (See Sec. V.D.2.)

The dimensional requirements for plastic phantoms are the same as those for primary phantoms but, because of the expense of the plastic, this may be accepted as a limitation on the maximum beam size that may be calibrated rather than a need for a 40-cm cube of plastic. From these considerations, it is recommended that the use of secondary phantoms be confined to check measurements rather than primary calibrations.

D. Calculation of the absorbed dose in water from instrument readings at depths greater than that required for electronic equilibrium

It is assumed that the ionization chamber has an internal diameter less than 1 cm. It is recommended that the "reference energy calibration and C_λ factor" technique be used to convert the instrument readings from coulombs or scale divisions to absorbed dose at the accelerator energy (λ). The reference energy recommended is the ^{60}Co gamma ray.

1. For measurements made in water

The dose in water is given by

$$\text{dose in water} = R \times N \times {}^{W}C_\lambda,$$

where R = instrument reading coulombs or scale divisions corrected to atmospheric conditions for calibration N; N = calibration factor for the chamber to convert to roentgens per coulomb or roentgens per division when exposed to ^{60}Co gamma rays; and

$${}^{W}C_\lambda \simeq \frac{(f_{\text{med}} A_c)^{\text{Co}} (S_{\text{air}}{}^{\text{water}})^\lambda}{(S_{\text{air}}{}^{\text{water}})^{\text{Co}}}.$$

Recommended values for ${}^{W}C_\lambda$ are available.[1]

2. For measurements made in plastic

The equivalent dose in water is given by

$$\text{dose in water} = \text{dose in plastic} \times \frac{(\mu_{\text{en}}/\rho)_{\text{water}}}{(\mu_{\text{en}}/\rho)_{\text{plastic}}}$$

$$= R \times N \times \left[{}^{P}C_\lambda \times \frac{(\mu_{\text{en}}/\rho)_{\text{water}}}{(\mu_{\text{en}}/\rho)_{\text{plastic}}} \right]$$

$$= R \times N \times K.$$

For example, recommended values for K at 4 MV are 0.94 in acrylic and 0.93 in polystyrene.[1]

3. Absorbed dose at depths other than calibration point

Tables of percentage depth dose should be prepared at the target-skin distances normally employed (see Sec. VI for discussion of depth-dose data). Tabulated values of TAR should also be prepared. If the percentage depth dose is P_5 at 5 cm depth and P_d at any other depth d, then

$$\text{dose at depth } d(D_d) = \frac{\text{absorbed dose measured at 5 cm}}{P_5} \times P_d.$$

E. Setting of monitoring chamber

It is assumed that the collection efficiency and linearity of response of the monitor chamber is known (see Sec. V.A).

(1) If the clinicians propose to employ a fixed target-skin distance F, the measurements are made at $F+5$ cm target-chamber distance for a 10×10-cm field. Field size is measured at $d_{\max}$, the depth of maximum buildup. The integrating and rate monitors are adjusted to read the dose delivered and dose rate at $d_{\max}$ for a 10×10-cm field using the equation in the above paragraph where P_d is taken as 100%. Backup integrators on machines with dual dosimetry are normally set a few percent slower than the primary integrating channel. Calibration factors at the depth of dose maximum, termed C_m[14], should be supplied for all other field sizes (see Sec. XI.C).

(2) For certain treatments, an isocentric setup is desirable. Dose calculations for the isocentric mode may be conveniently performed using TARs or TPRs,[15,16] although TPRs and TMRs are to be recommended for higher energies.[17–19] The integrating chambers are set in the same manner as for the fixed target-to-skin distance case except that a set of calibration factors measured at the isocenter, termed C_i[14], is used instead of the previous set of C_m values. For determination of C_i see paragraph (3).

(3) There are some clinicians who may wish to work in terms of a fixed target-tumor distance for all treatments. For these conditions, it may, therefore, be practical to set the integrator in terms of dose at the isocenter. To do this, the chamber in the phantom should be located at the target-tumor distance selected, or at the center of rotation, with a beam dimension of 10×10-cm at the chamber with 5 cm of phantom material overlying the chamber. The tissue-air ratio for a 5-cm depth and a 10×10-cm field (at that depth) may be denoted by ${}^{10}T_5$. Then, the dose to a small volume of tissue in air just large enough for electronic equilibrium and centered at the above-defined point will be given by $R^{10}\times N\times K/{}^{10}T_5$ where R^{10} denotes the chamber reading for a 10×10-cm field. At any other field size A it will be $(R^A\times N\times K/{}^AT_5)\times G_A$ where G_A is the collimator factor normalized to the calibration field size. The monitor may be adjusted to refer to absorbed dose or dose rate at this point and a table of G_A prepared for all other field sizes from

$$\frac{R^A\times N\times K/({}^AT_5)}{R^{10}\times N\times K/({}^{10}T_5)}=\frac{R^A\times {}^{10}T_5}{R^{10}\times {}^AT_5}.$$

The collimator factor (G_A) may be determined experimentally. This is described in Section XI.C.2.

