PHYSICAL ASPECTS OF QUALITY ASSURANCE IN RADIATION THERAPY

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PHYSICAL ASPECTS OF QUALITY ASSURANCE IN RADIATION THERAPY

AAPM RADIATION THERAPY COMMITTEE
TASK GROUP 24
with contribution by
AAPM RADIATION THERAPY COMMITTEE
TASK GROUP 22

Goran K. Svensson, Chairman, TG-24

Members TG-24

Norman A. Baily
Robert Loevinger
Robert J. Morton
Robert F. Moyer
James A. Purdy
Robert J. Shalek
Peter Wootton
Kenneth A. Wright

Members TG-22

William F. Hanson
Lowell L. Anderson
C. Clifton Ling
Robert Loevinger
Kenneth A. Strubler

Consultants

Arnold Feldman
Douglas Jones
C. J. Karzmark
Edwin C. McCullough
N. Suntharalingam

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Further copies of this report may be obtained from

Executive Secretary
American Association of Physicists in Medicine
335 E. 45 Street
New York, NY 10017

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CHAPTER 1

INTRODUCTION

Quality assurance in radiation therapy includes those procedures that ensure a consistent and safe fulfillment of the dose prescription to the target volume, with minimal dose to normal tissues and minimal exposure to personnel.

A comprehensive quality assurance program is necessary because of the importance of accuracy in dose delivery in radiation therapy. The dare-response curve in radiation therapy is quite steep in certain cases, and there is evidence that a 7-10% change in the dose to the target volume may result in a significant change in tuner control probability [53]. Similarly, such a dose change may also result in a sharp change in the incidence and severity of radiation induced morbidity.

Surveying the evidence on effective and excessive dose levels, Herring and Compton [38] concluded that the therapeutic system should be capable of delivering a dose to the tumor volume within 5% of the dose prescribed. Report 24 from the International Commission on Radiation Units and Measurements [53] lists several studier in support of this conclusion.

Surveys have indicated that errors occur with some finite frequency even in institutions which are regularly reviewed by physicists from the Radiological Physics Center [31] and the Centers for Radiological Physics [117]. A nationwide survey of Co-60 teletherapy units was conducted by the National Center for Devices and Radiological Health (NCDRH), which was fomerly the bureau of Radiological Earth and the National Bureau of Standards [128]. The survey included 75% of the Co-60 units (751) in use and showed that doses delivered by 17% of these units differed from the requested doses by at least 5% and that 4% of the delivered doses differed by 10% or more.

Sources of error in radiation therapy include tumor localization, lack of patient immobilization, field placement, human errors in calibration, calculation, daily patient setup, and equipment-related problems. Many of these equipment and calculational errors can be minimized through a program of periodic checks.

The discussion and accompanying flow chart of a systems approach to radiation therapy given in ICRU Report No.24 [53] and in the CR0S Blue Book [106] points out that the planning and delivery of a course of radiation therapy is a continuous process with any feedback loops. Looking at treatment in this manner allows one to realize that the assurance of quality at each step in necessary to permit credible assessment of results of treatment.

Even though a comprehensive quality assurance (QA) program in radiation therapy has both clinical and physical components, this document will address only physical tests and procedures necessary to ensure that a radiation therapy facility can accurately and reproducibly deliver the prescribed dose to the target volume with minimal dose to normal tissue. This document also addresses the problems of optimal design and operation of a facility with regard to radiation, mechanical, and electrical safety.

A QA program, should be established for each radiation therapy facility. However, the nature of the program may depend on the objectives and resources of the clinical services and facilities.

The medical radiological physicist is often called upon to exercise her/his judgment as to the magnitude of an adequate quality assurance program which is consistent with the goals of the radiation oncologist. It is, therefore, a major purpose of this report to provide guidance to the physicist called upon to design and implement a quality assurance program for radiation therapy. Furthermore, this document provides information to regulatory agencies, professional organizations, and hospital administrations in their consideration of the resourcer needed for high quality radiation treatment delivery.

The document has been divided into six major areas; Accuracy and tolerances. Measurements, Simulation and external beam treatment equipment, External beam treatment planning, Brachytherapy and Radiation safety.

We are indebted to the Center for Devices and Radiological Health, Rockville Maryland, for sponsoring a two day workshop on this document on 11-12 March 1982.

CHAPTER 2

DOSIMETRIC ACCURACY AND EQUIPMENT TOLERANCES

A quality assurance document needs to contain clinically relevant recommendations about acceptable uncertainties in dosimetric procedures sad in mechanical alignment of treatment equipment. A large number of parameters, all having some inaccuracy, contribute to the overall uncertainty in the three-dimensional dose distribution delivered to a patient.

It is our experience that most QA documents specify acceptable tolerance levels for individual parameters without considering the cumulative effect on the uncertainty in the dose delivered to a specified volume in a patient. The reason is that such an uncertainty propagation is very difficult and considered by many to be scientifically unsound because we are dealing with the combined effect of systematic (non-random) and random uncertainties [68]. On the other hand. detailed recommendations about individual equipment parameters and dosimetric procedures do not guarantee technical quality unless the cumulative effect at the patient level is addressed. Analysis of individual parameters should not be the main focus of a QA program but rather serious attempt should be made to understand the cumulative effect of all procedures at the patient level. One would begin by defining an acceptable overall uncertainty, resulting from all radiotherapy procedures. This uncertainty is the result of many procedures that have both random and non-random uncertainties associated with then. The problem is to define these various uncertainties sad combine then in a meaningful way.

The problem of characterising the result of a set of measurements by an overall uncertainty, combining random and non-random uncertainties, has received considerable attention in the recent scientific literature [68,91]. Recognizing the need for a consensus method of making that combination, an international working party, made up of representatives of the national standards laborstories of 12 countries, has fomulated such a recommendation [58]. While not universally agreed upon, and not free of subjective suspects, the recommended method represents a reasonable and self-consistent approach. It is recommended that random uncertainties be determined as usual by statistical methods. and be represented by standard deviations. All other uncertainties are to be estimated in some manner, generally as a simple "guesstimate"', so as to correspond roughly to one standard deviation by assuming that the distribution of uncertainties follows a normal distribution. These non-random uncertainties are to be combined in quadrature with the random uncertainties to obtain a combined uncertainty, characterized by a number that can be considered to be roughly like a standard deviation. Finally the combined uncertainty can be multiplied by some factor, say 2 or 3, to get an overall uncertainty, which can be looked upon as very l approximately a 95% or 99% confidence interval, respectively.

A somewhat similar method of uncertainty analysis was used by Loevinger and Loftus [76] in deriving a model for dosimetric accuracy in calibration procedures. The results of their analysis has provided valuable guidance as to the achievable dosimetric accuracy in radiation therapy [53].

In dealing with individual machine parameters, the suggested method of quadratic summation makes it possible to set specifications which are reasonable and conform with acceptable overall uncertainties.

Figure 1 shows how uncertainties of the various components described in this document may interact. One important specification in a QA program should be the precision uncertainty in delivering a dose to any point in a patient. It is generally agreed that ±5% (here assumed to represent 2 standard deviations) is clinically acceptable and technically achievable [53]. Figure 1a provides acceptable level6 of uncertainties of the various component.6 in the treatment procedure. The cumlative effect of there uncertainties is within the limits of the overall uncertainties provided that quadratic summation is an acceptable method of propagation.

The spatial uncertainty in aiming one or several beams at a target within a patient depends on the mechanical accuracy of the treatment machine and the effect of breathing and patient motion on organ displacement. While the effect of organ motion on the geometric precision can only be approximately evaluated at this time, mechanical accuracy is rather well documented. Estimates of the contributions to the geometric precision from both classes of uncertainties are exemplified in Figure 1b. The problem then becomes, what is the overall impact of all sources of spatial uncertainty on the expectation of delivering a specified dose to the target volume and to critical organs in a specific patient? It is no comfort to a patient that on the average the dose to the spinal cord in a given facility does not exceed cord tolerance if in that patient's case tolerance is exceeded.

Given that the uncertainties in treatment delivery outlined above are inevitable, several things follow: 1) The overall impact of all sources of uncertainty must be evaluated, rather than concentrating on individual components; 2) When geometric uncertainties predominate, their impact will be felt quite differently in different regions of the patient (i.e. regions near the field edge may be much more sensitive to positional uncertainties than regions in the field center; 3) It is therefore necessary to evaluate the anatomic impact of treatment uncertainties; and 4) The uncertainties in dose may be non-linearly related to the geometric uncertainties and may be asymetric. These points are now illustrated by an example: Consider a three-field treatment (anterior; right and left posterior obliques tangential to the spinal process) of an esophageal tumor using 8 MV x-ray beams (Figure 2).

