PROCEDURES IN RADIATION THERAPY DOSIMETRY WITH 5 TO 50 MeV ELECTRONS AND ROENTGEN AND GAMMA RAYS WITH MAXIMUM PHOTON ENERGIES BETWEEN 1 AND 50 MeV

Recommendations by the Nordic Association of Clinical Physics

The International Commission on Radiation Units and Measurements (ICRU) has published general recommendations on dosimetry procedures for photons (ICRU 1969), and others are in preparation for electrons (ICRU 1971). These may be supplemented to advantage by national or regional suggestions covering practical details of routine dosimetry procedures and taking into account the particular requirements and provisions of the country and region. Local data have been prepared for the United Kingdom (HPA 1969, 1971) and the USA (SCRAD 1966, 1971) and more are under way in West Germany (German Standards Association 1971). This paper deals with the establishment of recommendations that are pertinent to the situation in Denmark, Finland, Iceland, Norway and Sweden.

Objective. The aim is to give the hospital physicist a 'code of practice' to be followed at all radiation therapy centres in the Nordic countries so as to secure uniformity of dosimetry. This is intended to cover both the initial measurements when dosimetry is first performed with a new therapy apparatus and the continuous supervision necessary to ensure that the basic dosimetry is properly employed to facilitate adequate and consistent radiation therapy. In weighing high accuracy and theoretic strictness against practical usefulness, the latter has been given much emphasis so that the procedures may easily be followed at all therapy centres.

The implementation of these recommendations will probably have to be carried out in steps. The various centres following the suggestions are encouraged to adopt the procedures for the determination of the absorbed dose as soon as possible. On the other hand, the work aimed at improving beam uniformity, will, for instance, often necessitate gradual improvements and additional equipment, such as well designed sealed monitor chambers, balancing chambers, scattering foils and flattening filters and high quality equipment enabling good definition of the irradiation geometry. Above all, it is highly desirable that in considering the purchase of new accelerators much weight is given to the availability of equipment that facilitates correct dosimetry. Finally, each centre will have to base its control procedures on its own experiences.

It is implied that dosimetry connected with modern megavoltage therapy requires a qualified hospital physicist to accept responsibility for the complex physical measurements needed.

The recommendations are to a large extent based on work with accelerators at present in use in the Nordic countries, that is betatrons below 50 MeV and linear accelerators below 10 MeV, the latter only with photon beams.

Principal features. For the purposes of radiation therapy dosimetry the absorbed dose in water should be specified at a reference point in a water phantom (ICRU 1969, 1971); more research is needed on the absorbed dose in other materials. At the high energies with which this report deals, however, the absorbed dose in a small specimen of muscle, fat or bone at the reference point will rarely differ from that in water by more than ten per cent.

No standards of absorbed dose are at present available at any national laboratory. The question of transfer of absorbed dose calibration from the national laboratory to the user of the calibration is still a matter of research, an international situation reflected in the recommendations. Widespread calibration of the absorbed dose will presently have to be based on ^{60}Co exposure calibration and, in view of their simplicity and precision, ionization methods are recommended for the transfer of absorbed dose calibration to the user.

When an ionization chamber is used for the assessment of absorbed dose, a factor is necessary to convert its reading to the absorbed dose in water. Such conversion has been done with a conversion factor C_λ (ICRU 1969) for photon radiation while a factor C_E has been suggested (ICRU 1971) for electron radiation. The present recommendations retain factors C_λ and C_E but extend the applicability of the C_λ concept to other measurement depths by means of the experimental results of SVENSSON (1971) based on the use of an effective measuring point (DUTREIX & DUTREIX 1966, HETTINGER et coll. 1967, HARDER 1968).

With regard to the standardized depth of absorbed dose measurements, one depth (5 cm) is recommended over the whole range of photon energies considered. This eliminates the risk of mistakes in measurement depth at centres having several types of radiation equipment, and the construction of measurement phantoms is simplified. Contrasting these advantages, a risk of error in the conversion factor (C_λ) exists due to the possibility of electron contamination at high photon energies. A considerable degree of contamination will be clearly distinguished from examination of the shape of the depth dose curve. A twenty per cent contamination by electrons may occur without being easily discernible; in the worst case (at high energies) this would introduce an error of less than two per cent in the absorbed dose determination. This should be acceptable in view of the unambiguity and simplicity in using a single depth of measurement.

An accurate specification of the size and alignment of the radiation beam is essential in radiation therapy. Unfortunately, there is no generally accepted specification available, and further consideration is needed. One reason for the difficulties stems from the differences between the beams defined from theoretic geometric considerations and those of the actual radiation. The cross section area of the beam is now defined from purely geometric considerations whereas the alignment is made with due attention to the actual radiation beam.

Recent investigations (SVENSSON & HETTINGER 1971) have indicated that the flattening of the radiation beam of some betatrons leaves much to be desired. It is imperative that the beam flatness be investigated and adjusted to make the rest of the dosimetry meaningful. A uniformity index has been used to describe the flattening. This concept has been preferred because it includes the possibility of having irregularly shaped isodoses — with the present techniques such should still be common, at least with some types of accelerators.

The recommendations listed contain only the procedures without extensive comments on their background or alternative methods. The reader is referred to previously published papers for more details (HPA 1969, 1971, SCRAD 1966, 1971, ICRU 1969).

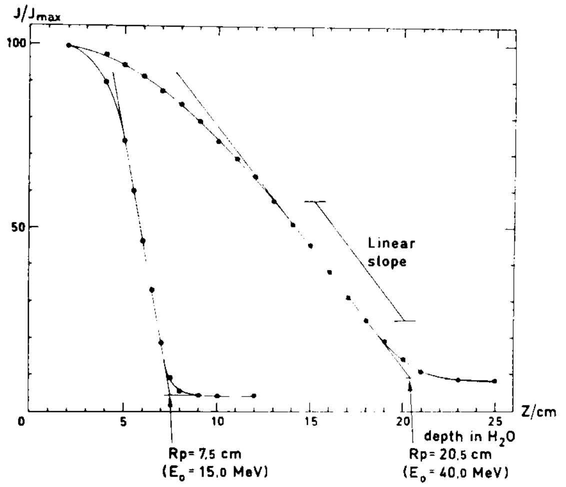


Fig. 1. Determination of energy at the surface by range analysis. SSD 100 cm. Field size > 12 cm × 12 cm.

$$E_0 = \frac{R_p + 0.3}{0.52}\,.$$

The recommendations concerning procedures with electron beams have been worked out after consultations with the ICRU task group on electron dosimetry, but may need modification when the final ICRU report becomes available. The recommendations for photon beams (ICRU 1969) have been followed with two exceptions (extension of the C_λ concept and the use of a single depth of measurement) which have been discussed above.