VI. SELECTION OF PERCENTAGE DEPTH-DOSE DATA

The generation of depth-dose data on an individual treatment machine as it is to be used is the preferred course. However, this presupposes the availability of appropriate equipment as well as machine and personnel time. If it is decided to use published data[20] then its choice shall be confirmed. A preliminary test may be conducted using the SCRAD phantom[7,8] making measurements at 8- and 16-cm depths for several field sizes and comparing their ratio to those from the proposed tables of depth doses. If the ratios are within ±5%, one may proceed with more extensive tests. The water or secondary phantom should next be set up so that the chamber is at $F+5$, $F+10$, and then $F+15$ cm from the focus. This should be repeated for at least three field sizes, including a 10×10-cm field. A table should be prepared of the measured dose rates at 5-, 10-, and 15-cm depths. The dose rate measured at 5-cm depth should then be normalized to the reported depth dose for that field size and the corresponding depth doses at 10 and 15 cm calculated.

The normalized measurements at 10- and 15-cm depths for all field sizes should not deviate more than 3% from the published values. If the readings consistently differ by more than 3% from the published data, it may be presumed that the most probable difficulty is an inappropriate choice of the nominal energy of the published table. If the values oscillate about the published data, then treatment unit stability should be checked.

Once selection of the depth-dose data has been made, the TAR appropriate to these depth-dose data may then be utilized. Alternatively, TARs (for several areas with different thicknesses of overlaying material) may be tested as for percentage depth dose by normalizing at 5-cm depth and comparing the measured and computed doses at other depths.

VII. ROUTINE CHECKS

A procedure for routine checking of integrating and dose-rate meters should be initiated. This should be done by or under the supervision of a physicist. A convenient device for this purpose is two detectors in a solid phantom material: When the detectors are set along the beam axis at different distances from the target, their respective readings indicate the machine output while the ratio of readings may be used as an index of depth dose and, consequently, of beam energy. When the detectors are set perpendicularly to the beam axis, the readings may be used as an index of beam symmetry. If the relevant data are generated at the time of initial calibration, such checks can be accurately and expeditiously performed at future times. It is recommended that the checks be performed on at least a daily basis for the first three months of operation. If instability is observed, then checks should be instituted during the treatment day. Alignment between the light localizer beam and the x-ray beam should be checked at monthly intervals and whenever a light projector lamp is replaced. Similarly, the accuracy of the distance indicating scale should be checked monthly and whenever a projector lamp is replaced, unless the design of the distance indicator is such that some inaccuracy is to be expected. Optical and alignment checks should then be made daily along with checks of beam output, quality, and uniformity. The machine should be recalibrated for standardized conditions and interlocks, lights, etc. checked for conformation with local regulations every six months. An entire calibration and check of isocenter should be repeated annually.

VIII. FACTORS AFFECTING DOSE IN THE BUILDUP REGION

As photons proceed into an absorbing medium, interactions generate an increasing flux of secondary electrons to a depth approximating the maximum electron range. Hence, megavoltage beams exhibit a buildup of forward-scattered electrons. As a result, the surface dose may vary from 15% to 100% of the maximum dose (D_{max}) depending on the beam energy and on the effective range of secondary electrons generated in the material between the x-ray target and the skin.

The depth of D_{max} will depend on (a) the maximum energy of the photons in the beam, (b) the angulation between the beam and the skin, and (c) the field size.[21] The value of the surface dose will depend upon items (a), (b), and (c), as well as (d) the nature and thickness of materials introduced into the beam (e.g., shadow tray, flattening filter), (e) the distance between these materials and the skin, and (f) the position of point of interest relative to the central axis.

The preservation of low surface dose relative to D_{max} is usually important clinically. Items (a)–(f) should therefore be examined to assess their effect on the relative surface dose. A number of publications have addressed themselves

to these questions,[22–25] while some have suggested ways of eliminating sources of high surface dose.[26]

Buildup curves from the surface to the depth of D_{max} should be measured for individual treatment units under the proposed conditions of use: field sizes, SSDs, etc. These should include the presence and absence of shadow trays within the range of shadow tray-skin separation to be encountered in practice. Off-axis studies for large fields should be included. The measurements can be conveniently carried out using a small 0.6 cm^3 parallel-plate ionization chamber[27] and thin absorbers of polystyrene. Alternative methods using TLD are available[23,24,28] although they are somewhat more time consuming and less accurate.