If one conriders the geometric uncertainty due to mechanical effects and inaccuracy of patient position and organ motion as shown in Figure lb, the uncertainty in dose per fraction is illustrated by the solid line in Figure 3. The Z axis is the patient midline in the anterior to posterior direction (Figure 2). The dosimetric uncertainties art illustrated by the dashed line in Figure 3. The uncertainties in these examples represent 2 standard deviations. The combined uncertainty per dose fraction in the dose profile along the Z axis is shown in Figure 4.

From this example it can be seen that the analysis in Figure 1a may be applicable to the central portion of the treatment volume but not to organs outside the main beam where the relationship between uncertainty in dose and position are not linear. For this reason it has been suggested that, where this lack of linearity exists, three calculations should be made for each cart. one with the nominal spatial relationships and one for each extreme displacement, perhaps of 1.5 standard deviations.

It is important to recognize that treating the problem of quality assurance in this manner allows some flexibility as to the tolerance values of the individual components in the system. For example, if j department, due to policy or limited resources, has eliminated one component (e.g. isocentric treatments) the additional

uncertainty caused by this component would at least in principle allow relaxing the tolerance on another component (e.g. target alignment) without reducing the quality of the overall treatment. It is also clear from this analysis that tolerances on individual machine parameters may vary somewhat between different departments depending on use and treatment objectives, without jeopardizing the treatment quality. given though uncertaintier should be kept as low as reasonably achievable, this analysis is helpful to determine that the combined effect of all uncertainties are acceptable.


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┌─────────────────────────┐
│ Combined uncertainty in │
│ dose to a patient    5% │
└─────────────────────────┘
```

```
┌──────────────────────────────┐   ┌──────────────────────────────┐
│ Cumulative uncertainty in dose│   │ Uncertainty in the treatment │
│ delivered   to a tissue-phantom│  │ planning computation of      │
│            2.5%               │   │ dose to a patient     4.2%   │
└──────────────────────────────┘   └──────────────────────────────┘
```