Energy determination at accelerators

A knowledge of some measure of radiation quality is necessary both because the absorbed dose conversion factors C_λ and C_E are energy dependent and because standardized depth dose tables may be used by laboratories having accelerators similar in construction, provided that the energy is determined in a uniform manner (Svensson & Hettinger 1971, Svensson 1971a). Different methods dependent on the particular aspect in which interest lies are recommended (that is, conversion factor determination or depth dose table selection).

Electrons. The electron energy should be evaluated by means of a range analysis. The depth ionization curve in water is measured at a beam size of 12 cm × 12 cm (above 35 MeV 16 cm × 16 cm) or larger by means of the concept of an effective measuring point (p.611). The point where the extrapolation of the linear fall-off at the inflexion point of this curve meets the roentgen ray background is called the practical range R_p (Fig. 1). The energy at the surface E_0 of the electrons is derived (Markus 1964, SCRAD 1966, Svensson & Hettinger 1971) from the relationship

$$R_p = C_1 \cdot E_0 — C_2 \qquad (1)$$

where $C_1 = 0.52$ cm $(\text{MeV})^{-1}$ and $C_2 = 0.3$ cm. (The electron energy determined from eq. (1) is close to the most probable energy at the surface of the phantom.) The average energy $\bar{E}$ of the electrons at depth z in the phantom is estimated (Harder 1965 b) with

$$\bar{E} = E_0\ (1 — z/R_p) \qquad (2)$$

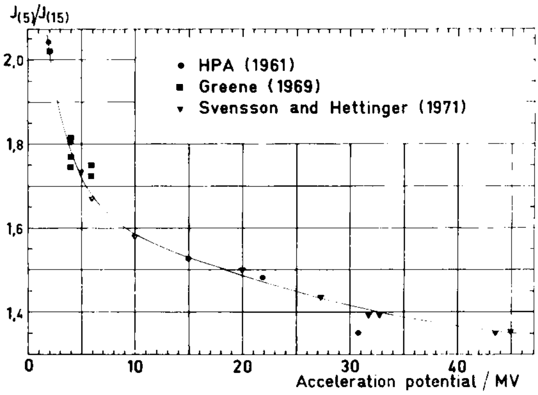


Fig. 2. The ratio of the 5 cm and 15 cm depth ionizations, $\mathcal{J}(5)$ and $\mathcal{J}(15)$, (SSD 100 cm, 10 cm × 10 cm) as a function of the acceleration potential (maximum photon energy). The full line gives the recommended values.

Photons. When photon and electron beams are available with the same betatron the photon energy may (within a few MeV) be obtained from the electron energy at the same energy setting by calculation of the energy of the electrons before they leave the acceleration tube. This calculation means that electron energy losses in all scattering materials in the radiation beam must be added to the electron energy measured. The sum will give an estimate of the photon energy, sufficiently accurate for determination of the absorbed dose conversion factor C_λ.

When it is not possible to use this simplified procedure for energy determination, and the maximum photon energy is less than 10 MeV a depth ionization method should be used for evaluation of the maximum photon energy in the spectrum used, both for conversion factor determination and for selection of depth dose tables. A calculation is made of the ratio of the ionization measured with the effective measuring point (p. 611) of the chamber at 5 cm and at 15 cm depth in a water phantom. The maximum photon energy is then taken from the full line of Fig. 2; the spread of the experimental results in Fig. 2 gives an idea of the accuracy of the method.

When the maximum photon energy is higher than 10 MeV the ionization ratio method indicated above is sufficiently accurate for an evaluation of the absorbed dose conversion factor. The published depth dose data (Table 7), however, should only be used if the maximum photon energy of the spectrum has been determined by methods based on (γ, n) or (γ, 2n) threshold energies. The four recommended reactions and their threshold energies (ICRU 1969) are listed in Table 1 along with a short commentary on measuring procedures.

Determination of the thresholds at the (γ, n) processes may be made with a pulse-counting radiation detector measuring annihilation quanta or beta radiation. Considerable interference from the (γ, n) process occurs at the detection of the (γ, 2n) process in oxygen, the activity produced being several decades higher. Measurement of the 2.3 MeV γ-ray from the former reaction is therefore necessary by means of pulse-height analysis. A pile-up of pulses from competing annihilation photons may be considerably reduced by filtering with several centimeters of lead. The settings of energy at the threshold values are determined by extrapolation to the energy axis in a diagram of the square root of the measured net counting rate against instrument setting (SCRAD 1966; Fig. 3).

Table 1

Recommended threshold reactions. The irradiated specimens should always be measured without the irradiation container or cover

Reaction	Threshold energy/MeV	Irradiation procedure
$^{63}Cu(\gamma,n)\ ^{62}Cu$	10.8	Pure copper plate irradiated in 0.5 mm cadmium cover
$^{16}O(\gamma,n)^{15}O$	15.7	Distilled water in plastic container
$^{12}C(\gamma,n)^{11}C$	18.7	n-heptane p. a. in plastic container
$^{16}O(\gamma,2n)^{14}O$	28.9	Distilled water in plastic container

Geometric considerations

The definition of the point from which the radiation emerges is not critical for the beam size determination nor for the beam alignment. The essential factors in the specification of beam size are the source-surface distance and the beam defining diaphragm, and in the alignment the properties of the radiation beam at the point of irradiation are the most significant. The term source centre, which is primarily defined with the source-surface distance in mind, will therefore also be used in discussing alignment although it is realized that strictly speaking the term is ambiguous.

The use of a nominal specification in terms of geometric beam size is only justified if there is a close correspondence between the geometric and the useful radiation beams. Requirements concerning alignment and beam size are given below to ensure such a correspondence. The discussions concern unmodified beams only, that is open beams without wedges or blocks.

Geometric beam. Source centre refers to a point that is defined in a ^{60}Co source as the centre of the front surface of that source, in accelerators producing photon beams as the centre of the front surface of the target, and in accelerators emitting electron beams as the point determined by the cross-wire method (Pohlit 1965). The first grid G_1 in this method (Fig. 4) is made up of four wires (1 to 3 mm) and the second grid G_2 of two wires (under 1 mm); a photographic film is irradiated behind G_2. (The transmission chamber may be removed from the beam and an external monitor behind G_2 may be used instead to decrease electron scattering and thus improve the film image.) The position of the source centre is determined from the relation given in the figure. (The misalignment indicated results in a non-uniform beam.)

The nominal specification of the radiation beam should be by means of the geometric beam. This beam is defined by the straight lines drawn from the source centre through the distal end of the final beam defining diaphragm.

The geometric beam axis at symmetric diaphragms is defined as the straight line passing through the source centre and the centre of symmetry of the plane figure formed by the edge of the beam defining diaphragm system.

