ICRU REPORT 23

Measurement of Absorbed Dose in a Phantom Irradiated by a Single Beam of X or Gamma Rays

INTERNATIONAL COMMISSION
ON RADIATION UNITS
AND MEASUREMENTS

ICRU REPORT 23

Measurement of Absorbed Dose in a Phantom Irradiated by a Single Beam of X or Gamma Rays

Issued January 15, 1973

INTERNATIONAL COMMISSION ON RADIATION
UNITS AND MEASUREMENTS
7910 WOODMONT AVENUE
WASHINGTON, D.C. 20014
U.S.A.

Library of Congress Catalog Card Number 72-97332
International Standard Book Number 0-913394-16-5

Copies of this report can be purchased for U.S. $3.00 each from

ICRU Publications
P.O. Box 30165
Washington, D.C. 20014
U.S.A.

(For detailed information on the availability of this and other ICRU Reports
see page 26)

Preface

Scope of ICRU Activities

The International Commission on Radiation Units and Measurements (ICRU), since its inception in 1925, has had as its principal objective the development of internationally acceptable recommendations regarding:

(1) Quantities and units of radiation and radioactivity,

(2) Procedures suitable for the measurement and application of these quantities in clinical radiology and radiobiology,

(3) Physical data needed in the application of these procedures, the use of which tends to assure uniformity in reporting.

The Commission also considers and makes similar types of recommendations for the radiation protection field. In this connection, its work is carried out in close cooperation with the International Commission on Radiological Protection (ICRP).

Policy

The ICRU endeavors to collect and evaluate the latest data and information pertinent to the problems of radiation measurement and dosimetry and to recommend the most acceptable values and techniques for current use.

The Commission's recommendations are kept under continual review in order to keep abreast of the rapidly expanding uses of radiation.

The ICRU feels it is the responsibility of national organizations to introduce their own detailed technical procedures for the development and maintenance of standards. However, it urges that all countries adhere as closely as possible to the internationally recommended basic concepts of radiation quantities and units.

The Commission feels that its responsibility lies in developing a system of quantities and units having the widest possible range of applicability. Situations may arise from time to time when an expedient solution of a current problem may seem advisable. Generally speaking, however, the Commission feels that action based on expediency is inadvisable from a long-term viewpoint; it endeavors to base its decisions on the long-range advantages to be expected.

The ICRU invites and welcomes constructive comments and suggestions regarding its recommendations and reports. These may be transmitted to the Chairman.

Current Program

The Commission has divided its field of interest into eleven technical areas and has assigned one or more members of the Commission to serve as sponsor for each area. A body of consultants has been constituted for each technical area to advise the Commission on the need for ICRU recommendations relating to the technical area and on the means for meeting an identified need. Each area is reviewed periodically by its sponsors and consultants. Recommendations of such groups for new reports are then reviewed by the Commission and a priority assigned. The Technical areas are:

Radiation Therapy
Radiation Diagnosis
Nuclear medicine
Radiobiology
Radioactivity
Radiation Physics—X Rays, Gamma Rays and Electrons
Radiation Physics—Neutrons and Heavy Particles
Radiation Protection
Values of Factors—W, S, etc.
Theoretical Aspects
Quantities and Units

The actual preparation of ICRU reports is carried out by ICRU report committees working in each of these technical areas. The currently active report committees in the various technical areas are as follows:

Radiation Therapy	Methods of Arriving at the Absorbed Dose at any Point in the Patient (In Vivo Dosimetry)
	Methods of Compensating for Body Shape and Inhomogeneity and of Beam Modification for Special Purposes (Beam Modification)
	Dose Specification for Reporting
Radiation Diagnosis	Modulation Transfer Function, Its Definition and Measurement
Nuclear Medicine	Scanning of Internally Deposited Radionuclides

	Methods of Assessment of Dose in Tracer Investigations
Radiobiology	Radiobiological Dosimetry
Radiation Physics—Neutrons and Heavy Particles	High Energy and Space Radiation Dosimetry
	Neutron Dosimetry
Values of Factors—*W*, *S*, etc.	Average Energy Required to Produce an Ion Pair
Quantities and Units	Fundamental Quantities and Units

The Commission recently determined to initiate a new study of the concepts and principles of radiation protection measurement. Because the work is to be carried out in cooperation with the International Commission on Radiological Protection, the ICRU decided to establish a separate committee, with membership drawn largely from the two Commissions, to undertake this work. Thus, the Committee on Concepts and Principles of Radiation Protection Measurement was added to the above substructure. In 1962, the Commission decided to abandon its past practice of holding a meeting together with all its subunits every three years. Instead, it was decided that the Commission would receive reports from the subgroups at the time of their completion rather than at fixed deadlines. Meetings of the Commission and of the subgroups are held as needed.

ICRU Reports

In 1962 the ICRU, in recognition of the fact that its triennial reports were becoming too extensive and in some cases too specialized to justify single-volume publication, initiated the publication of a series of reports, each dealing with a limited range of topics. This series was initiated with the publication of six reports.