```
┌──────────────────────────────┐ ┌──────────────────────────────┐ ┌──────────────────────────────┐
│ Effect on dose computation of │ │ Computation of relative      │ │ Central axis                 │
│ tumor localization and        │ │ dose distribution (with      │ │ factors for                  │
│ contour delineation      2%   │ │ out heterogeneity)           │ │ blocks, wedges               │
│ If depth dose change is 4%    │ │           3%                 │ │ and compensators             │
│ per cm, the contour and       │ │                              │ │           2%                 │
│ target must be delineated     │ │                              │ │                              │
│ with an accuracy of 5 mm.     │ │                              │ │                              │
└──────────────────────────────┘ └──────────────────────────────┘ └──────────────────────────────┘
```
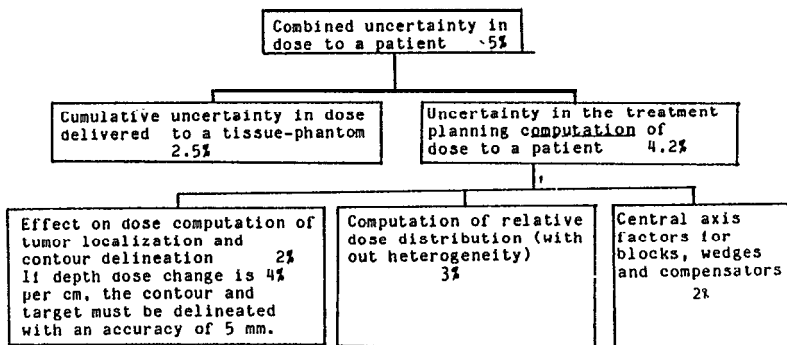
Figure 1a: Example of dosimetric uncertainties in the radiation therapy process. The uncertainties represent approximately the 95% confidence level.
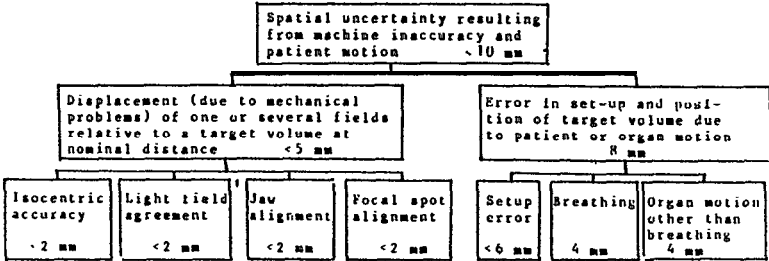
Figure lb: Example of spatial uncertainties (at the 95% confidence level) in the radiation therapy process.
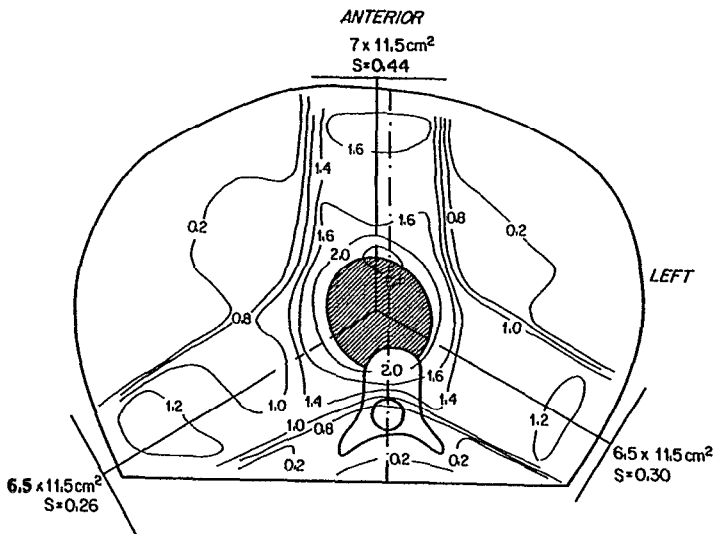
Figure 2: Three-field plan for treatment of the esophagus to 2.0 Gy per fraction.
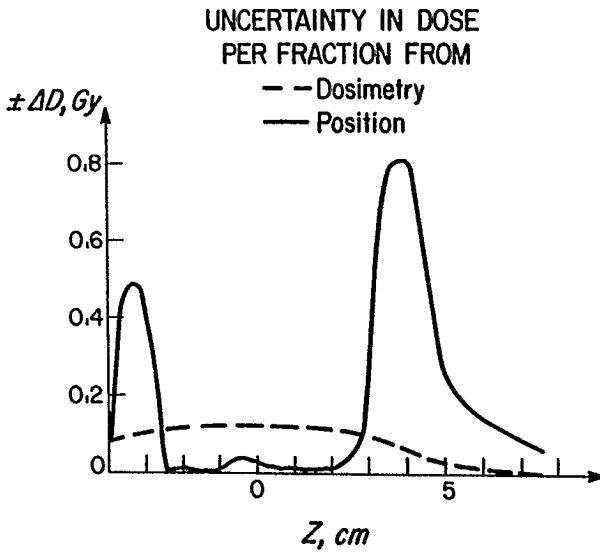
Figure 3: The dose uncertainly in the three-field plan shown in figure 2. The profile is taken in the AP direction along the midline. The dashed line shows the uncertainty in the dosimetry and the solid line is the uncertainly due to set-up errors, organ motion and breathing. These errors are identified in figure lb.

Figure 4: The solid line shows the Profile of the dose per fraction from the treatment plan in Figure 2. The profile is taken in the AP direction along the midline. The dashed lines show the dose uncertainty expressed as ±2 σ. Figures 1-4 are reprinted with permission from Int J. Rad. Onc. Biol. Phys. Supplement 1. Svensson, GK: Quality Assurance in Radiation Therapy (1983) Pergammon Press, Ltd.

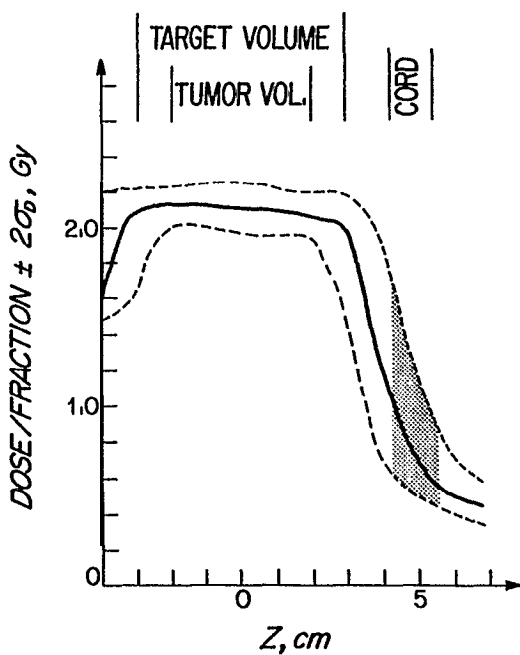CHAPTER 3

MEASUREMENT EQUIPMENT USED IN RADIATION THERAPY*

INTRODUCTION

The evaluation of accuracy and precision of determination of absorbed dose is a very important component of any physical quality assurance program. Commonly employed dosimeters do not measure dose or exposure directly and the accuracy of l given dosimetric system is subject to change without obvious indication. Accessory equipment (e.g., isodose plotters) also can contribute significant errors, therefore this equipment should receive equal scrutiny.

There are many steps in the process of estimating dose in a patient. Bach step may introduce errors; therefore careful control of all factors is justified. Variation in biological response between patients and uncertainties of optimal therapeutic dose do not justify dosimetric expediency, due to potential compounding of error*. Uncertaintier in theoretical conversion constant are on the order of 3% [50]. The incorporation of refinements in these factors (or reduction of other types of systematic errors) in patient dosimetry requires consideration of the clinical experience obtained with less accurate data. The effect on the delivered target dose or dose distribution must be clearly understood before changes are implemented.

It is possible that a significant error can escape detection under the best of circumstances. For this reason, it is highly recommended that all facilities subscribe to some form of outride check of their dose delivery capability. Dosimetric comparisons between institutions are useful for this purpose. Some examples of such services follow. The AAPM Radiological Physics Center provides on-site visits and mailed thermoluminescent dosimeter (TLD) comparisons for institutions engaged in certain treatment protocols [36]. The National Bureau of Standards conducts mailed Fricke dosimeter comparisons for high-energy electrons [26]. The MPH-coordinated Centers for radiological Physics (CRP) offer on-site dosimetry checks and wiled TLD evaluation to certain facilities (funded by NCI). There are some private concerns and universities that offer mailed TLD measurement service as well. Site visits by an outride group are more comprehensive and preferred, but mailed TLD checks are recommended as the minimum necessary l m part of a QA program.

The following are basic characteristics that should be evaluated for all newly introduced dosimetric instrumentation and periodically verified during use by recalibration or constancy checks (when appropriate). Some of these characteristics apply to ionization chambers only.

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*Detailed considerations are limited to photon and electron therapy.

1. Accuracy and constancy
   a. Energy dependence
   b. Dose rate dependence
   c. Angular dependence
   d. Collecting voltage polarity dependence and equilibration tine
   e. Dose history dependence
   f. Size and shape limitations relative to dose gradients for anticipated use
   g. Air cavity venting

2. Reproducibility

3. Nonlinearity of response

4. Spurious signals
   a. Charge leakage
   b. Extra-cameral radiation signals (cable, connector, chamber stem, pre-amplifier effects)
   c. Cable stress
   d. Electromagnetic interference
   e. Assorted artifacts for light emission and transmission dosimeters

   The user of each instrument should be capable of analyzing all of the above potential sources of error (or of judging when they need not be evaluated).

   Appropriate quality assurance tests depend on equipment type. For the purpose of this report, equipment will be assigned to the following categories.

1. Radiation measurement equipment
   a. The local standard instrument
   b. Relative dosimetric equipment (TLD, film, diodes, ion chambers, et al., including devices for evaluating beam constancy)
   c. Multipurpose electrometers and separate readout devices
   d. Survey instruments

2. Dosimeter positioning and recording equipment (scanners and plotters)

3. Phantoms

4. Accessory equipment (thermometer, barometer, ruler, et al.)

RECOMMENDATIONS   AND LITERATURE REVIEW

1. Radiation measurement equipment

   a. The local standard instrument

   Field instruments are portable instruments that arc used for calibration and other measurements on radiation therapy machines [103]. A field instrument is said to have a calibration directly traceable to NBS when the instrument has been calibrated either at NBS or at an AAPH-Accredited Dosimetry Calibration Laboratory (ADCL) against a secondary standard that has itself been calibrated at NBS [103].

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*Radionuclide calibration equipment will be discussed in Chapter 6

One field instrument, having a calibration directly traceable to NBS, should be considered the local standard. As such it should be reserved for calibration of radiation therapy beams, for intercomparison with other instruments that have calibration directly traceable to NBS, and for calibration of other field instruments that are used for measurements other than therapy beam calibration.

The local standard instrument should be maintained with care by a qualified medical radiation physicst [2]. Redundancy in calibrated instrumentation (and sources) is required [5,41]. The optimal frequency of calibration is controversial at the time of writing [4,63,103,113]; however, a period of 2 years was suggested in the AAPH code of practice for x-ray linear accelerators [2] and is a requirement of the Nuclear Regulatory Commission for Co-60 teletherapy units [131]. A minimum period of four years with interim intercomparison is being recommended by the AAPH at the time of preparation of this report [4]. If the instrument is shipped to and from the calibration laboratory, special attention must be paid to satisfactory packing to guard against mechanical shock and damage. It is suggested that linearity and extra-camera1 radiation signal teats be conducted just prior to the time of each instrument calibration, Radionuclide constancy checks [2,81] should be done before and after each chamber calibration, and just prior to the time of and immediately after each machine calibration. This applies especially if a significant difference in indicated dose or dose rate is noted. Simple electronic constancy tests should be conducted prior to each use [44,79,103]. Tests should include (where appropriate) charge leakage, chamber bias, electrometer potential confirmation (if battery powered), and electronic constancy check. This can be accomplished by condenser chamber "discharge check" or the use of a constant-current source. Explicit records should be kept of all constancy tests. The initial calibration should include as many radiation qualities as possible in the anticipated region of use. Careful consideration should be given to any deviation from chamber calibration conditions during machine calibrations (notably dose rate. field size, and energy, e.g., HVT and homogeneity coefficient).

Numerous small sources of error exist during instrument calibration intercomparisons resulting in an uncertainty, under "optimal" conditions, of approximately 1% [53]. Individuals performing calibration comparisons should be error-conscious and maintain a detailed history for each instrument. The local standard should be returned to the RCL if sensitivity changes of more then 2% are detected.

Field instruments, used for measurements other than therapy beam calibration. i.e., on-patient dose measurements, where therapy patient dose may be adjusted, may be calibrated by comparison with the local standard instrument. The constancy of them field instruments can be maintained with the same constancy check methods used for the local standard.

b. Relative dosimetric equipment

Readouts labelled "dose" can be especially misleading to the user. Accuracy. precision, linearity, and the presence of spurious signals should be checked frequently. Energy dependence is very great in some systems, e.g., radiographic film and diodes [15]. Diodes also are subject to changing sensitivity with use. Systems used for in vivo patient dosimetry and those noted for their variable, non-linear response (e.g., film), should be calibrated frequently under similar scattering conditions (ideally, during each use).

When relative dosimetric equipment is employed to obtain relative treatment factors (field factors, dose vs. depth, etc.), the user should be aware that there data are as important as the primary calibration, sod all the errors listed in the