Beam alignment. A parallelepipedic phantom is often used in measurements relating to dosimetry. The phantom surface is positioned normally to the geometric beam axis. The reference plane is defined at a given depth z beneath, and parallel to, the phantom surface. The selection

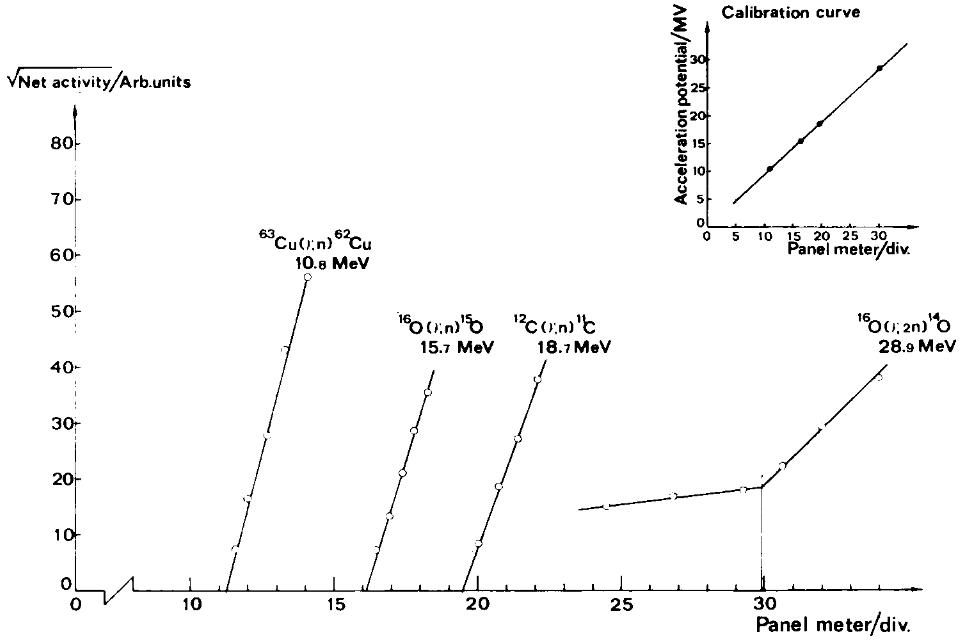


Fig. 3. Evaluation of the maximum photon energy by the threshold method.

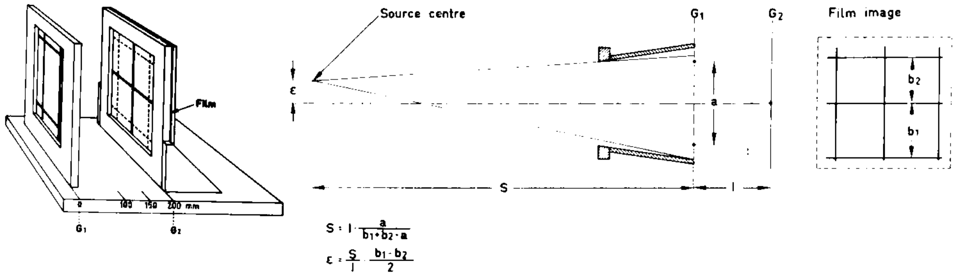
of the depth z was previously discussed (p. 604) and the recommended values are given in Table 2.

A reference point lies in the reference plane of symmetric diaphragms and is the intersection point of the geometric beam axis and the reference plane (Fig. 5). The commonly used light beam should be adjusted so that the light source is at the same distance from the irradiated surface as the radiation source centre. The symmetry axis of the light beam should intersect the reference plane at the reference point.

The centre point of the radiation beam in the reference plane may be defined as the centre of gravity of the area within which the absorbed dose exceeds 50 per cent of the maximum absorbed dose in the same plane. This point should be found and should be less than 4 mm from the reference point. The centre point will be closely the same if the 50 per cent area of net film blackening or ionization is employed, as discussed below (p. 610).

The light beam should be used to indicate the treatment area on the patient. In the absence of a light beam in electron therapy the treatment area will in practice be defined by the inner contour of the collimator.

Practical alignment procedures have been detailed in the case of photon beams (HPA 1970). The cross-wire method should be used with electron beams (Fig. 4). It is strongly recommended that the alignment is checked on the installation of a new accelerator. The accelerator manufacturer should be held responsible for any adjustments required before the accelerator is handed over for routine treatments.



a b

Fig. 4. Determination of the source centre of electron beams with the cross-wire method. The source centre does not necessarily coincide with the position of the scattering foil. a) Set-up for the determination. b) Evaluation of source centre and the source-surface distance from the measurement.

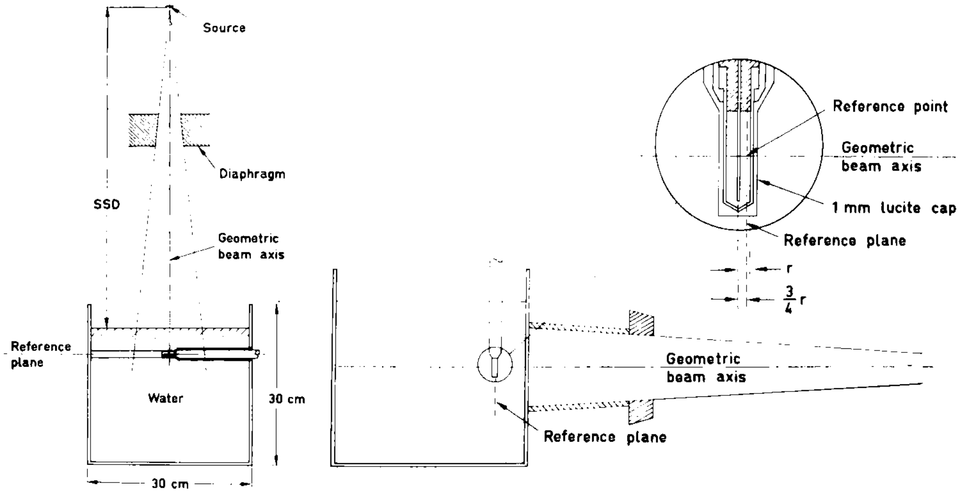


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Fig. 5. Examples of measurement geometries. a) Determination of absorbed dose in the reference point. The symmetry axis of the chamber is positioned in the reference plane. b) Determination of absorbed dose at points along the beam axis. An effective measuring point enables simple determination of the depth absorbed dose curve from the depth ionization curve. In the example, the ionization measured is assigned to the reference point.

Uniformity of the radiation beam in a given plane. A useful measure of beam uniformity is the uniformity index. This is defined in the reference plane for a specified quantity (e. g. absorbed dose or net film blackening) as the ratio of the area containing points where the value of this quantity exceeds 90 per cent of its value at the reference point, and the geometric beam cross section area of the phantom surface. The uniformity index of absorbed dose should exceed 0.80 with both photon and electron beams. In addition, the beam uniformity with electron beams should be such that the absorbed dose at an arbitrary point in the reference plane should be less than 105 per cent of that at the reference point. The corresponding figure with photon beams should be 103 per cent.