ICRU Report 10a, *Radiation Quantities and Units*
ICRU Report 10b, *Physical Aspects of Irradiation*
ICRU Report 10c, *Radioactivity*
ICRU Report 10d, *Clinical Dosimetry*
ICRU Report 10e, *Radiobiological Dosimetry*
ICRU Report 10f, *Methods of Evaluating Radiological Equipment and Materials*

These reports were published, as had been many of the previous reports of the Commission, by the United States Government Printing Office as Handbooks of the National Bureau of Standards.

In 1967 the Commission determined that in the future the recommendations formulated by the ICRU would be published by the Commission itself. This report is published by the ICRU pursuant to this policy. With the exception of ICRU Report 10a, the other reports of the "10" series have continuing validity and, since none of the reports now in preparation is designed specifically to supersede them, they will remain available until the material is essentially obsolete. All future reports of the Commission, however, will be published under the ICRU's own auspices. Information about the availability of ICRU Reports is given on page 26.

ICRU's Relationships With Other Organizations

In addition to its close relationship with the International Commission on Radiological Protection, the ICRU has developed relationships with other organizations interested in the problems of radiation quantities, units and measurements. Since 1955, the ICRU has had an official relationship with the World Health Organization (WHO) whereby the ICRU is looked to for primary guidance in matters of radiation units and measurements and, in turn, the WHO assists in the world-wide dissemination of the Commission's recommendations. In 1960 the ICRU entered into consultative status with the International Atomic Energy Agency. The Commission has a formal relationship with the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), whereby ICRU observers are invited to attend UNSCEAR meetings. The Commission and the International Organization for Standardization (ISO) informally exchange notifications of meetings and the ICRU is formally designated for liaison with two of the ISO Technical Committees. The ICRU also corresponds and exchanges final reports with the following organizations:

Bureau International des Poids et Mesures
Council for International Organizations of Medical Sciences
Food and Agriculture Organization
International Council of Scientific Unions
International Electrotechnical Commission
International Labor Office
International Union of Pure and Applied Physics
United Nations Educational, Scientific and Cultural Organization

The Commission has found its relationship with all of these organizations fruitful and of substantial benefit to the ICRU program. Relations with these other international bodies do not affect the basic affiliation of the ICRU with the International Society of Radiology.

Operating Funds

In the early days of its existence, the ICRU operated essentially on a voluntary basis, with the travel and operating costs being borne by the parent organizations of the participants. (Only token assistance was originally available from the International Society of Radiology.) Recognizing the impracticability of contin-

uing this mode of operation on an indefinite basis, operating funds were sought from various sources.

Prior to 1959, the principal financial assistance to the ICRU had been provided by the Rockefeller Foundation which supplied some $11,000 to make possible various meetings. In 1959 the International Society of Radiology increased its contribution to the Commission, providing $3,000 for the period 1959-1962. For the period 1962–1965 the Society contributed $5,000. For each of the periods 1965–1969 and 1969–1973 the Society's contribution was $7,500. In 1960 the Rockefeller Foundation supplied an additional sum of some $4,000 making possible a meeting of the Quantities and Units Committee in 1960. The Council for International Organizations of Medical Sciences contributed $500 in 1960.

In 1960 and 1961 the World Health Organization made available the sum of $3,000 each year. This was increased to $4,000 per year in 1962, $6,000 in 1969, and $8,000 in 1970.

In connection with the Commission's Joint Studies with the ICRP, the United Nations allocated the sum of $10,000 for the joint use of the two Commissions.

The most substantial contribution to the work of the ICRU has come from the Ford Foundation. In December 1960, the Foundation made available to the Commission the sum of $37,000 per year for a period of five years. This grant was to provide for such items as travel expenses to meetings, secretarial services and other operating expenses. In 1965 the Foundation agreed to a time extension of this grant making available for the period 1966–1970 the unused portion of the original grant. To a large extent, it is because of this grant that the Commission has been able to move forward actively with its program.

In 1963 the International Atomic Energy Agency allocated the sum of $6,000 per year for use by the ICRU. This was increased to $9,000 per year in 1967.

In 1970 and again in 1971 the Statens laegevidenskabelige Forskningsråd of Denmark contributed $1,000 in support of the Commission's work.

The Radiological Society of North America contributed $5,000 in support of the Commission's work in 1971. The Commission received a grant of $1,900 from the John och Augusta Persson stiftelse of Sweden in 1971. As a result of the effort of Prof. Flemming Norgaard, Honorary Secretary-Treasurer Emeritus of the International Society of Radiology (ISR), the Commission, in 1971, received over $500 in contributions from individual members of the ISR. In 1971 also, the Japan Industries Association of Radiation Apparatus approved a grant to the ICRU of $1,200 per year for a period of three years.

In 1971 the BAT Cigaretten-Fabriken GMBH contributed $4,425 towards support of the Commission's activities. Also in 1971, the U.S. Bureau of Radiological Health of the Food and Drug Administration approved a grant of $25,000 per year for two years.

From 1934 through 1964 valuable indirect contributions were made by the U.S. National Bureau of Standards where the Secretariat resided. The Bureau provided substantial secretarial services, publication services and travel costs in the amount of several thousands of dollars.