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Introduction are possible. For example, no system can be assumed to have **a** linear response, and. in addition, the spurious signal level may very during or between measurement. When potential errors of this type exist, systems used for phantom studies to establish treatment factors should be spot-checked with a second system (e.g., TLD) at each radiation quality.

Thermoluminescent dosimeters (TLD) and similar small detectors typically have relatively large variability between dosimeter elements. This require6 the user to be knowledgeable in statistical sampling and analysis techniques in order to obtain results with the necessary accuracy.

Teletherapy beam constancy evaluation devices are very useful for rapid checks of several parameters (see Chapter 4); however, adjustment of machine parameters should not be based solely on measurements obtained with such instruments. Periodic evaluation using l Cobalt-60 teletherapy unit can be employed to check constancy devices which are used for x-ray and accelerator therapy machines. However. it is well documented that even radionuclide teletherapy units are not infallible [69].

c. Multipurpose electrometers and separate readout devices

Electrometers, digit.l voltmeters, etc., have been singled out due to the significant increase in their use and as a reminder that these instruments are an integral part of a dosimetric system. Due to their complexity, the average user probably does not understand the full theory of operation. Semiconductor components can provide long periods of dependable service but are subject to damage by voltage transients. Each sensitivity range should be evaluated separately; autoranging is not recommended unless each range is checked periodically, due to possible differences in electronic sensitivity and/or shifts of the zero position. The collection potential for ionization chamber mad the electrometer battery pack (if present) should be checked at least once during each measurement sequence. Constant-current end standard capacitance calibration or constracy check procedures are useful to differentiate between chamber and electrometer me the source of changes in sensitivity or precision [66,79]. Any separate readout device must be included in the system calibration and constancy checks.

d. Survey instruments

The typical survey instrument is prone to meet source, of errors listed at the beginning of this chapter, notably energy dependence, angular dependence, and non-linearity [101]. A greater overall uncertainty is considered acceptable (+30%) for measurement near the maximum permissible dose rates [51]; however, regulatory agencies may require more demanding accuracy limits [133]. Tests for singular and energy dependence are relatively difficult to perform in a typical hospital environment, Survey meters purchased for the purpose of estimating exposure or dose should be obtained only from manufacturers who supply appropriate detailed data obtained with acceptable techniques [7]. Wherever possible. these data should be spot-checked. e.g., side vs. front exposure. Relatively low energy sensitivity can be spot-checked in the hospital setting (with some difficulty) by using calibrated high-activity radionuclide sources (corrected for self absorption), or by exposure Of calibrated field instruments to scattered radiation from a superficial therapy unit. The generally accepted routine calibration procedure involve6 recording reading at varying distance from calibrated Cs-137, Co-60, or Ra-226 sources with due consideration to the dimensions of the sensitive volume. In a typica1 room, scattered radiation is significant when using an uncollimated source, and lack of correction will result in underestimates of exposure rates during an actual survey (>25% error is possible). The scatter contribution can be estimated with sufficient

accuracy during calibration by making additional measurements with a lead shield (approximately 7 HVT's) placed midway between the source and the instrument. The lead brick holder should be left in place for all readings. The overall correction is determined by the ratio of calculated free-air exposure rate to instrument reading without lead minus the reading with lead. The scatter correction varies with distance, nuclide, and instrument type due to differences in scattered radiation energy and changes in scatter geometry. Collimated sources must be calibrated in terms of exposure due to scatter from their containers.

End caps or windows should be in place when the secondary electron range exceeds the inherent wall thickness. Although somewhat complex and arbitrary, additional (approximately air-equivalent) buildup cap material should be used if the cap supplied does not approach the electron range during calibration or survey (typically above approximately 1 MeV). Wall thickness for calibration should match the nuclide used, not the energy to be surveyed, and vice versa. For example, total wall thickness (cap plus inherent) of approximately 0.4 g/cm^2 should be used for instrument calibrations with Co-60 or Ra-226, whereas a cap of approximately 2.5 g/cm^2 would be required to assure near charged-particle equilibrium for surveys of a 10-MeV photon unit, and omission of cap (<10 mg/cm^2 inherent wall) would be most appropriate for measurements of photon sources less than 100 keV to minimize wall attention. The surveyor should be aware that readings obtained with a hand-held instrument accurately calibrated in air with Cs-137, may deviate from actual dose by approximately -30% to +10% due to tissue absorption and scattering differences from free air.

Instruments should be calibrated at least annually at two or more positions on each sensitivity level (one position near maximum reading and one position below 1/2 maximum). built-in radionuclide check sources are highly desirable; check-source readings should be obtained prior to each measurement sequence.

Care should be exercised regarding ion collection or counting efficiency as a function of instantaneous dose rate, e.g., the peak instantaneous dose rate typically is approximately 1000 times greater than the average rate for pulsed high-energy linear accelerator x-ray units.

RF interference sometimes is experienced and shielding of the instrument or RF source may be necessary.

2. Dosimeter positioning equipment

The following relationships should be evaluated prior to and after each measurement sequence; the spatial accuracy goal should be ±1 mm (actual vs. indicated position in three dimensions).

   a. Coincidence of the center of the sensitive detector volume with position scales on the scanning device both at the center and extremes of the region to be evaluated.

   b. Coincidence of the scanner scale position with the plotter and remote-control-indicated position at both the center and the extremes (or configuration of position recorded by digital systems).

   c. Mechnical hysteresis (coincidences of plotter and summer position when a given position is approached from different directions). Certain commercial models have been very poor in this regard.

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The following additional problem areas will generally need to be addressed by a physicist due to their complexity.

a. Change in detector position with respect to scanner- or computer-indicated position (static or dynamic).

b. Spurious signals due to irradiation of different portions of cables, connectors, or signal amplifiers [50].

c. Nonlinearity of percentage stepping circuits (e.g., automatic isodose . plotters). There are several sources of nonlinearity.

d. Response-time interactions between detector signal. servo mechanisms, and beam intensity transients [50].

e. Variations in pressure around air-chamber volumes in a water phantom.

f. Variation in apparent sensitivity of film densitometer scanners due to changes in distance between film and light sensor (a mechanical problem of scanning system).

g. All applicable potential errors previously discussed in Item 1 (Radiation measurement equipment).

3. Phantoms

Whenever possible, relative dose measurements should be made in water phantom with the beam entering through the open top or through thin side windows. Water is not exactly soft-tissue equivalent but is considered the best readily available substance for phantom material at all energies. Basic considerations for solid phantom design and use have been discussed by others [135]. The following tests should be carried out for quality assurance purposes.

a. Individualism solid phantom sheets. Measure and record mass thickness and linear thickness. Calculate density and compare it to the standard value for the substance used.

b. Check stacked mass thickness of layered solid phantoms vs. summed individual mass thicknesses (improve flatness if indicated and practical). Compression mechanisms are useful and often essential, e.g., for parallel-to-beam film dosimetry.

c. Check actual depth of fixed detector holders below surface, as well as accuracy of hole diameter and depth(s) for detector insertion to confirm that only minimal air spaces exist.

d. If the beam enters through a solid side of a water phantom, measure degree of bulge or sag prior to each use (0.5% to >1% dose errors are possible before this is noticeable by eye).

e. Determine the temperature of the phantom material during each use or allow sufficient time for it to come to equilibrium with the air temperature.

f. Confirm that phantom dimensions are adequate in all directions for intended use. A classic error results if additional phantom material is not added outside of water tanks when data are collected near one or more of the rider of a tank.

g. Apply appropriate correction factors to data collected in solid phantoms.

4. Accessory Equipment

Each individual who performs calibrations of radiation therapy equipment should have access to a thermometer, barometer, and linear rule of appropriate accuracy. Mercury barometers are conridered inherently accurate if they have been checked with a long, accurate rule and if gravity and temperature corrections are applied (typically -3 mmHg). Aneroid barometers should be compared to a mercury barometer at least once per year (ideally near the time of each use). The reader is reminded that most common barometric reports and instruments relate to a specific elevation. Serious errors could result if these instruments or reports were used without proper correction when there is a significant difference from the reference elevation. Aneroid barometers may lose their calibration when exposed to extremes of pressure, such as during air travel in an unpressurized compartment [2]. Errors of the order of 1 degree Celsius are common, and, if combined with 1 mmHG (133 Pa), and 1 mm distance error, could introduce errors in the order of 0.5% to 1%. It should be noted that graph paper scales may have errors approaching 1% and that copy machines may significantly distort graphic materials.