Table 2

Depth of reference plane

Type of radiation		Depth z/cm
Photons, maximum energy 1—50 MeV		5
Electrons, energy at the surface	5—10 MeV	1
	10—20 MeV	2
	20—50 MeV	3

Some accelerators are 'overflattened' in order to produce uniformity at a specified depth differing from that of the reference plane. The uniformity figures given should then apply at the particular specified depth.

Beam uniformity may be measured in different ways. Photographic film in a polystyrene phantom offers the advantages of high spatial resolution, simplicity of handling, short irradiation times and above all the fact that it will lead to simultaneous recording of the entire radiation field. With some care, as discussed below, the figures given above for absorbed dose uniformity may be substituted by the same figures for net film blackening uniformity. A drawback of the film method is, however, that it can hardly be employed without an automatic or semi-automatic density plotter.

Alternatively an ionization chamber, traversing the beam in the reference plane in a water tank for gantry angles at 90° from the vertical, could be used. This method will produce higher precision than the film method provided that the readings are related to a highly reproducible monitor chamber preferably covering the central part of the beam. If the ionization method is used, the uniformity at other gantry angles could be investigated by means of a polystyrene block with holes drilled in the side to take the ionization chamber (Naylor & Chiveralls 1970). The absorbed dose uniformity figures may then be substituted by the same ionization uniformity figures, provided that the chamber meets the specifications given later (p. 611).

With the film method the beam uniformity should be investigated by means of photographic film in a light tight cover of regular thickness but not of a radiation fluorescent material; industrially pre-wrapped film may be used. The film should be irradiated in a polystyrene slab phantom and the absorbed dose should exceed 50 rad so as to minimize the influence of initial pertubations in accelerator beams and of shutter movement in ^{60}Co beams. Before irradiation, accelerators should have been run under operating conditions for a sufficient period of time to effect a proper warm-up. The relation between film blackening and the absorbed dose depends critically on the development procedure used; parameters of importance are type of film and developer, development time and temperature. All these should be combined to produce a linear relationship between blackening and absorbed dose over a large range of the former. The aperture diameter of the density reader should be selected to exert negligible influence on the spatial pattern recorded. The variation in film density on a homogeneously irradiated film should be less than ± 2 per cent; only a few types of film seem to meet these requirements (Rassow et coll. 1969).

The film blackening should be checked regularly for slope and linearity against the absorbed dose curve, at least every time the film emulsion number or developer is changed.

Determination of absorbed dose at the reference point

The absorbed dose determination should be made by ionization methods.This determination must also be thoroughly controlled when new conditions of irradiation are employed, for instance when an accelerator comes into action for the first time. The checking should preferably be done with an independent dosimetric method, for instance based on calorimetry or ferrous sulphate dosimetry. Even less accurate methods, for instance those based on solid state dosimetry, may be worth while. If no alternative dosimetry method is available, all steps involved in the absorbed dose determination should be checked by somebody other than the one responsible for the determination.

It is frequently useful in measurements with a cylindric ionization chamber to assign the measured ionization to a point displaced three-quarters of the radius of the chamber cavity (irrespective of the diameter of the central electrode; cf. ionization chamber requirements below) from the centre of the sensitive volume of the chamber towards the radiation source, parallel to the beam axis. This is called the *effective measuring point.*

Ionization chamber and electrometer. The ionization chamber for the assessment of absorbed dose must fulfil certain requirements. It should have an inner diameter of less than 8 mm and a length of less than 20 mm and the central electrode must not be too massive. The spectral sensitivity should vary by less than 5 per cent in the range from moderately filtered 100 kV roentgen rays (filter 2 mm Al, HVL 2 mm Al) to ^{60}Co radiation. It should not have a metal stem that causes marked influence on the ionization current. The current produced when only the chamber stem is irradiated must be negligible. If the losses due to ion recombination at the absorbed dose rates used are less than 1 per cent, recombination correction will not always be necessary. It is obvious that instruments giving this low recombination should preferably be employed. A low recombination may be difficult to realize, however, in the case of pulsed radiation (Ellis & Read 1969); the loss is for instance 2 per cent with the Siemens Sondenfingerhutkammer (collection voltage 300 V) and 3.5 per cent with the Farmer 0.6 cm^3 chamber and the Farmer dosimeter (185 V) at a dose rate of 0.15 rad/pulse. (The recombination loss is a function of the charge liberated per pulse in the chamber. The ratio of the absorbed dose and the ionization, and therefore the recombination losses as well vary by less than 20 per cent for the radiations with which this report is concerned. The figures above are calculated with $\bar{E} = 20$ MeV at the measurement point.) Correction must then be made for recombination losses, either by calculation (Boag 1956, ICRU 1964) or by measurements (Loevinger 1961); the current in the latter instance is plotted against the inverse of the applied voltage (in the region of recombination losses below 5 per cent) and the corrected current is determined by extrapolation to infinite applied voltage.

Suitable ionization chambers are marketed by Nuclear Enterprises (Farmer), Victoreen, Siemens and Physikalisch-Technische Werkstätten (Pychlau), among others. Almost any commercially available high quality low current measuring instrument may be used in connection with an ionization chamber. The current measurement system should preferably be based on either an integrating Townsend-balance system or on one with an electrometer amplifier with loop-gain exceeding 10^3 in order to reduce variations of the collecting electrode voltage. The Farmer Secondary Standard Dosemeter is a Townsend-balance electrometer. Several makes of vibrating reed electrometers, such as those manufactured for instance by Cary and Keithley, may be obtained. Special attention should be drawn to the possibility of using electrometer operational amplifiers. A solid state electrometer amplifier may be built by any laboratory with Field Effect Transistors (FET) (Mauderly & Bruno 1969). An alternative to FET input amplifiers is offered by varactor bridge input amplifiers (Johansson et coll. 1970).

Both types may be obtained, for instance through Analog Devices, Betatron, Burr-Brown or Keithley.

The radio frequency fields that exist about microwave linear accelerators may affect the responses of electrometers coupled with ionization chambers. Special attention is needed to ensure that this does not occur.

Each radiation therapy centre should have a local ionization chamber, together with an electrometer selected as a reference (secondary standard) instrument, preferably for the purpose of calibration of other dosimeters only. The reference instrument should be recalibrated at a standardizing laboratory particularly for ^{60}Co gamma rays at least once every two years. Its sensitivity should be checked at least quarterly against a suitable radioactive source in the interval between these calibrations. When a ^{60}Co teletherapy source is used for these controls occasional constancy controls against a second teletherapy source is advisable. A ^{60}Co half-life of 5.27 a (±0.01 a; RYTZ 1970) is recommended for such controls. Any change in sensitivity of more than 2 per cent revealed by the constancy control should lead to a thorough investigation of the instrument and subsequent re-calibration at the standardizing laboratory.

Ionization chambers of dosimeters for routine clinical measurements should be calibrated against the local secondary standard and be subjected to constancy controls. The frequencies of these must depend on local conditions.