IX. CHECKS ON ANCILLARY DEVICES

A. Shadow-tray attenuation

Shadow trays to support beam shaping blocks are usually constructed of 0.6-cm thick Lucite. Such a solid tray will typically attenuate a 4-MV x-ray beam by 3%. The magnitude of the shadow tray attenuation should be ascertained for each tray to be used and checked as a function of field size. Similar data should be obtained for beam shaping "coffee tables" often used near the patient for large field irradiations. Treatment data charts should be clearly marked as to the presence or absence of the shadow tray attenuation factor.

B. Wedge filters

The wedge filters supplied with or constructed for a particular machine may be specified by a statement of their wedge angle and wedge factor (transmission factor). The wedge angle has been defined by the ICRU[29] and others[30] and may be conveniently obtained from a comparison between an open-field isodose curve and a wedged-field curve for the same field size.

The transmission factor is defined as the ratio of the dose with and without the wedge filter, measured on the central axis at the depth of the open-field maximum. This important factor should be verified before wedges are employed in treatment.

C. Shielding blocks

Beam-shaping blocks are used in addition to the fixed and adjustable treatment-unit collimators to attenuate the beam in undesired directions. Relevant attenuation data for these blocks should be available. Typical thicknesses for 4-MV radiation and 5% primary transmission are 5 cm for lead and 6.5 cm for Cerrobende (a low-melting-point lead alloy). For certain treatments, blocks that transmit significantly more than 5% are useful.[31] No attempt should be made to use such blocks clinically until a thorough investigation of the primary and scattered beam characteristics under these blocks has been performed.

X. CONVENTIONS

A. Field size

Field size is defined at the nominal target-skin distance (SSD) or target-axis distance (SAD). The field boundaries are delineated geometrically by lines from the front center of the target intersecting the inner edges of the collimator. The exposure rate along these lines is usually 50% of that at the center of the field, within the limits of experimental error.

The diverging field so defined will coincide approximately with the 50% isodose curves at the depth of maximum electron buildup in the phantom.

The collimator dial settings should record the field size at the nominal SSD or SAD. Inconsistencies in backscatter factor and tissue-air ratios introduced by this definition[32] are offset by the convenience of measuring field size on the patient's skin and simplicity of constructing a light source that is in alignment with the radiation field over a large range of SSDs.

The basis for the description of the treatment data (e.g., tissue-air ratios, depth dose, etc.) should be in agreement with the definition of field size appropriate to the specific machine.

B. Scales

Integration of simulator, treatment machine, computer treatment planning, and the prospect of computer control emphasizes the need for a standard system of coordinates for the treatment couch, gantry, yoke and collimator, etc. Such a system has been developed by the Hospital Physicists Association.[33] Adoption of this system is recommended wherever possible.

C. Normalization

Many of the parameters used in dose calculation in radiation therapy are interrelated. They are usually relative values normalized to some reference point. For consistency, it is convenient that this reference point be the depth of maximum buildup along the central axis. Consequently, depth doses, TARs, open-field isodose curves, wedged-field isodose curves, buildup data, etc. should be normalized at this point.

D. Notation

It is advisable to have a consistent notation convention for physical quantities in order to facilitate communication and reduce error. The chosen system should be internally consistent but general enough to simplify communication between institutions. One system that has been widely disseminated[14] is recommended.

XI. DATA FOR DOSE CALCULATION

A. Tissue-air ratios (TAR)

That TAR is a useful parameter in dose calculation for isocentric treatments or large irregular field calculations. TARs may be determined experimentally or calculated from percentage depth-dose tables if the backscatter factors are known and the inverse square law has been verified for the particular treatment unit. Since TARs are independent of SSD over a wide range, a single set of values for various field

sizes and depths is sufficient for all typical SSDs used on a particular treatment unit.

B. Scatter-air ratios (SAR)

This parameter, introduced by Cunningham,[34] is particularly useful for irregular field calculations in conjunction with tissue-air ratios.[35] As with TARs, the SAR may be calculated from percentage depth dose and a single set for a particular machine is used for all SSDs.

C. Other useful ratios

Other ratios have proved useful in special circumstances, such as where it is desired to avoid "in air" measurements: TMR[17] and TPR.[14,20]

D. Field size dependence

The dose rate at the reference point on the central axis of a therapy unit increases as the collimator is opened. This field size dependence of the dose rate may be measured in two ways depending upon the particular method of setting the monitoring chamber.