The Commission wishes to express its deep appreciation to all of the organizations and individuals that have contributed so importantly to its work.

Composition of the ICRU

It is of interest to note that the membership of the Commission and its subgroups totals 91 persons drawn from 14 countries. This gives some indication of the extent to which the ICRU has achieved international breadth of membership within its basic selection requirement of high technical competence of individual participants.

The current membership of the Commission is as follows:

H. O. Wyckoff, *Chairman*
A. Allisy, *Vice Chairman*
K. Lidén, *Secretary*
F. P. Cowan
F. Gauwerky
J. R. Greening
A. M. Kellerer
R. H. Morgan
H. H. Rossi
W. K. Sinclair
F. W. Spiers
A. Tsuya
A. Wambersie

Composition of ICRU Subgroups Responsible for the Drafting of this Report

Initial work on this report was carried out by the Task Group on Measurement of Absorbed Dose at a Point in a Standard Phantom and the Task Group on Methods of Arriving at the Absorbed Dose at Any Point in a Patient. Serving on the Task Group on Measurement of Absorbed Dose at a Point in a Standard Phantom were:

M. J. Day, *Chairman*
Z. P. Balon
J. Dutreix
J. B. Massey

Serving on the Task Group on Methods of Arriving at the Absorbed Dose at Any Point in a Patient were:

M. Cohen, *Chairman*
A. Dutreix
J. E. O'Connor
H. Skoldborn

The two Task Groups worked under the aegis of the Planning Board on Radiation—Medical and Biological Applications (Therapy). Serving on the Planning Board were:

W. J. Meredith, *Chairman*
J. Dutreix
F. Ellis

F. Gauwerky, A. Wambersie and L. S. Taylor served as Commission Sponsors for the Planning Board.

The Commission wishes to express its appreciation to the individuals involved in the preparation of this report for the time and effort they devoted to this task.

Harold O. Wyckoff
Chairman, ICRU

Washington, D. C.
October 15, 1972

Contents

Measurement of Absorbed Dose in a Phantom Irradiated by a Single Beam of X or Gamma Rays

1. Introduction

The aim of clinical radiation dosimetry is the precise statement of the absorbed dose at all points of interest in an irradiated patient. Since direct measurement is seldom possible, and always fraught with great difficulty, indirect methods are usually employed. Over the years several different approaches to this problem have been devised and used in various departments. Even where the same basic method is used, the detailed techniques may, in practice, be quite diverse. In consequence, and also because of a striking lack of agreement between some of the sets of basic data employed, dosage in different centers is not really comparable. The exchange of clinical experience is thereby impeded and progress in radiotherapy has been retarded. There is a need for an unambiguous set of working rules which can be accepted generally for practical dosimetry.

In 1963, as a contribution to the general raising of radiotherapy standards, the International Commission on Radiological Units and Measurements published a report "to explain the principles of good radiotherapeutic technique in words rather than formulae, and to make recommendations based on these principles" (ICRU, 1963). More recently, the Commission has charged various of its subgroups with the review of practical radiation beam dosimetry and the formulation of recommendations on methods for the establishment of the absorbed dose at any point in the patient.

Four stages are usually involved. First, a determination of the radiation is made at the calibration point. This determination can be considered to be the calibration of the beam. Such a determination is required for all beam sizes and source distances that are to be used. In the special case of low energy (below 150 kV) x rays, the quantity determined is the exposure rate and the determination is free in air. For all other photon energies, the quantity determined is the absorbed-dose rate at the specified point in a standard (water) phantom. The position of this specified point depends on the energy of the photon beam.

Secondly, the peak absorbed-dose rates—or, for low energies, the surface absorbed-dose rates—are deduced either by relative measurements or, more usually, with the aid of published depth-dose tables.

In the third stage, the absorbed-dose rate at any point of interest is related to the peak or surface absorbed-dose rate by the use of appropriate standard depth-dose tables and isodose charts.

Finally, allowance may have to be made for the fact that the shape, size and composition of the patient are different from those of the phantom in which the standard measurements were made. These allowances are not dealt with in this report, it being planned that they will be included in a report being prepared.

2. Determination of Absorbed-Dose Rates

First, attention must be directed towards the measurement of the absorbed-dose rate at the calibration point and towards the derivation of the peak (or the surface) absorbed-dose rates. For this purpose a number of simple recommendations are made. These concern:

(i) the measuring system to be used,
(ii) the desirable features of the instrument based on that system and
(iii) the way in which the instrument is used.

2.1 The System of Measurement

When making measurements of absorbed dose or of any other physical quantity, a distinction must be drawn between the instrument which is used for measurements under working conditions and the standard instrument against which it has been calibrated. These latter devices are generally designed to operate under strictly defined laboratory conditions and would normally be inconvenient—or even completely unsuitable—for the type of measurement required in practice. For example, a free-air ionization chamber would not give an accurate measurement of the exposure rate at the end of the applicator of a typical 250 kV x-ray apparatus. For other reasons, neither calorimetric nor chemical methods are appropriate for regular clinical measurements. It is preferable to use one of the dosimeters which have been designed for this type of measurement. Although a number of physical effects (e.g., thermoluminescence, fluorescence, photoconductivity) have been used in the design of dosimeters—and indeed have advantages for special purposes—there is no doubt that the calibrated ionization chamber should remain the basis of clinical dosimetry. An important practical advantage of this recommendation is that most radiotherapy departments are already equipped with a suitable dosimeter of this type. The specifications for this instrument are discussed in the following section.