Exposure calibration. Reference (secondary standard) instruments should be exposure calibrated through the entire energy range over which they are employed at least once every second year. The exposure calibration for ^{60}Co should be made in free air against a teletherapy ^{60}Co unit at a field size of 10 cm × 10 cm and a distance of 100 cm between the front of the source and the centre of the chamber. The latter should then have an additional polymethylmethacrylate (trade names Perspex, Lucite, Plexiglass) cap with a total wall thickness of about 0.5 g/cm^2.

The energy spectra of photons from ^{60}Co teletherapy units have a continuous distribution from low energies up to the two primary gamma ray energies. Along the beam axis, the contribution to the total exposure from secondary photons amounts to 10 to 15 per cent (ICRU 1970, LÖFROTH 1970). Energy spectrum differences between different teletherapy units are not likely to be of any significance in the exposure calibration except with very accurate measurements.

(The exposure calibration factor, R/division, of the secondary standard chamber used as national Swedish standard at the National Institute of Radiation Protection, Stockholm, has recently been reassessed. As from 1 January 1972 the new calibration factor (which is 1.03 times the old one) will be applied by the Stockholm laboratory when calibrating instruments from other Swedish institutions.)

Measurement procedure. The absorbed dose should be determined with a water-filled polymethylmethacrylate or polystyrene phantom with outer dimensions of 30 cm × 30 cm × 30 cm, the water filling being at least 25 cm (Fig. 5). At large field sizes a larger phantom with a water filling exceeding 25 cm should be used in such a way that a minimum distance of 5 cm between the edge of the beam and the phantom wall exists at the entrance surface. The thickness of phantom walls oriented towards the radiation source should be 0.5 cm or less. The ionization chamber should be protected during the measurement by a tube with a wall thickness of 1 mm, manufactured from polymethylmethacrylate. This tube is attached to a holder that can be adjusted for measurements at various depths. The symmetry axis of the chamber must be positioned in the reference plane.

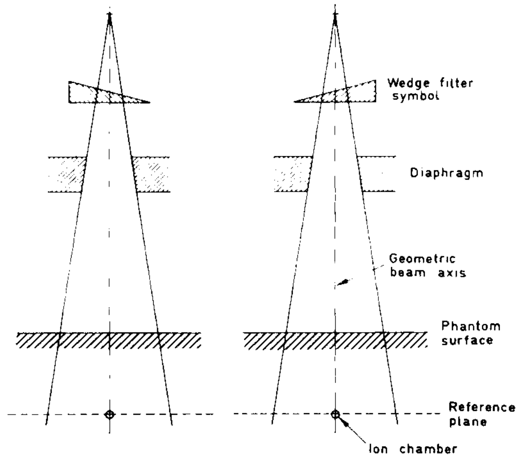

Fig. 6. Determination of absorbed dose of photon beams with a wedge. The absorbed dose at the reference point should be taken as the average of the results from the two measurements indicated. The difference between the two cases arises from 180° rotation of diaphragm and wedge.

Measurements should be made for all combinations of irradiation conditions. A horizontal or vertical beam direction may be employed. Whether this influences the dose determination has to be controlled. With wedge fields, the edge of the wedge should be placed parallel to the symmetry axis of the ionization chamber. The measurement should be made at the two possible, 180° different orientations of the wedge (Fig. 6) and the average result should represent the absorbed dose with the wedge.

Calculation of absorbed dose. The assessment of absorbed dose is based on the use of an exposure calibration factor N (R/division) for ^{60}Co (p. 612) and a conversion factor C_λ or C_E (p. 604). The absorbed dose D_W (rad) in water at the reference point is calculated from the exposure-meter reading M (divisions, corrected for temperature, pressure, stem effects and the like) with eq. (3a) for photon and eq. (3b) for electron radiation.

$$D_W = C_\lambda \quad MN \tag{3a}$$

$$D_W = C_E \quad MN \tag{3b}$$

Eq. (3a) thus defines the conversion factor C_λ in the same way as it was indicated by the ICRU (1969) although the definition is extended to other measurement depths. The recommended numerical values of C_λ in Table 3 have been adjusted above 10 MeV to allow for the changed depths by means of the experimental data of Svensson (1971 a). At these energies, the C_λ value at 5 cm is typically 1 per cent higher than that at 7 cm or 10 cm.

The energy dependence of C_E for electron beams may be assessed to a sufficient degree of accuracy with the average electron energy $\bar{E}$, calculated from eq. (2) (Harder 1965, Svensson & Pettersson 1967, Rassow 1970). The values of C_E presented in Table 3 have been evaluated with $\bar{E}$, but for convenience are listed for different energies at the phantom surface, E_0 and are given for the reference depth. The values recommended are within about ± 1 per cent consistent with data calculated from theoretic considerations and are also in close agreement with the mean values of experimental results from different investigators (Rassow 1970).

The following relationship was used in the theoretic derivation of C_E values

Table 3

Recommended values of the conversion factors C_λ and C_E at the reference point in a water phantom

Electron radiation				Photon radiation	
Energy at surface E_0/MeV	Reference depth z/cm	Average energy at reference depth $\bar{E}/\text{MeV}$	Conversion factor $\frac{C_E}{\text{rad/'R'}}$	Radiation quality	Conversion factor $\frac{C_\lambda}{\text{rad/'R'}}$
6	1	3.9	0.90	^{60}Co-γ	0.95
8	"	5.9	0.89	4 MV	0.94
10	"	8.0	0.87	6 "	0.94
12	2	8.0	0.87	8 "	0.93
14	"	10.0	0.86	10 "	0.93
16	"	12.0	0.85	15 "	0.92
18	"	14.0	0.85	20 "	0.91
20	"	16.0	0.84	25 "	0.91
25	3	19.1	0.83	30 "	0.90
30	"	24.1	0.82	35 "	0.90
35	"	29.1	0.81	40 "	0.89
40	"	34.1	0.80	45 "	0.89
45	"	39.2	0.79		

$$C_E = S_{w,\,\text{air}} \cdot \frac{W}{e}\, p_{\text{air}} \cdot A$$

where

$S_{w,\,\text{air}}$ = mean mass stopping power ratio water to air calculated for different energies, E_0, and depths (Kessaris 1970).

$\frac{W}{e}$ = 33.7 J/C = 0.869 rad/' R' (W = 33.7 eV/ion p_{air}).

The factor p_{air} corrects for the absence of electron scattering in the air volume of the ionization chamber and its numerical values have been chosen for a cylindrical 5 mm diameter chamber (Harder 1968). The largest deviation of p_{air} from unity is for low energies ($p_{\text{air}} = 0.978$ at $\bar{E} = 3$ MeV). Within one half per cent the same values will apply for chamber diameters between 3 mm and 8 mm. Attention is paid to the attenuation in the build-up cap at ^{60}Co exposure calibration by the use of the correction factor $A = 0.985$ which applies for the 0.5 g/cm^2 cap recommended.