Substances employed for photon attenuation analysis (HVT) should be of established purity. These also should be individualized (each piece checked and labelled) and linear thicknesses determined by measurements of mass thickness.

No measurement device can be trusted to maintain its calibration over any extended interval of time or to possess the calibrated degree of accuracy in uncalibated regions. Arbitrary but practical limits of calibration and check frequencies have been established based on pert experience and logic. Table I lists recommended minimal tests, specific frequencies, and accuracy goals for the confirmation of measurement equipment used in clinical radiation therapy. Any indication of malfunction should be followed by detailed evaluation, e.g., as for new equipment.

TABLE I

PARTIAL LISTING OF MINIMAL QUALITY ASSURANCE TESTS AND LIMITS FOR MEASUREMENT EQUIPMENT

Instrument Type	Test		Frequencies*	Tolerance**
Local standard (see text)	1.	ADCL calibration	4 y	D
	2.	Linearity	4 y	0.5%
	3.	Venting	4 y	D
	4.	Extra-cameral signal	I	0.5%
	5.	Leakage	E	0.5%
	6.	Radionuclide check	E	2%
	7.	Recombination	I	0.5%
	8.	Collecting potential	E	D
Other field instruments	1.	Loc. Std. Comparison	1 y	2%
(see text)	2.	Linearity	4 y	D
	3.	Venting	4 y	D
	4.	Extra-cameral signal	4 y	D
	5.	Leakage	E	0.5%
	6.	Radionuclide check	E.	2%
	7.	Recombination	I	0.5%
	8.	Collecting potential	E	D
Relative Dosimetric Equipment				
1. TLD	1.	Calibration	B	D
	2.	Linearity	I	D
	3.	Electronic sensitivity	E	3%
2. Film	1.	Dose/response	B	D
	2.	Densitometer linearity	1 y	D
	3.	Position sensitivity	I	D
3. Air Ioniz. Chamber System				
	1.	Linearity	1 y	D
	2.	Extra-cameral signal	I	1%
4. Diode System	1.	Energy dependence	I	D
	2.	Extra-cameral signal	I	D
	3.	Linearity	I	D

			Frequencies*	Tolerance**
Survey Instruments	1.	Calibration	1 y	D
	2.	Linearity	1 y	D
	3.	Constancy	E	5%
	4.	Battery voltage	E	D
	5.	Time constant		
	6.	R.F. interference		D
Positioning Equipment	1.	Accuracy	E	2 mm
	2.	Hysteresis	E	2 mm
Phantoms and Attenuators	1.	Thickness	I	D
	2.	Density	I	D
	3.	Phantom stacked density	I	D
	4.	Integrity	E	
	5.	Detector fit		D
Accessory Equipment				
1. Thermometer	1.	Calibration	I	0.5%
2. Barometer (aneroid)	1.	Calibration (Hg)	3 mo	1 mmHg
3. Linear rule	1.	Calibration	I	0.3%

* I = Initial use for each mode of use or following malfunction and repairs.
  E = Each use (measurement sequence) or ongoing evaluation.
  B = Each batch or box at appropriate energy (dosimeter element precision also should be considered).

** D = Documented and correction applied or noted in report of measurement, when appropriate.

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CHAPTER 4

EXTERNAL BEAM TREATMENT AND STIMULATION EQUIPMENT

INTRODUCTION

The ability to deliver the correct target dose to a patient depends on several factors, the most significant of which are an exact dose calibration, accurately determined depth dose and off-axis dose characteristics, and knowledge of the precise patient geometry used during irradiation. Although these requirements are generally common to all types of treatment equipment (sources), a detailed description of the influencer of the various factors entails categorizing equipment according to design end use. For example, using **a** modern isocentric treatment machine requires understanding of the exact geometry in which the patient is treated. Only when the size and direction of the beam and the source-to-axis distance are known with precision can an accurate calculation of the relative dose distribution end/or total dose be performed. The validity of such a calculation is dependent on the mechanical precision of the movements of the machine itself and of propertier of the treatment accessories such as wedges and blocks, etc. As a result, a quality assurance program must include tests of dosimetric characteristics as well as of mechanical and geometric integrity.

Table II lists the types of equipment and the different parameter for which quality assurance testing is recommended.

I. DOSIMETRY

The first item, Dosimetry, is subdivided into a central axis dose calibration and constancy checks. Constancy checks refer to periodic tests of performance of certain equipment parameters, in this case the five listed in I.B.1 to I.B.5.

I.A. Central axis dose calibrations should follow established guidelines as outlined in detail in various publications [1,2,41,50,105].

The instrument of choice for these calibrations should be a local standard ionization chamber or field instrument (see section on measurement equipment for definitions) having a calibration factor directly traceable to the National Bureau of Standards. For high-energy photon beams, it is recommended [1,2,105] that due to the influence of secondary electron contamination, calibrations be performed at the depth of dose maximum or at a defined greater depth. Calibration depths vs. photon energies are tabulated in [105]. For electron beams, calibrations should be performed et the depth of dose maximum [105]. The central axis dose calibration should be performed in water or a suitable solid phantom [52,105]. The technique for converting ion chamber readings to absorbed done in water or plastic has been thoroughly reviewed [1,2,41,50;105] and if followed, results in an acceptable clinical uncertainty in central axis dose calibrations. Of the institutions reviewed by the Radiological Physics Centers [122] or by the six Centers for Radiological Physics, over 90% currently fulfill criteria of ±3% for machine calibrations. and 88% are within ±2%. It should thus be possible to calibrate the treatment machine periodically to within 2% of its previous calibration,

using the same field instrument. The frequency for such calibrations is regulated by the NRC and/or state Radiation Control Program. For Co-60 and Cs-137 units it is at least every 12 months. Provided that adequate constancy checks are performed, annual full calibrations of X-ray and electron machines would be reasonable.

I.B. Constancy checks (I.B.1 - I.B.5) are central to the overall quality assurance program in a department.. Such tests must be preceded by baseline tests which should be performed when the equipment is installed, and periodically thereafter. The constancy of machine dose rate or dose per moniter unit (I.B.1) should be checked frequently. For Co-60 units and conventional X-ray machines, once a week may be sufficient. However, an accelerator is more vulnerable to failures that cause changes in the output, and therefore constancy checks should be performed more than once a week. Constancy checks can be carried out by a competent member of the technical staff under the supervision of a physicist. Guidelines for action levels need to be recommended by the physicist. If, for example, the constancy check shows more than a 5% deviation from the most recent full calibration, a prompt calibration check should be performed before treatments resume.

A variety of instruments such as ionization chambers, diodes, film. and TLDs can be considered for use in constancy checks. One must choose a detector consistent with the desired accuracy of the test. Reference [2] describes techniques and equipment for constancy checks of machine output. This can easily be combined with checks of beam penetration and beam uniformity.

Beam uniformity (flatness and symmetry) has traditionally been defined as the dose variation over 80% of the nominal field size at 10 cm depth in a plane perpendicular to the central axis. The dose uniformity defined in this manner is expected to be within ± 3% [103]. This definition is only useful in the principal planes of the treatment field. In many situations, it is valuable to consider the beam uniformity in off-axis planes and diagonal planes. The International Electrotechnical Commission (IEC) has proposed an elaborate definition which addresses the flatness and symmetry over the whole beam surface at 10 cm depth [47]. The tolerances for acceptable flatness, as defined in the IEC document, are a function of field size.

The Nordic Association of Clinical Physicists has introduced a quantity known as the Beam Uniformity Index which is defined for a plane orthogonal to the central axis and at a given depth [105]. The uniformity index is defined as the ratio of the area over which the dose rate exceeds 90% of the central axis dose rate to the area over which the dose rate exceeds 50% of the central axis value. Guidelines for flatness symmetry depend on the selected definition. The reader is referred toe the cited literature for advice on acceptable tolerances.

There are many sources of malfunction which can affect beam profiles. For high energy x-ray machines, misalignment of the target and flattening filter are common reasons for non-uniform beam profiles. The effects produced by mis-steering of the electron beam and beam energy variations are of course similar. For such x-ray units, beam uniformity constancy checks should be performed often; a reasonable frequency would be once a week. The checks should be made along both principal planes and for both vertical and horizontal beams. For Co-60 units, the beam flatness and symmetry are not likely to change as long as the source holder and shutter assembly are intact. These should be checked frequently, while the actual beam uniformity need not be checked more than once a month.

End effects, including timers used to terminate the treatment, need to be checked once a month. A procedure for timer error tests is described in ANSI documents [8,9].

II. GEOMETRY

As illustrated in Table II, Geometry is divided into several subsections. Each deals with some mechanical characteristic of teletherapy units.