For x rays generated at potentials of 50–250 kV, exposure standards, using the free-air ionization chamber, are well established and a vast amount of radiotherapeutic experience is based upon them. In this quality range clinical dosimeters should always be calibrated directly or indirectly against one of these national standard instruments, as described below. Essentially the same considerations apply to cobalt-60 gamma rays or to the x rays of similar quality generated at 2 MV, except that for these qualities the standard instruments are graphite cavity chambers.

For x rays generated at potentials above 2 MV, the problem is more difficult. Although several alternative methods are available for measurement of absorbed dose, none has so far been adopted by any standards laboratory. Each individual user of a dosimeter must, therefore, calibrate it either by carrying out his own absolute measurements or by making use of the cobalt-60 gamma ray, or 2 MV x ray, exposure calibration. The latter alternative involves an additional factor appropriate to the energy of the radiation being used. This procedure, which is described in more detail in subsequent sections, represents the best method available at the present time and, in the interests of consistency, should be generally adopted until cavity chambers can also be calibrated for higher energy photons.

Despite these differences in *principle* between measurements of high energy and medium energy radiations, in practice a single *technique* is applicable to nearly the whole range of radiation qualities. The only exception occurs with the relatively low voltage x rays which are used for superficial therapy.

2.2 The Working Instrument

Three main features of an ionization chamber have to be considered, namely its size, the materials used in its construction, and the thickness of its walls. Since the aim is to measure the exposure at a point, the ionization chamber must be small. It is satisfactory if the internal diameter is about 5 mm and the length about 15 mm. Dimensions twice as great as these should never be exceeded.

It is necessary that the chamber response should be as independent as possible of radiation energy. The chamber should be constructed of suitable materials so that it is effectively "air-equivalent", i.e., its response (scale divisions per roentgen) to a given exposure should not vary with energy by more than 5%, at least for x rays generated between 100 and 300 kV. Strict "air-equivalence" is difficult to achieve with lower energies, but no chamber should be used for such purposes that cannot satisfy the stated criterion in the medium energy range. If it is satisfactory in that range, it can generally be relied on also to have satisfactory characteristics for higher energy radiations, though this should not be taken to imply that the

medium energy calibration factor can be extrapolated directly to higher energies.

For any particular photon radiation, an ionization chamber should be used for the measurement of exposure only if its wall thickness is such that there is negligible contribution to the ionization within the chamber from secondary electrons produced outside. The requisite thickness increases with photon energy. It is about 50 mg/cm² (0.5 mm of material of density 1 g cm^{-3}) for x rays generated at 300 kV. Since, for reasons of strength, most clinical dosimeters have chamber walls of about this thickness, they are directly applicable up to this generating potential. For higher energy radiations, thicker walls are needed and it is usual to supplement the chamber wall with close-fitting caps of Perspex (Lucite or Plexiglas). An extra thickness of 4–5 mm of this material is needed for measuring cobalt-60 gamma rays or 2 MV x rays.

A number of modern commercial instruments fulfill the desired conditions very satisfactorily, and in what follows, it is assumed that one of these is being used and that is has a thimble chamber whose cavity diameter is less than 8 mm and whose length is about 1.5 cm. It is also assumed that the instrument satisfies some further criteria. The first of these is that the chamber does not have a metal stem which produces marked attenuation of the scattered radiation when used in a phantom. The second is that it does not exhibit the stem leakage effects of some earlier instruments (Braestrup and Mooney, 1958; Adams, 1962). Thirdly, there must be negligible ion recombination in the chamber.

A test to determine whether there is any stem leakage is quite easy to perform (ICRU, 1963), whilst the ion collection efficiency can be checked by making comparative measurements with different collecting potentials (Boag, 1966). However, it is strongly recommended that the manufacturers of dosimeters should specify the exposure rate at which the loss of charge due to recombination becomes 1%. No correction for the effect is likely to be needed unless the mean exposure rate exceeds 200 R/min, but special care is needed with pulsed radiation emission and especially when the pulses are very short (less than a few microseconds) so that the instantaneous exposure rates may be very high. About 1 R per pulse of 1 microsecond duration can be recorded in chambers of the dimensions given above with an error due to recombination of about 5%, which can be reduced if a higher than usual collecting potential is applied (Boag, 1966).

Before an instrument is used it should be calibrated against a national standard at a number of appropriate radiation qualities. If direct access to a national standard is not possible, the instrument may, alternatively, be compared with another instrument which has been calibrated against a national standard.