Table 3 gives the conversion factors C_λ and C_E in units of rad in water per roentgen, rad/'R'. The C_E values are calculated for use when the absorbed dose is assigned to the effective measuring point. The same values may also be employed, however, at the reference point when the absorbed dose is assigned to the centre of the chamber with an error that rarely exceeds 0.5 per cent; this is because of the slow variation in the depth ionization curve near the reference depth.

Table 4

Main sources of inconsistency between different centres in the determination of absorbed dose in water at the reference point from exposure calibration of ^{60}Co gamma rays. About 95 % confidence limits of random errors, attainable under well controlled laboratory conditions, are listed

Source of inconsistency (eqs (3a) and (3b))	Uncertainty (per cent)	
	Electrons	Photons
1. Transfer of exposure calibration factor, N	0.5	0.5
2. Exposure meter reading including corrections, M	0.5	0.5
3. Differences in stem scattering and leakage conditions between calibration and absorbed dose determination	0.2	0.2
4. Differences in the conversion factor, C_λ or C_E, due to minor differences in photon or electron spectrum	1.5	0.5
5. Differences in the conversion factor, C_λ or C_E, due to chamber construction, e.g. caused by scattering in the air cavity	1.0	1.0
Overall rms uncertainty	1.9	1.3

The C_E values may also be conveniently described by the relationship

$$C_E = C_3 - C_4 \log_{10} (\bar{E} \cdot C_5 + 1) \qquad \text{(HARDER 1965a)}$$

where

$C_3 = 0.987$ rad/'R', $C_4 = 0.120$ rad/'R' and $C_5 = 1$ MeV^{-1}, with a thimble ionization chamber of 5 mm diameter.

(This relation is also valid for calculations of C_E for depths other than that of the reference point, as described below (p. 618). It could be employed in the energy range $3 \leqslant \bar{E} \leqslant 40$ MeV.)

Consistency and accuracy. The main sources of inconsistency between different centres in the absorbed dose determination, under well controlled laboratory conditions, appear in Table 4. The overall uncertainty amounts to less than ± 2 per cent, which should be a lower limit to the kind of consistency that might be attained. It should be possible for the various centres following these recommendations to have a consistency within ± 3 per cent in statements concerning the absorbed dose in water at the reference point. Should any evidence suggest a greater difference, a reassessment must be made.

It should be noted that in addition to being subject to the sources of error given in Table 4, the absorbed dose may be incorrect due to uncertainties in the reference value of exposure of ^{60}Co and in the C_λ and C_E values. The latter two uncertainties, however, do not influence the consistency between various centres, firstly, because a coordination of the Nordic national reference values of exposure with ^{60}Co is being planned, and secondly, because the same values of C_λ and C_E will be used by all centres.

Table 5

Depth dose data for electron radiation with BBC betatrons. Depth (cm) at which a certain percentage depth dose is obtained. Data at 6—30 MeV derived with 8 different BBC 35 MeV betatrons and those at 35 and 40 MeV with one 45 MeV betatron. The energy at the surface was determined by range analysis. SSD = 110 cm according to the manfacturer. The data refer to circular beams except for the square 10 cm × 10 cm beams

Energy at phantom surface E_0/MeV	Beam size Diameter/cm	Percentage depth dose									
		95	90	80	70	60	50	40	30	20	10
6	≥ 10 × 10	1.7	1.8	1.9	2.1	2.2	2.3	2.4	2.5	2.6	3.0
10	5	2.2	2.5	3.0	3.3	3.6	3.8	4.1	4.3	4.5	5.0
	≥ 10 × 10	2.6	2.8	3.2	3.4	3.6	3.9	4.1	4.3	4.5	4.9
15	4	2.5	2.9	3.6	4.2	4.6	5.1	5.6	6.1	6.6	7.3
	6	3.3	3.8	4.5	4.9	5.3	5.7	6.0	6.4	6.7	7.3
	8	3.5	4.0	4.7	5.2	5.6	5.9	6.2	6.6	6.9	7.5
	≥ 10 × 10	3.8	4.3	5.0	5.4	5.7	6.0	6.3	6.6	7.0	7.4
20	4	2.8	3.4	4.3	5.0	5.7	6.3	7.0	7.7	8.5	9.6
	6	4.2	4.9	5.9	6.5	7.0	7.7	8.1	8.6	9.1	9.8
	8	4.3	5.1	6.2	6.9	7.4	8.0	8.5	9.0	9.5	10.3
	≥ 10 × 10	4.7	5.6	6.6	7.3	7.8	8.2	8.6	9.0	9.5	10.1
25	4	3.1	3.8	5.0	5.9	6.7	7.5	8.3	9.3	10.3	11.9
	6	4.7	5.7	6.9	7.8	8.5	9.2	9.9	10.6	11.4	12.4
	8	4.9	6.1	7.4	8.3	9.1	9.8	10.4	11.1	11.7	12.8
	10 × 10	5.3	6.5	7.9	8.8	9.5	10.2	10.7	11.3	11.9	12.7
	> 12	5.4	6.6	8.0	8.9	9.7	10.3	10.8	11.3	11.9	12.7
30	4	3.5	4.5	5.8	6.8	7.8	8.7	9.6	10.8	12.1	14.0
	6	4.3	5.9	7.6	8.7	9.7	10.5	11.4	12.3	13.2	14.2
	8	5.4	6.8	8.5	9.6	10.6	11.4	12.3	13.1	13.9	15.1
	10 × 10	5.5	7.2	9.1	10.3	11.2	12.0	12.8	13.4	14.3	15.1
	> 12	5.6	7.3	9.2	10.5	11.4	12.2	12.9	13.5	14.3	15.1
35	4	3.7	4.8	6.3	7.5	8.6	9.8	10.9	12.2	13.8	16.5
	8	4.6	6.1	8.2	9.8	11.1	12.4	13.6	14.9	16.2	18.0
	> 15	5.7	7.3	9.5	11.1	12.5	13.8	14.8	15.8	17.0	19.9
40	4	3.8	5.0	6.7	8.1	9.3	10.5	11.9	13.4	15.8	19.4
	8	4.8	6.5	8.7	10.6	12.2	13.6	15.0	16.5	18.4	21.4
	> 15	6.2	7.7	9.8	11.8	13.5	15.1	16.4	17.9	19.5	26.0

Table 6

Depth dose data for electron radiation with Siemens 42 MeV betatron. Depth (cm) at which a certain percentage depth dose is obtained. Data measured for two different betatrons with agreement within 0.2 cm. SSD = 103 cm by the cross wire method (the manufacturer's value is SSD = 100 (cm The energy at the surface was determined by range analysis