II.A. The first subsection on field positioning aids lists the various devices used in attaining proper positioning of the patient in the treatment field. The light source should define the useful radiation beam regardless of the selected treatment geometry. The virtual light source must therefore be adjusted and maintained so that it remains on the axis of collimator rotation and at the same point as the radiation source. In this manner, the light field will always define the geometric bounderies of the radiation field. Severe1 documents [2,8,27,42,47,78,108] describe in some detail how to check the agreement between the light end radiation fields. Commonly, x-ray film is used to test the x-ray and light field coincidence. A piece of prepacked film is positioned perpendicular to the central axis of the radiation field at a standard source to skin (or axis) distance and marked to show the light field corners and cross hair. The radiation exposure is done with a build-up layer sufficiently thick to provide electronic equilibrium. The film can then be scanned by using a densitometer and the agreement between the therapeutically useful beam and the light field can be determined. A practical recommendation is to adjust the light field to correspond with the 50% isodensity curve within 3 mm at dose maximum for a given field size (e.g. 10 cm x 10 cm). For constancy checks, visual inspection of the film may be sufficient. In that case, the measurement need not be done under conditions of electronic equilib-rium. This method is less accurate, however, and the tolerance criterion needs to be relaxed to about 4 mm. This constancy procedure should be repeated at least monthly with the gantry in the four principal positions.

Scanning devices using ionization chambers or diodes are also suitable for light field/radiation field checks [2].

Other field positioning aids such as readouts. mechanical pointers, lasers and SSD range lights need to be adjusted and checked with sufficient regularity. Most of the listed references describe methods for some of these tests. Marks on the floor and walls are useful for constancy checks.

II.B. Mechanical alignment is of fundamental importance for the performance of a teletherapy unit. A quality assurance program for an external beam treatment unit should include tests capable of detecting photon beam misalignment. The determina-tion of the rotational axis of the collimator, the rotational axis of the gantry and the collimator symmetry must be accurate and unambiguous since both the radiation field end positioning aids are aligned to those parameters.

Techniques for mechanical alignment are described in [2,8,9,27,42,47,78.109]. As a constancy check of the overall system, a split-field test method [78] is recommended due to its rapid and simple execution. This test determines the lateral shift between two opposing isocentric fields in the plane of rotation. Such a shift can be caused by a focal spot displacement and/or asymmetric collimators and/or nonintersecting collimator and gantry rotational axis. It is clinically meaningful to specify that the combined effect of these alignment parameters on the displacement of two opposing fields should not exceed a certain acceptable value. If recommendations about tolerances are put forth on individual alignment parameters

without addressing the combined effect, a machine could in principle pass a QA test and yet be clinically unacceptable. A minimal and clinically justifiable criterion is that the displacement between two opposing treatment fields should be less than 5 mm (see Fig 1b). Keeping this in mind, one can proceed to set tolerances for the individual alignment parameters. It may be reasonable to accept the published recommendations [8,47] that the isocenter should be within a 4 mm diameter circle (for modern isocentric equipment, 2 mm can easily be achieved [2,105]). Furthermore, the jaws and target should be aligned so that they do not displace the field edges by more than 2 mm at the plane of the isocenter. The implications of these recommendations are that all alignment parameters cannot be off by their maximum amount in the same direction because the combined effect on the opposing beam displacement would exceed the 5 mm criterion. For isocentrically mounted Co-60 or other rotational treatment machines, it is reasonable to check the opposing field displacement monthly.

The couch turntable should be installed and tested so that its vertical axis of rotation passes through the isocenter and the up-down motion is vertical. Furthermore, the couch top must be levelled. The sag of the table top must be within manufacturers specification.

III. ELECTRON BEAM EQUIPMENT

Useful electron beams are generated in a broad energy range from 3 MeV to 50 MeV. Most electron producing accelerators are equipped with some kind of scattering foil and collimator system. The most common scattering technique uses a uniform foil positioned near the exit window of the accelerator. An alternative technique [18.71] used in some treatment machines utilizes a dual set of foils, where the second foil is conical and positioned at some distance from the first. Large electron treatment field. can also be generated by scanning beam techniques for which various collimation techniques have been devised. Some systems use applicators that define the electron beam close to the patient surface. while others employ adjustable collimators at some distance from it. Depth dose and beam uniformity are dependent upon the angular and energy distributions of the electrons, which strongly depend on the collimation and scattering system.

Following a model by Loevinger and Loftus [76], one can derive an uncertainty representing 2 standard deviations in the optimal absorbed dose calibration for electrons based on the current practice of using a Co-60 calibrated ionization chamber. In their model, the calibration of a field instrument has an uncertainty which is at best 1.7%. When a photon calibrated ionization chamber is used to calibrate an electron beam, additional uncertainties arise from the errors in stopping power ratio (2%). and from uncertainties in correction for wall material and beam perturbation. An optimal correction for wall material and beam perturbation may have an uncertainty of the order of 2%. By combining in quadrature, one can estimate the overall optimal uncertainty to be about 3%. The uncertainty may also include errors due to chamber positioning. The reference plane for calibration should be at the depth of maximum dose. If a less than optimal procedure is used for depth positioning, the depth error may be 2 mm, which for a low energy electron beam (3 or 7 Mev) could translate into a 2% error. Thus this would result in an uncertainty of about 4%. A complete central axis calibration need not be done more often than annually [103] if constancy checks are performed. Constancy checks of dose per monitor unit for electrons can be carried out with the same precision (2%) as for photon beams and should be performed with the same frequency (more than once a week). The beam uniformity (flatness and symmetry) can be determined using the same methods as for photon beams. Due to the sensitivity of there parameters to the exact beam design universal guidelines for these parameters are not meaningful. It

should be noted, however, that for electron-producing linear accelerators in which the electron scattering foil and the photon flattening filter move into position on a carriage or rotating wheel, frequent and perhaps daily checks of flatness and symmetry need to be performed. Complete depth dose curves for all field sizes and energies must be measured using ionization chambers in water or plastic at least once a year. Constancy checks of the depth for the 80% dose and the surface dose should be checked more frequently for all energies and a given field size. Film may be used with care for constancy checks with minimal machine time [28,90].

The dose rate delivered by an electron accelerator is controlled by the pulse repetition rate and the number of electrons per pulse. It is essential to fully explore the dose responsible linearity of the monitor chamber and other dosimetry system. Significant recombination may occur if the machine is running at a low pulse repetition rate but high does per pulse. This can be a significant problem, especially for a scanning beam machine.

IV. Co-60 TELETHERAPY EQUIPMENT

Quality assurance of Cs-137 and Co-60 teletherapy equipment is thoroughly discussed in the documents produced by the American National Standards Institute (ANSI) [8.9]. The same procedures as recommended in Sections I and II can be used for dosimetry, mechanical stability, and alignment testing.

V. TREATMENT ACCESSORIES

Quality assurance of wedges and blocks are discussed in Chapter 5 on treatment planning.

VI. SIMULATORS

In regard to mechanical parameters, the simulator should be subject to the same rigorous quality assurance program as the treatment unit. The objective must be that the various simulator motions should be at least as accurate as those of the therapy machine. In addition, all the elements in the simulator system needed for good image quality must be tested.

One important aspect of the use of a simulator is that a patient coordinate system be established [124]. Skin marks showing the coordinate ares are commonly used. This coordinate system is referenced to the machine coordinate system by using laser lights aimed at the isocenter and/or other positioning aids. It must be possible to accurately transfer the patient coordinate system from the simulator to the therapy machine, which requires that the positioning aids on the two systems are the name and subject to the same quality control. If accessories arc used on the radiation therapy simulator, special attention must be paid to the affect of the weight on long-term stability.

VII. EMERGENCY OFF SYSTEMS

Production of radiation and the mechanical motions are operated by numerous electrical control circuits. These can fail in an on or off mode, resulting in failure to interrupt radiation or stop motion of equipment. To avoid personal injury or damage to equipment, quality assurance checks are necessary to verify that the various back-up systems to the primary control system are functional. The most important back-up system available on all therapy machines is the emergency off system. The emergency off switches should be located at easily accessible area in the treatment room. particularly near the treatment table, and near the console. It

is important that these switches are wired to turn off all power to the system, including the motorized treatment table. Weekly tests of the emergency off system are recommended.

On radionuclide machines. the source motion is electrically/hydraulically controlled. For those machines, the electrical/hydraulic system including the electrical and mechanical source-condition indicator should be thoroughly overhauled periodically [8.9].

TABLE II

QUALITY ASSURANCE OF EXTERNAL BEAM TELETHERAPY AND SIMULATION EQUIPMENT

	Frequencies	Tolerances