1. Monitor chambers set for fixed SSD techniques

The field size dependence of the calibration factors (C_m) is determined with a small detector at the depth of maximum buildup in a water phantom positioned at the nominal SSD for the unit. Readings obtained for the range of field sizes of the treatment unit are normalized to unity for a 10×10-cm field. The range of values of C_m reflects the effect of blocking of the fixed primary collimator by the movable secondary collimator, and the variation of backscatter with field size. (See Sec. V.E.1.)

2. Monitor chambers set for fixed SAD techniques

The field-size dependence in air is necessary for units set up in this way. A small detector with an equilibrium cap is positioned on the central axis at the fixed target-tumor distance that will be used for therapy. Again, readings are obtained for the full field size range and normalized to unity for the 10×10-cm field at the detector. This field size dependence which reflects only the effect of collimator movement is denoted as G_A. (See Sec. V.E.3.)

E. Off-axis data

Off-center ratios (OCR)[36] are beam profiles taken at various depths in the phantom and normalized at the central axis. The OCRs are plotted as a function of X/W, where X is the distance of the point from the center of the field in a plane normal to the central axis and W is the distance to the edge of the field in that plane. This normalization permits the use of the same OCR over a large variety of field sizes and only a limited number of off-center ratios need be determined to cover the field sizes from the smallest to the largest. The OCR is applied to the central-axis dose in the plane of calculation to permit the calculation of dose for off-axis points. The edge of the field in this calculation may be the actual field edge or an artificial edge caused by the presence of an external block.

A two-dimensional description of the off-axis beam distribution is provided by isodose curves. Some sets of isodose curves are provided by the manufacturers of treatment units and others may be generated by specially designed treatment-planning computer programs using data such as central-axis depth dose and beam profiles measured on the treatment unit for which the isodose curves will be used. The applicability of isodose curves to a particular machine must be verified before clinical dose calculations are made with such data. This may conveniently be performed with a movable probe in a water phantom or with film of linear dose response in a solid phantom.

APPENDIX I: CALCULATIONS AND MEASUREMENTS

Calculations and measurements that shall be undertaken on accelerators by a qualified radiological physicist follow.

A. Radiation protection

(1) Design of radiological protection shielding for the particular installation from radiation data supplied by the manufacturer, usage and occupancy data supplied by the owner, and data from pertinent radiological literature to standards set by the appropriate licensing body.

(2) Performance of a post-installation radiation protection survey including a verification of the leakage radiation around the head, inspection of safety interlocks, warning signs, etc.

(3) Provision of a signed, written report of the radiation protection survey in a form suitable for submission to the relevant licensing authority that the installation is in compliance with the regulations.

B. Machine calibration

(1) Verification that the equipment is operating in compliance with the specifications as stated by the manufacturer, including checks on (a) light localizer, (b) side light and backpointer alignment with the isocenter when applicable, (c) variation in the axis of rotation for the table, gantry, and jaw system, and (d) beam flatness and symmetry at the specified depth.

(2) Initial machine calibration including measurements made over the range of field sizes available at all target-skin distances to be employed. Applicability of inverse square law should be determined within that range.

(3) Provision of depth-dose data and isodose curves applicable to the specific machine.

(4) Verification of the applicability and transmission factors of all accessories such as wedges, shadow trays, compensators, etc., and their effects on electron buildup (skin sparing).

(5) Development of a written procedure to ensure, on a daily basis, that the machine is operating under the conditions in which the treatment data were determined.

(6) Arrangements for periodic recalibration of the equipment and checks on the alignment of light localizer,

etc., and rechecks of safety features, in accordance with recommended practice. (See Code of Practice, Part II.)

(7) Arrangements for provision of assistance with the physical aspects of patient treatment planning.

(8) Supervision of custom-made shielding blocks for individual patients.

(9) Verification of machine performance after repairs or adjustment by service personnel.

(10) Supervision of a regularly-scheduled preventive maintenance program.

Note: The items (1) through (7) should be provided in sufficient detail that the physical dose to adjacent as well as tumor bearing structures may be calculated to within $\pm 5\%$, in accordance with current recommended standards of practice.

APPENDIX II: QUALIFIED RADIOLOGICAL PHYSICIST

A qualified radiological physicist shall mean a physicist who holds a degree in physical sciences and who is certified by the American Board of Radiology, either in radiological physics or in x- and gamma-ray physics, is eligible for such certification, or has equivalent training and experience.

Equivalent training and experience shall be interpreted as having: (a) a bachelors degree in physical sciences and three years full-time experience working under the direction of a physicist certified by the American Board of Radiology, (b) a doctorate or masters degree in physical sciences and two years such experience, or (c) a doctorate or a masters degree in radiological or medical physics and two years of full-time, postdoctoral training with clinical experience.

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