Energy in MeV according to MeV meter*	Energy at phantom surface E_0/MeV	Scattering foil Lead thickness /mm	Field size Diameter/cm	Percentage depth dose									
				95	90	80	70	60	50	40	30	20	10
6	6.0	0	> 12	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.5	2.6	2.7
10	10.0	0.1	> 12	2.9	3.2	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9
15	15.0	0.25	> 12	3.9	4.6	5.3	5.8	6.1	6.4	6.7	7.0	7.3	7.6
15	14.8	0.1	8	4.3	4.5	5.0	5.4	5.7	5.9	6.3	6.6	6.8	7.2
15	14.8	0.1	6	3.9	4.4	4.9	5.3	5.6	5.9	6.2	6.5	6.7	7.2
20	20.0	0.25	> 12	4.5	5.5	6.5	7.3	7.8	8.2	8.7	9.1	9.6	10.1
20	19.8	0.1	8	4.4	5.3	6.3	7.0	7.5	8.0	8.5	8.9	9.3	9.8
20	19.8	0.1	6	4.3	5.1	5.9	6.6	7.1	7.6	8.2	8.6	9.2	9.7
25	25.0	0.5	> 12	4.6	5.7	7.2	8.4	9.3	10.0	10.6	11.3	12.0	12.7
25	24.6	0.25	8	4.5	5.8	7.2	8.2	9.0	9.6	10.2	10.9	11.5	12.2
25	24.6	0.25	6	4.5	5.5	6.8	7.7	8.4	9.1	9.8	10.5	11.2	12.0
30	30.0	0.5	> 12	4.6	5.8	7.8	9.4	10.6	11.7	12.5	13.4	14.3	15.4
30	29.6	0.25	8	4.8	6.3	8.0	9.3	10.3	11.2	12.0	12.9	13.7	14.8
30	29.6	0.25	6	4.7	5.8	7.4	8.6	9.5	10.4	11.4	12.3	13.3	14.5
35	35.0	1.0	> 12	4.7	6.0	8.3	10.2	11.6	13.0	14.3	15.5	16.7	18.5
35	34.2	0.5	8	5.1	6.6	8.6	10.1	11.3	12.4	13.5	14.6	15.8	17.5
35	34.2	0.5	6	4.9	6.1	7.9	9.3	10.5	11.5	12.7	13.8	15.1	16.7

* It is supposed that the MeV meter has been calibrated for large field sizes and thus with a thicker scattering foil in the beam than when smaller field sizes are used.

Determination of absorbed dose at any point in a phantom

Points along the beam axis. The absorbed dose at the reference point is essential for the determination of the absorbed dose at other points in a phantom for all radiations. The absorbed dose at points of interest along the beam axis may usually be obtained from published beam axis depth dose tables. The absorbed dose at the reference point is then multiplied by the ratio of the depth doses at the point of interest as well as at the reference point.

The tables published by HPA (1961, 1968) should be used with ^{60}Co radiation, both with open and wedge fields. The depth dose curves, both of photon and electron beams with different accelerators of similar design, tend to nearly equal; Tables 5, 6 and 7 should be used when

Table 7

Depth dose data for photon radiations. The energy was determined by the 5 cm—15 cm ionization ratio method at 6 MV and threshold methods at the higher energies

Type of accelerator	Varian 6 MV linear accelerator			BBC 35 MeV betatron			Siemens 42 MeV betatron	BBC 45 MeV betatron
Accelerator voltage/MV	6			32			43	45
SSD/cm	100			100			100	110
Field size/ cm × cm	6×6	10×10	20×20	4×4(X_4)*	⩾10×10 (X_4)*	8×8(X_2)*	⩾10×10	⩾10×10 (X_4)*
Depth/cm								
1.3	100.0	100.0	100.0					
2	99.2	99.0	98.7	88.7	92.6	86.0	92.8	92.5
3	94.9	95.0	95.1	96.6	98.2	95.0	98.4	98.0
4	90.2	90.7	91.2	99.7	100.0	98.8	100.0	99.8
5	85.7	86.4	87.5	100.0	99.4	100.0	99.3	100.0
6	81.2	82.4	83.8	98.6	97.3	99.3	97.7	99.2
7	76.9	78.5	80.3	96.1	94.5	97.6	95.5	97.2
8	72.7	74.6	76.8	93.1	91.4	95.2	93.1	94.3
9	68.7	71.0	73.6	89.7	88.3	92.2	90.3	91.5
10	64.8	67.4	70.3	86.4	85.1	89.1	87.4	88.7
12	57.8	60.7	64.2	79.9	79.2	82.7	81.4	82.5
14	51.6	54.5	58.3	73.8	73.6	76.7	76.0	76.5
16	46.0	48.9	53.2	68.1	68.5	71.0	70.7	71.0
18	41.1	43.9	48.3	62.9	63.9	65.8	65.7	66.4
20	36.7	39.5	43.9	58.2	59.4	61.1	61.0	62.0
22	32.8	35.5	40.0	53.9	55.3	56.6	56.7	57.8
24	29.3	31.8	36.3	49.9	51.6	52.5	52.8	54.0

* X_4 and X_2 designate different beam flatteners.

appropriate (Horsley et coll. 1968, Svensson 1971). The shape of these curves should then be subject to a rough control at one or two points outside the reference point, and if these are more than 4 mm off the published curve, the latter should be avoided. In other cases the beam axis depth dose curve of photon beams should be assumed to equal the beam axis depth ionization curve as measured with effective measuring points (Svensson 1971). An additional adjustment of the depth ionization curve must be made with electron beams by means of eqs (2) and (3) and Table 3.

Points outside the beam axis. The absorbed dose of electron beams at points outside the beam axis may be assessed by means of photographic film placed parallel to the beam axis in polystyrene phantoms. A significant difference between the relative depth dose curve and the relative depth blackening curve exists at depths under 2 cm (LOEVINGER et coll. 1961, HETTINGER & SVENSSON 1967). The beam axis depth dose curve is first obtained as already described (p. 617) and is used to assign a depth dose value to all points along the beam axis in the film. Isodensity curves joining points in the film with the same net blackening are assigned to the depth dose at the point where they pass the beam axis. It is frequently sufficient to construct the isodensity curves with gross blackening.

The same method for photon beams as for electron beams may be employed although the accuracy of this method in the penumbra region is less satisfactory. An approach involving little experimental work consists in transversal measurements at four depths with an ionization chamber (decrement line method (ORCHARD 1964, ORR et coll. 1964)), followed by computer calculation of the isodose curves (KALNAES & MUNK 1971). Alternatively, complete ionization curves also present the isodose pattern directly.

Control systems relating to the basic dosimetry

The following paragraphs deal only with control systems relating to the basic dosimetry. All technical checking procedures prescribed by the apparatus manufacturer should also be followed. In deciding upon the frequency of the various procedures, the attainability of a high degree of safety for the patient must be weighed against the high cost of frequent controls. The number will also to some extent depend on the behaviour of the particular machine and its intended use; if previous examinations indicate few or slow changes, some decrease in their frequency may be satisfactory. A good evaluation of the results should make use of all possibilities of cross-controls that will be available — usually one particular test directly or indirectly involves several items of interest. The controls listed below are as a rule part of a suggestion of how a system could be designed; in this case the word 'could' has been used. Where the word 'should' has been used only strong counter-arguments might justify a different control system or lower control frequency.