I. Dosimetry		
A. Central axis dose calibration	A	2%
B. Constancy checks		
1. Dose per monitor unit along central axis	D	3%
2. Depth dose	M	2%
3. Beam uniformity	W	3%
4. Dose monitor	N	N
5. Timer constancy	M	N
II. Geometry		
A. Field positioning aids		
1. Light field and radiation field agreement	W	3 mm
2. Mechanical distance pins, lasers and SSD lights	M	2 mm
3. Scale readouts	M	N
B. Machine alignment		
1. Focal spot position	A	N
2. Jaw symmetry	A	2 mm
3. Coincidence of collimator (jaw) and gantry axes with isocenter	A	2 mm
4. Stability of gantry arm and bearing under rotation	A	2 mm
5. Couch motion and table-top sag	A	
III. Electron beam equipment		
A. Dose calibration	A	3%
B. Beam uniformity (See I.B.3.)	W	5%
C. Depth dose	M	3 mm at 80%
D. X-ray contamination	A	N
E. Dosimetry reproducibility and linearity	A	N
F. Dose per monitor unit constancy check *	W	3%
IV. Co-60 teletherapy equipment (Items not covered in Sections I and II)		
A. Dose rate constancy	W	3%
B. Source condition indicator check	M	N
C. Source holder/shutter movement check	M	N
D. Source leakage, beam off leakage	M	N
E. Timer end effects	N	N
V. Treatment accessories[†]		
A. Wedges and standard compensation	A	N
B. Field Shaping Blocks	A	N
VI. Simulators		
A. Geometry, see II above	–	–
B. Accessories	A	N
VII. Emergency off system	N	–

* Constancy checks of electron beam dose per monitor unit may include 3-5 modes of operation. It is reasonable to have all modes of operation checked once a week if the patient's treatments are individually monitored by TLD or other patient dosimetry. If patient dosimetry is not used, the frequency of the constancy checks should be increased to twice a week.

† Attenuation in blocks, wedge factors and compensator data should be checked annually. A visual inspection of the mechanical integrity of these accessories should be done more frequently, i.e. monthly.

A Annually
M Monthly
W Weekly
D Daily
N No suggestion

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CHAPTER 5

TREATMENT PLANNING

INTRODUCTION

For the purpose of this document, treatmant planning refers to procedures and decisions to be made preceding a radiation treatment.

Both physical and clinical procedures are components of the treatment planning problem and a quality assurance program must reflect each. While treatment planning is usually thought to be the step preceding the treatment, one must recognize that it can occur am frequently throughout a course of treatment as clinical or physical factors indicate a need for treatment modification.

The first column of Table III summarizes the treatment planning actions necessary for high quality radiation therapy. The second column shows the procedures and equipment commonly used in treatment planning and the third column indicates the associated quality assurance items. Admittedly, treatment planning as shown here is complex and in reality only a fraction of the listed equipment and procedures may in fact be used at any individual department. However, within any radiotherapy department, there is an obvious need to develop quality assurance programs in treatment planning since it represents the integration of dosimetric principles, tumor localization studies, and diagnostic examinations designed to individualize patient treatment plans. Because treatment planning is a dynamic process which varier greatly from place to place and in which clinical judgements are mixed with objective diagnostic and physical data, the task of setting guidelines for tolerances is extremely difficult. One reasonable guideline to keep in mind is that it is desirable to keep the overall uncertainty of the delivered dome to the irradiated volume to within $\pm 5\%$ [76]. Considering that the optimal procedure for field instrument calibration, treatment beam calibration and delivery of dose to tissue phantom may have au uncertainty of about 2% [53,76] one can therefore deduce that the physical treatment planning process must not contribute more than 4.2%. Figure 1a is an example of how the treatment planning procedure may contribute to the overall uncertainty by about 4.2%. Rigorous procedures and QA test methods for treatment planning must be developed to meet such stringent requirements.

A. The patient data acquisition depends largely on the quality of the physician's judgement in interpreting the diagnostic information and delineating a target volume including gross tumor and microscopic disease, but excluding normal dose-limiting tissues. The use of one or more diagnostic modalities is essential for determination of the extent of the disease.

TABLE II   TREATMENT PLANNING

Action		Procedure, Equipment	Quality Assurance
Diagnostic Patient Data Acquisition	A	Diagnostic X-rays Nuclear Medicine Ultrasound	Image Q.A. Procedures By AAPM, ACR, BRH
		CT	Image Q.A. CT Numbers, Machine Coordinates Table Motion, Patient Positioning Magnification, Image Distortion, Organ Motion
Tumor Localization Treatment Decision	B	Diagnostic Data Synthesis Contour Device Simulator Delineation of Target Volume and Sensitive Organs	Clinical Q.A. Simulator Q.A. (Appendix I). Phantom for Contour Test. AP-LAT Separation. Method for Data Transfer Between Image Modalities. Organ Motion, Internal-External Patient Marks.
Computation of Dose And Dose Distributions.	C	TAR/SAR And/Or Other Dose Concepts. Computers Algorithms Field Shaping	Data Verification For Individual Machines. Accuracy of Calculational Methods. Software Input-Output Devices of Computer. Documentation of Dose Data And Calculational Methods. Patient And Machine Data (Table I). Machine Output, Flatness, Symmetry.
Immobilization Blocks Wedges Compensators	D	Immobilization Material And Devices Mould Materials Block Cutters	Alignment And Stability Check of Immobilization Devices, Block Cutters, Attachment Holders On Simulators And Therapy Machines. Patient Identification, Block Thickness Personnel Safety In Regard To Material Toxicity (Pb, Cd, etc) And Shop Procedures. Patient Safety (See Table II)
Treatment Verification	E	Port Film Verification	Field Delineation And Adequacy of Tumor Coverage Physician Should Sign Films Image Quality
		Treatment Verification	Determination (In-Vivo Confirmation) Consistency With Treatment Plan. Dosimeter Placement, Reporting
		Patient Chart	Dose Calculation And Summation
		Equipment Log	Adequate Calibration Record Machine Problems And Performance (See Table III)

In general, quality assurance procedures Pertaining to diagnostic imaging methods already exist. For example, there are recommendations by the American College of Radiology, the American Association of Physicists in Medicine, and the National Center for Devices and Radiological Health in diagnostic radiology, nuclear medicine, ultrasound, and CT [6,33.116].

However, in addition to there procedures there may a be need for modifications to suit the particular demands of treatment planning. For example, uncritical use of CT scans for treatment planning may, because of the vast amount of anatomical information available, introduce an unjustified feeling of security. It should be emphasized that quantitative use of CT scans for treatment planning requires special attention to patient Position on the CT table relative to the treatment position, and information about accuracy and reproducibility of the motion of the CT table. In addition, CT magnfiction factors end distortion in the CT image as a result of positioning in the scanning ring, nonlinearity of the video image, or aberrations in the photographic reproduction aced to be addressed. Organ motion as a result of breathing and swallowing will contribute to the uncertainty of organ location (in some instance 1-2 cm) and should be kept in mind when CT scans are used for treatment planning. It is strongly recommended that the patient data generated from

CT be checked for consistency relative to the simulator and the treatment portal films. The calibration of CT numbers to express physical tissue densities is described in numerous articles [32,84] and such calibrations should be part of the quality assurance program. Lymphangiograms and in particular lymphoscintigraphic technique. [25,125] have found use in the localization of lymph node.. The space coordinate. of these lymph node. can be transformed into the treatment coordinate system and included in the target volume.

B. In addition to diagnostic patient data acquisition, treatment decisions are made using procedures and equipment within the radiation therapy department. The radiation therapy simulator generates a diagnostic quality x-ray beam which, when imaged on film or fluoroscopy, augments the diagnostic modalities for tumor localization. Ultimately, the equipment is also used for simulation of the treatment beam arrangement.

There are several methods used to obtain the patient's contour, which depending on resources range from simple lead wire contours to semi- or fully-automated contouring equipment. A simple phantom should be used to periodically check the more sophisticated equipment. It is also recommended that for each patient contour taken a redundant measurement of antero-postero and left to right lateral separation should be made using a caliper. It should be emphasized that during the contouring process the patient must be positioned to resemble the actual set-up with any immobilizing device used in place. Boundaries of fields and any fiducial marks should be drawn properly. The accuracy of the contouring equipment and contouring data needs to be checked frequently. The acceptable tolerances should be set by the individual department bearing in mind the desired overall accuracy of the dose delivered to the patient. From the introduction of this chapter, we have deduced that an acceptable uncertainty due to physical treatment planing procedure. is about 4.2% (2σ). It seems that even a relatively simple contouring device should be capable of recording contour data with an accuracy of ±0.5 cm. If we assume that the depth dose change is 5% per cm of missing tissue, the uncertainty in dose delivered by two opposed isocentric Co-60 fields would mount to ±0.5 x $5/2$ = $\pm1.2\%$ from this source alone. An RMS error analysis shows that there is a remaining $\pm4\%$ uncertainty which can be "used up" by other treatment planning procedures. Of course, one should always try to keep the uncertainties as low as reasonably achievable. However, this type of analysis could still be useful to determine if the achievable uncertainties conform with acceptable overall uncertainties in patient dose. It is quite clear that the clinician's treatment policies have a major impact on this analysis. The average number of treatment fields per patient, the X-ray or electron energy, and the use of isocentric vs. nonisocentric (fixed SSD) technique. all play an important role in the amount of support activity required.