2.3 The Technique of Measurement

Since it is highly desirable that different workers should use the same measurement technique, it is very convenient that a single technique is applicable to nearly the whole range of x-ray and gamma-ray energies. Despite the differences in fundamental methods mentioned earlier, the technique to be described is applicable to a very large proportion of the radiations in regular use for radiotherapy. X rays for superficial therapy form a minor exception which is dealt with in a subsequent section.

2.3.1 X Rays Generated at Potentials Above 150 kV and High Energy Gamma Rays

This category includes radiations which are used when the region of chief clinical interest lies several centimeters below the skin. For this reason, and for others that have been extensively discussed in other publications (e.g., ICRU, 1963), it is recommended that the calibration measurement be carried out with an ionization chamber positioned on the central axis of the beam, at a depth, d, below the surface of a water phantom. The values of d recommended for various radiation qualities are given in Table 1. The chamber should be protected from the water by enclosure in a water-tight Perspex (Lucite or Plexiglas) tube. Figure 1 shows the general design of the phantom with the protective tube. The constructional material is Perspex, Lucite, Plexiglas or similar material and, as laid down in an earlier publication (ICRU, 1963), the phantom should have a cross-sectional area of 30 cm × 30 cm and be 20 cm deep. A smaller phantom may suffice if only small beams are under study.

The absorbed dose, expressed in rads, can be calculated from the equation

$$D = R \cdot k_1 \cdot k_2 \cdot N \cdot F$$

where D is the absorbed dose at depth d in the undisturbed water phantom with the chamber removed, and the meanings of the other symbols are as follows:

R is the instrument reading;

k_1 is a factor to correct for any difference in temperature and pressure at the time of measurement from those prevailing when the instrument was calibrated;

k_2 is a factor to correct for differences, such as quality, between the radiation field used for calibration and that being used;

N is the calibration factor, determined by the standardizing laboratory at a stated quality of radiation, and under stated conditions of temperature and pressure, for the conversion of the instrument

TABLE 1—*Recommended values of the calibration depth (d) in water*

Radiation	d/cm
150 kV–10 MV x rays	5
Cesium-137, cobalt-60 gamma rays	5
11 MV–25 MV x rays	7
26 MV–50 MV x rays	10

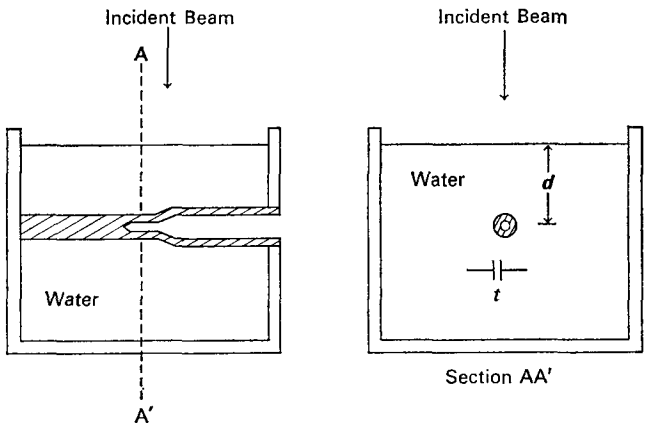

Fig. 1. Phantom with protective tube for measurements at a depth in water. Phantom dimensions: perpendicular to beam 30 cm × 30 cm, depth 20 cm. Alternatively, the phantom should extend laterally to leave a margin of at least 5 cm around the beam. The wall thickness, t, of the perspex sleeve should be approximately 2 mm, but it is not critical.

reading into a statement of exposure, expressed in roentgens;

F is a composite coefficient relating the exposure in roentgens to the absorbed dose in water expressed in rads. It incorporates a "displacement correction" (Section 3.2), and its precise significance is different when applied to medium energy radiations and when applied to high energy radiations (Section 3.3). The product $(N \cdot F)$ may be regarded as the absorbed dose calibration coefficient of the instrument for the specified measurement conditions. The value of F depends on the radiation quality (Table 2).

2.3.2 X Rays Generated at Potentials Between 40 and 150 kV

The limits of this radiation category are not intended to be rigid. The essential feature is that this section applies to radiations of low penetrating power, and treatments in which the absorbed doses of interest are in or near the surface. Under these circumstances it is recommended that the calibration measurement should be made with the chamber positioned free in air on the central ray of the beam, as close as possible to the eventual position of the treated surface. The surface absorbed dose, D, in a water phantom, is then related to the ionization chamber reading R by

$$D = R \cdot k_1 \cdot k_2 \cdot N \cdot F \cdot \left(\frac{s + x}{s}\right)^2 \cdot B$$

where:

k_1, k_2, N, and F have the same meanings as above;

s is the source-surface distance used in treatments;

x is the distance between the locations of the surface and of the chamber center, e.g., the distance between the end of the applicator (treatment cone) and the chamber center. The sign of x is positive when the chamber is further from the source. If no applicator is used, it is desirable to center the chamber at the treatment distance, in which case $x = 0$;