The control system for the ionization chambers and associated instruments has been discussed earlier (p. 612).

Beam monitoring of accelerators. The radiation quality, absorbed dose rate, position of the source centre and similar parameters are with ^{60}Co units likely to remain constant for a given set of irradiation conditions. With accelerators, however, variations do occur and it is essential that these are kept under control. Some general principles concerning this control are given below and a number of recommended applications of these principles appear later (p. 019).

It is fundamentally important that the total absorbed dose at the reference point delivered during a given period of irradiation should be known. To that end, the accelerator should be provided with an integrating absorbed dose monitor; this should be well calibrated, that is the relationship between its response and the absorbed dose at the reference point should be accurately known when a given field size and energy setting are used. The calibration should as far as possible be insensitive to changes in the settings of the accelerator panel (e.g. MeV meter and extraction), the field size, absorbed dose rate, temperature of the accelerator magnets, accelerator beam direction, the scattering foil or flattening filters, etc. The response of hermetically sealed monitor chambers should be examined as regards their independence upon air pressure and temperature.

The nominal absorbed dose monitor calibration factor refers to a given set of values of some of the parameters mentioned (for instance, dose rate or extraction). These parameter values will in the normal course of accelerator operation fluctuate. Permissible ranges should be stated for all the values involved in order to ensure that the use of the nominal calibration factor leads to acceptably small errors in absorbed dose determination at the reference point. The ranges should be selected in such a way that at any setting of parameters within the given ranges the absorbed dose monitor calibration factor differs by less than ±2 per cent from the nominal factor.

The absorbed dose at any point within the irradiated volume bears a certain relationship to the absorbed dose at the reference point. It is essential that this relationship is not significantly changed during normal accelerator operation. The isodose pattern and the beam uniformity should thus be investigated similarly to the absorbed dose at the reference point as regards the influence of beam parameter variation.

Geometric controls. The purpose of these should be to ensure that the pointers, the geometric beam and the light beam are all centred at the reference point; further the relationship between the sizes and centre points of the radiation field (e.g. the 50 % isodose line) and the light field must not change. Rotational therapy units or units with isocentric set-up of patient also have to be examined regularly for consistency between the radiation beam axis and the centre of rotation. Deviations of the order of a few millimeters contribute significantly to the overall errors. These controls should be made in several beam directions, at least —90°, 0° and +90°, and in the 180° direction if this is used for treatments. It will often be convenient to combine the control of consistency between light field and radiation beam with the examination of field homogeneity. Detailed information on suitable procedures has been given by the HPA (1970a).

Beam uniformity controls of accelerators. The uniformity may be examined with photographic film in the reference plane by the methods outlined earlier (p. 610). Each control should determine the position of the maximum blackening point of the film, the blackening of this point relative to the reference point and the blackening along two axes through the reference point, perpendicular to each other. Naturally a full evaluation of the film blackening is of greater value as the uniformity index may then be calculated. Other control systems should present information corresponding to that obtained from the film measurements as given above. Parameters to be included in the control system of the uniformity are the following: accelerator beam direction (for instance —90°, 0°, +90°); all foils, flattening filters and energies used. The controls could be made weekly with cyclical permutation of some parameters so that each combination is controlled at least once every month. A special balancing system is required with some betatrons (PETTERSSON & HETTINGER 1965, VON ARX 1965, ROBINSON & MC DOUGALL 1967). When applicable, this system should also be subjected to a control program.

Energy controls of accelerators. Some accelerators designed for one fixed energy may not need a separate control of the beam energy. Control of the energy setting for electron beams only is however sufficient when photon and electron beams are available with the same betatron. The measurement should be based on depth ionization and the control system calibrated in connection with the energy determination (p. 605). An energy below 20 MeV is necessary. The measurement could be performed with an ionization chamber inserted in the polymethylmethacrylate or polystyrene block forming part of the phantom employed for control of the absorbed dose. The response of this chamber could be compared with that of the same chamber placed approximately at the reference point; the reading at the former depth should be 40 to 50 per cent of that at the latter (POHLIT 1969). The energy could be controlled once a week.

When only photon beams are available the energy control could be made with the ratio of ionization measurements at 5 and 15 cm depth in water or polystyrene. Alternatively, above

10 MV, one of the reactions in Table 1 could be selected and a certain amount of material irradiated. The control should then aim at proving that the activation measured at fixed irradiation and measurement conditions is constant.

Absorbed dose controls. The constancy of the absorbed dose in the reference point should be examined by ionization measurements in a special control phantom, designed for ease of handling. Parameters to include in the system are the same as above (p. 620) and the same frequency of the controls could be applied.

Control of the absorbed dose given to the patient

It is essential that the absorbed dose given to each patient in each treatment is under proper control (ICRP 1970). Pertinent radiation protection aspects are being dealt with by a Nordic working party that will soon produce detailed recommendations for the Nordic countries (LINDELL 1971). The comments given below have been discussed with this committee but carry no official cognizance.

To protect the patient from overdose or from incorrect treatment conditions dual monitoring systems are recommended. Apart from mistakes made by the operator, incorrect functioning of the dosimetry system will significantly add to other sources of error connected with radiation therapy (LINDSKOUG et coll. 1972, AYLING & HENDERSON 1972, RASMP 1969). The measurements and control systems indicated below should be used at each treatment. In addition, whereever there are dual monitoring systems these should be controlled against one another each morning before patient treatments start. Monitoring ionization chambers should be hermetically sealed, particularly if they are located in the close proximity of magnetic coils that can become heated.

All ^{60}Co units should be provided with a timer that will automatically return the beam control mechanism to the 'off' position after the pre-set time has elapsed. In addition, a checking chamber could be positioned on the patient side of the shutter, to be employed as an integrating meter capable of preserving its accumulated response in the event of any failure or interruption in the operation of the equipment during treatment. Alternatively, an independent timer system triggered by the shutter could be used. The absorbed dose derived from the monitor or control timer reading should for each patient be compared with that derived from the timer setting.

All accelerators should be provided with dual integrating monitoring systems. Both of these should be capable of terminating the exposure after a pre-set value has been reached. One of these values should correspond to the absorbed dose intended for the patient, the other to a higher value, for instance a fixed high value (several times hundred rad) or a certain increment (several times ten rad) above the desired value. At least one system should have its sensitive volume on the patient side of any scattering foils or flattening filter. At least one of these systems should preserve its accumulated signal in the event of any failure or interruption in the operation of the equipment during treatment. At least one of the systems should start at zero setting at the beginning of the patient treatment. Both monitor readings should be compared for each patient treatment.

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SUMMARY

Recommendations for dosimetry procedures of ^{60}Co radiation therapy apparatus and accelerators in the Nordic countries are presented. These deal both with initial measurements of the apparatus and continuous controls of items important for the dosimetry. They include methods for energy determination, considerations regarding beam definition and means of calculating the absorbed dose at any point in a phantom.

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