B is the back scatter factor appropriate to the field size and radiation quality

TABLE 2—*The conversion coefficient, F*

Primary Beam Quality (HVL, MV or Nuclide)	F/rad·R^{-1}
0.5 mm Al	0.89
1 " "	0.88
2 " "	0.87
4 " "	0.87
6 " "	0.88
8 " "	0.89
0.5 mm Cu	0.89
1.0 " "	0.91
1.5 " "	0.93
2.0 " "	0.94
3.0 " "	0.95
4.0 " "	0.96
^{137}Cs, ^{60}Co	0.95
2 MV	0.95
4 MV	0.94
6 MV	0.94
8 MV	0.93
10 MV	0.93
12 MV	0.92
14 MV	0.92
16 MV	0.91
18 MV	0.91
20 MV	0.90
25 MV	0.90
30 MV	0.89
35 MV	0.88

3. Commentary on Numerical Values of the Factors Involved in the Determination of the Absorbed-Dose Rate

3.1 The Temperature and Pressure Correction Factor, k_1

If the ionization chamber is unsealed, the value of the correction factor, N, given by the standardizing laboratory applies only to measurements made at a specific temperature (t_0), usually 20, 22 or 25°C, though sometimes 0°C, and pressure (p_0), usually 760 mm Hg pressure. Frequently measurements are carried out with the air ambient temperature (t) and pressure (p) different from those specified, and allowance must be made for this by use of the factor which is given by:

$$k_1 = \frac{273 + t}{273 + t_0} \cdot \frac{p_0}{p}$$

The temperature is that of the air in the ionization chamber, and this is only the same as the room temperature—which is the temperature usually measured—if adequate time is allowed for the chamber, and any phantom in which it is to be used, to come to room temperature.

3.2 The Exposure Calibration Factor, N

For radiations generated at potentials up to 400 kV, the value of N is found by calibrating the ionization chamber against a standard free-air chamber. N is the number by which the instrument reading (corrected as above for the ambient temperature and pressure) must be multiplied to yield the exposure in roentgens. Since, especially for low energy x rays, the value of N changes with changes of quality, the half value layer of the beam must be determined with appropriate accuracy.

For higher energy radiations, the only exposure calibration facilities available at standards laboratories are for cobalt-60 gamma rays or 2 MV x rays. Consequently, the value of N for gamma ray beams from cesium-137 and cobalt-60, and for x-ray beams generated at or above 2 MV, will be that obtained for cobalt-60 gamma rays or for 2 MV x rays. Calibration of the chamber at these qualities requires that it should have a cap of sufficient size to bring the total thickness to 500–800 mg per cm², in order to obtain electronic equilibrium.

This cap, which is usually of Perspex, Lucite, Plexiglas or similar material, attenuates and scatters the beam to some extent, and this is allowed for in the factor N, the use of which gives the exposure at the location of the center of the chamber, *in the absence of the chamber and its extra cap*. When, as here recommended, the chamber is used for the measurement of exposure in a phantom, allowance must be made for the effect of the material which the chamber and its calibration cap displace. An appropriate factor, which is about 0.98 for a chamber with an air cavity of diameter 6 mm, is incorporated in the value of F quoted for the higher radiation energies (Greene et al., 1962). It should be noted that the reading of the chamber is virtually unaffected if the chamber is used in the phantom without its calibration cap, whose thickness is then replaced by an equal thickness of water. Day et al., (1965) showed that under such conditions the chamber reading changed by less than 0.7% for Perspex cap thicknesses ranging from 0 to 20 mm, for radiation qualities ranging from that of cesium-137 gamma rays to x rays generated at 6 MV.

For the lower energy radiations, for which no added cap is necessary, there will still be some perturbation due to the displacement of phantom material by the different materials of the chamber system. Therefore, in principle, some correction is necessary. In practice, for the type of ionization chamber envisaged in these recommendations, the magnitude of this correction is much less than 1% (Greene et al., 1962; Massey, 1967).

3.3 The Conversion Coefficient, F

In the 40–400 kV range, F is essentially the "f-factor" (ICRU, 1964) which is appropriate for calculating the absorbed dose from the exposure under conditions of electron equilibrium. This coefficient takes account of W, the average energy necessary to produce an ion pair in air, and of the relative energy absorptions in air and water. For monoenergetic radiation, F is proportional to $(\mu_{en}/\rho)_{water}/(\mu_{en}/\rho)_{air}$, where (μ_{en}/ρ) is the mass energy absorption coefficient.

For the heterogeneous beams encountered in practice, the value of F has been obtained using an equivalent

photon energy, defined as the energy of a monoenergetic beam which has the same half value layer in aluminium or copper as the radiation being considered. The relevant half value layer is not that of the primary beam, but one which takes into account the fact that the quality of the radiation inside the phantom is different from that of the primary beam because of filtration and scattering in the phantom. Data are available (ICRU, 1964) which enable this quality to be deduced with sufficient accuracy from knowledge of the primary beam quality. Due allowance has been made for this quality change in the calculation of the F values given in Table 2, in which the stated beam qualities are those of the primary beam. The values were obtained for a field size 10 cm × 10 cm. If a particular value of F is applied to a different field size, the error introduced will be less than 2%.

In the case of measurements of cesium-137 and cobalt-60 gamma rays, and of x rays of higher energy (for which the factor N is obtained either with cobalt-60 gamma rays, or with x rays generated at a potential of 2 MV), the tabulated values of F embody all the necessary factors (stopping power ratios, including allowance for the polarization or density effect; and allowance for the perturbation produced by the presence of the measuring device in the phantom) for converting the corrected instrument reading into the absorbed dose in water expressed in rads. In this quality range F is identical with the factor usually known as C_λ. The physical basis of this method is fully discussed in ICRU Report 14 (ICRU, 1969).

3.4 The Back Scatter Factor, B

Unless special facilities for the measurement of back scatter are available, standard backscatter factors should be used (e.g., HPA, 1961).

3.5 The Depth of Measurement, *d*

To avoid ambiguity it is desirable to specify a definite depth of measurement. The criteria which guide the choice are firstly that the result should not depend on very exact positioning of the chamber, secondly that there should be electron equilibrium and thirdly, that the measurement should be made within the region of interest to the radiotherapist. For generating potentials in the range 150 kV to 10 MV, the recommended depth of 5 cm essentially fulfills all of these criteria. At higher generating potentials, the recommended depth is 7 cm (11–25 MV) or 10 cm (26–50 MV). The precise value of the depth is not critical, provided that it is known.

3.6 The Inverse-Square Factor, $(s + x)^2/s^2$

Use of the factor $(s + x)^2/s^2$ in section 2.3.2 implies that the inverse-square law is obeyed, but, in practice, this may not be so. To minimize the resulting error, x should be, if possible, zero and, in any case, sufficiently small that the correction to be applied is less than 5%. If this condition cannot be met, it is necessary to make measurements for various values of x, using the smallest available chamber, and to extrapolate the readings to $x = 0$.

4. Practical Implementation of the Recommendations

4.1 Dosimeter Calibration

The consistancy of radiation dosage in any department depends on the constancy of the local dosimeter. This instrument should be recalibrated at a standardizing laboratory over as much of the required range of radiation qualities as possible at least once every two years. In the interval between these calibrations its sensitivity should be checked at least monthly against a suitable radioactive source. Any change of sensitivity of more than 2 per cent should lead to re-calibration at the standardizing laboratory, after any necessary repair.

An instrument should never be sent through the post but rather it should be taken to the standardizing laboratory by one of the staff of the department concerned, and brought back in the same way after calibration. A check against its radioactive test source should be carried out immediately on arrival at the laboratory and again immediately prior to its being removed so that any effects of transportation may be revealed. It is appreciated that for many parts of the world this procedure is impossible, since no accessible standardizing laboratory is available. In these circumstances, it is strongly urged that secondary standard instruments, against which departmental instruments can be checked, be made available regionally until such time as more widespread standardizing facilities are available.

It is strongly recommended that each radiotherapy center should reserve one fully calibrated dosimeter as its reference or secondary standard instrument, to be used for regular checks of other instruments, but not for routine clinical measurements.

4.2 Determination of the Peak Absorbed-Dose Rates

The procedures described above enable the absorbed dose at a particular point (the "calibration" point) in a standard phantom to be determined in any department in a manner strictly comparable with that in any other department. However, the particular absorbed dose which is measured is not one which is of general use in radiotherapy. In clinical work it is customary to state, for each beam size and shape used, the absorbed-dose rate at the reference point of the central percentage depth-dose values (see Appendix for Glossary); that is, at the point at which the value of the percentage depth dose is 100. For radiations generated by potentials below 400 kV, the reference point is at the surface, whilst for higher energy radiations it is at the position of the peak absorbed dose.

To obtain the peak (or surface) absorbed-dose rate from the calibration absorbed-dose rate measurement obtained as above, it is necessary to know the value (P) of percentage depth dose at the calibration depth for the field concerned. The peak (or surface) absorbed-dose rate, $\dot{D}_0$, is calculated from the calibration absorbed-dose rate, $\dot{D}$, using the formula:

$$\dot{D}_0 = \dot{D} \times \frac{100}{P}$$

The acquisition of suitable percentage depth dose data for this and other purposes, is discussed in a later part of this report (Section 5.1).

4.3 Routine Checks of Absorbed-Dose Rate

Once each beam has been calibrated and its peak (or surface) absorbed-dose rate determined for the required operating conditions, frequent repetition of all the measurements is unnecessary. It is more convenient to rely on a single definite check measurement which, in effect, provides a statement of the radiation emission of the source. If the test situation is suitably chosen, then constancy of this measurement is sufficient to confirm the constancy of dose rates for other situations. Various alternative specifications of the test measurement are permissible. Whichever is adopted, it is essential that the value should be unambiguously related to the various calibrated dose rates. Moreover, this relationship must be determined empirically for each radiation generator.

The test situation need not be one which is used for treatment purposes, but it must be one which is accurately reproducible. A suitable arrangement utilizes the reading of a chamber at a fixed depth (greater than or equal to d) in a phantom of convenient size and material, using a 10 cm × 10 cm field, but other arrangements may be equally suitable. It is only the constancy of this reading that is important and not its dosimetric significance. Of course the reading must be carefully observed and recorded at the time the calibration absorbed-dose rate determinations are made.

As long as the same reading is found on subsequent occasions, the calibration absorbed-dose rates will remain unchanged. Any minor change in the reading can be taken into account by adjusting all the peak absorbed-dose rates in the same proportion. Allowance can similarly be made for radioactive decay of teletherapy sources.

Since the radiation output may well fluctuate, checks of this kind should be carried out regularly on all equipment, not excluding equipment which is provided with a monitor dosimeter. No apparatus is perfect and there are dangers if the use of a monitor is allowed to induce a false sense of security. It is advisable that checks be carried out daily as a matter of routine unless experience shows that weekly, or less frequent repetition is sufficient. However, any suspicion of unsteady or otherwise unsatisfactory performance—either of the radiation generator or of the monitor—should always lead to an immediate check reading. Similarly, a check must be made immediately after any major repair or change in the equipment, such as the installation of a new x-ray tube. Only in this way can the patient be protected against the hazards of over- or under-dosage.

4.4 Treatment Control by Timer

For radionuclide teletherapy units and for x-ray therapy units which embody a rate monitor, treatment control by means of a timer is appropriate. In such a case it must be remembered that dosage errors are introduced if cognizance is not taken of, and allowance made for, the way in which the radiation beam is switched on and off, in relation to the switching of the timer. The dose rate may build up to its full value during the first few seconds of the timed period; or the timer may not start until the x-ray shutter is fully opened or the radioactive source is fully in position, even though some radiation has been delivered during this starting phase; or the shutter may start to close or the source to move away only at the end of the timed period, with irradiation continuing for a short time afterwards. Such "end-effects" are negligible in most treatment periods, but may seriously affect the accuracy of calibration measurements. Allowances for them can, however, very readily be made as follows.

Measurements should be made for a single irradiation with an appropriate timer setting and also for a double irradiation using two timer settings each half the original amount. If the reading for the single irradiation is R_1 and the total reading for the double irradiation is R_2, then the "end-effect" error is R_2-R_1 and the true reading is therefore $2R_1-R_2$.

4.5 Treatment Control by Monitor Chamber

Even in the most carefully operated machine the x-ray output fluctuates. Therefore it is desirable, and strongly recommended, that the radiation output be monitored by an ionization chamber, which should be mechanically rigid and sealed to avoid changes in sensitivity due to ambient temperature and pressure variations. This chamber should extend right across the beam, so that it casts no local shadows. It should be positioned so that, under constant operating conditions, it is unaffected by changes in treatment beam size.

If the meter indicates output rate, all the machine calibrations must be made for a fixed meter reading which, of course, must also be strictly maintained during treatments. As already indicated, treatments monitored in this way should be timed and terminated by the timer.

Preferably, however, an integrating monitor can be used to terminate the treatment when some pre-determined absorbed dose has been delivered. The monitor may be calibrated to give the peak absorbed dose for a particular field size, but it must be remembered that, for a given monitor setting, the peak absorbed dose received by a patient does depend on the field size being used for treatment. The difference must be taken into account when using this device.

In the first few seconds after an x-ray beam is switched on there may be some changes in the direction of maximum radiation emission. Therefore, during this period, a rate monitor may be inaccurate. This results in an "end-effect" error similar to that which occurs with a timer. The error can be virtually eliminated by adopting the calibration procedure exactly as indicated in the previous section. It is necessary to check the constancy of the monitor sensitivity over the full range of absorbed doses and absorbed-dose rates which are used in practice.

No monitoring device can be perfect and it cannot be stressed too strongly that the price of dosage accuracy and safety is eternal vigilance. This is especially so in cases where the dose rate is high and the treatment time very short, so that the consequence of breakdown may be serious overexposure. Complete and independent duplication of the monitoring system may be needed in such cases.

4.6 Specification of Radiation Quality

The values of N and F, as well as the backscatter factor B and the percentage depth dose P which relates the calibration measurement to the peak dose, all de-

pend on the radiation quality. It is therefore important to know the quality of the beam being used. Furthermore, it must be borne in mind that the quality of the radiation at a depth inside a phantom will generally differ from that of the primary beam to an extent which depends on the proportion of primary and secondary radiations. Note that the values of F in Table 2 include due allowance for the change of quality inside the phantom. Fortunately, none of the four factors varies rapidly with changes of beam quality. Simple statements of quality are therefore quite satisfactory.

For radiations generated below 400 kV, the half value layer in aluminium or copper provides the most convenient quality specification. Throughout this report, the half value layer specified is that based on exposure measurements. In the case of higher energy x rays, a statement of the generating potential, or of the maximum photon energy is sufficient for most clinical purposes. Similarly, the quality of gamma rays is sufficiently defined by a statement of the emitting nuclides, e.g., "cobalt-60 gamma rays".

Having established the peak, or the surface, absorbed-dose rate for the field being used, attention must now be transferred to the determination of the absorbed-dose rate at any other point in the irradiated phantom. This can be done using appropriate tables of relative dose rates, e.g., depth-dose tables (for points on the beam axis) or isodose charts (for points off the axis).