C. Computation of Dose

1. Computation of dose from photons or electrons involves the calculation of monitor units or treatment time to deliver a prescribed dose along the central axis of a given fixed or rotational treatment field. Such calculations must take into account all variables contributing to the dose from both primary and scattered radiation at a given point in the patient. Table IV lists important factors that directly affect the accuracy of the calculated treatment time or monitor units. These factors must be accurately determined and included in the calculations for each treatment field, to ensure a successful transfer from treatment plan to the machine setting.

TABLE IV

Patient and Machine Data

Contour
Collimator settings
Tissue density
Output factor
Treatment depth (isocenter)
Target-skin distance/target-isocenter distance
Central area depth dose
Field size
Compensation factor
Complete isodose distributions
Hedge factor
Tray factor

Determinations of these parameters for each field being treated require a quality assurance program which ensures both accuracy and long-tern constancy. Whatever calculational method is chosen, these variables must be accurately determined for each treated field. The magnitude of such a program can be determined by the l analysis discussed above.

Similarly, electron treatments must be subject to quality assurance procedures. Because of the scattering characteristics of electrons, the dose distributions are strongly dependent on the design of the scattering and collimation system [18,71]. In contrast to photon beams, it becomes difficult to identify a simple set of variables controlling the quality of the electron treatment fields. Particular attention should be paid to the effects of the secondary shield on the output factor, depth dose, rod field flatness.

2. Computation of complete dose distributions can be done either manually by using measured isodose curves or by computer. Data may be obtained from a variety of sources. Regardless of technique, all data should be measured or at least checked for the individual treatment unit. Significant errors can be made by the uncritical use of published data.

It is important that the physicist understands the limitations of the approximate manual method he may be using and/or the algorithm chosen for the computer calculations. For example, some treatment planning codes calculate the treatment1 time or monitor units directly. This puts high demands on the accuracy of patient and beam data and the adequacy of such calculations must be thoroughly tested. Similarly, it is necessary to clearly understand whether or not the computer programs include wedge or other factors in the calculations. Lack of communication of these problems create the potential for serious errors. References [53, 138] are helpful to illustrate different calculational methods.

There are a variety of treatment planning computers and coder in current use. To ensure that the more common treatment planning systems perform adequately and consistently, teat methods need to be developed. As a minimum, a manual calculation to at least one critical point is recommended for each computation. Protocols for verification of treatment planning programs and computer systems have been proposed [83].

D. The attachment of blocks. compensators, and wedges is a powerful way of modifying dose distributions. Misalignment of compensators and wedges directly affects the central-aria dose due to changer in attenuation. The relative dose distribution may also be significantly affected resulting in an unacceptable dose heterogeneity throughout the target. It is thus necessary to align these beam modifiers accurately and reproducibly in the treatment beam and establish a quality

assurance protocol for periodic alignment tests. These tests should apply to therapy machines, simulators and the equipment used to fabricate and verify the accuracy of the low-melting-point alloy blocka. A clinical physicist must also be prepared to take the responsibility for patient and personnel safety when treatment devices are fabricated and applied. The mechanical integrity of mounting systems must be verified periodically. Safe shop procedures must also be established. When potentially toxic elements, such as lead, low-melting-point alloys, and foam products are used [85], an industrial hygienist can be helpful in advising on safe operating procedures. The more important items to be checked are shown below in Table V.

E. Treatment verification

The need for quality assurance of patient set-up procedures and beam delineation with respect to the desired treatment volume and normal anatomical structures is readily apparent. In external beam radiation therapy, this is commonly accomplished by having the patient radiographed in treatment position. The radiographs (portal films or verification films) should clearly demonstrate coverage of the tumor volume and demonstrate that critical organs not under treatment are not within the radiation field. These films are an extremely valuable aid to the radiotherapist and technologist in providing quality treatment, and their frequent use has been shown to reduce significantly the number of treatment field errors [80].

While portal films produced either with medium or high energy photon beams yield images of notoriously poor quality compared to diagnostic films, a technique has been suggested [110] to enhance the image of field placement and target volume coverage to a useful quality. The technique involves a film duplication. The portal file is postioned on top of an unexposed film, the two films are briefly exposed in a light beam and the new film is subsequently developed. On the new film, the density range has been shifted relative to that of the old film, and more importantly, the contrast as expressed by the effective "gamma" has increased significantly. This results from the principle of "gamma" multiplication in the contact copying process. Since the technique results in a shift toward a higher density range, it is a particularly useful technique for improving film readability in under-exposed films. Published work [24] suggests that the following items should be considered for improvement of the overall portal film quality.

Highest Contrast:

1. Select high "gamma" film.

2. Select an optimal screen.
   a. The selection of metal screen is in general not dependent on the film type, since the film contrast "gamma" is not affected by the screen material.
   b. 1.5 g/cm^2 copper front screen is suitable in the energy range Co-60 to 8 Mv X-rays. If lead is used the thickness should be increased to about 2.5 g/cm^2, which is significantly thicker than that usually employed in mega-voltage imaging. These thicknesses represent a situation where the ratio Of scatter to primary radiation reaching the film is minimized, thus producing "good" contrast. Of course the screen must be thick enough to stop secondary electrons.

3. Expose for an optical density of between 1.3 and 1.8. The contrast is less at low and high densities and in general standard light boxes are not intense enough at higher densities.

4. Use high quality processing.

    a. Full strength developer

    b. Regular replenishment with good nixing

    c. Highest workable temperature

    d. Minimal roller marks

5. Contact copying ("gamma" multiplication) can, in some situations, improve readability.

Best sharpness:

1. Motion unsharpness is reduced if the patient is instructed to lie still or even to hold his/her breath.

2. Fairly fine grain film. Small grain size results in slower film and thus longer exposure time. Longer exposure time increases motion unsharpness and patient exposure. This trade-off must be conridered when choosing film speed.

    By carefully considering the influence of these parameters on the image quality, one should be able to select a high quality portal film system. It is worth pointing out that the viewing conditions arc important for film readability. Some simple and obvious precautions are to reduce room light and reflections and mask off bright areas around the film.

    Treatment fields should coincide with the planned fields within 5 mm, and in the case of critical organs such as the spinal cord, within 2 mm. The use of large screen fluoroscopic systems is recommended for use in this portion of the program [16]. Specific problems to be addressed are listed in Table VI.

    In-vivo dosimetry is a valuable tool to confirm calculational, planning and set-up procedures. In many instances such measurements can be made with minimal effort and patient discomfort while providing a degree of confidence to both the physicist and physician regarding treatment planning and set-up procedures. Both surface and intracavitary TLD and ionization chamber measurements lend themselves to many clinical treatment protocols.

TABLE V

Treatment Aids

Immobilization Devices

1. Mechanical stability
2. Patient identification/labelling
3. Alignment

Blocks

1. "Block cutter" central axis integrity relative to simulator/therapy machines
2. Styrofoam mold thickness
3. Block support trays for damage
4. Voids in shielding blocks
5. Block weight
6. Irregular field definition
    a. Fabrication
    b. Mounting
7. Patient identification/labelling
8. Standard blocks
9. Materials hazard
10. Working conditions in block room

Other Treatment Aids

1. Compensating absorber
    a. Fabrication
    b. Patient identification/labelling
    c. Alignment/use
2. Wedges
    a. Mounting/interlock
    b. Orientation/use
    c. Verification of isodose modifications
    d. Measurement of wedge factor
3. Bolus
    a. Correct thickness
    b. Deterioration (e.g., loss of moisture)

TABLE VI

Treatment Verification

1. Field delineation and adequacy of tumor coverage, exclusion of
    other organs
    a. Verification films
    b. Patient immobilization
    c. Port films

2. Film quality (see discussion above)
    a. Contrast
    b. Visibility of anatomical detail
    c. Verification of day-to-day set-up procedures: angulation,
       reproducibility of patient placement, comparisons with CT
       and simulator films

3. Fluoroscopic or digital image monitoring of treatment beams

4. In-vivo confirmation of dose delivery
    a. Dosimeter calibration
    b. Dosimeter placement
       Frequency of verification dosimetry

CHAPTER 6

BRACHYTHERAPY

INTRODUCTION

Brachytherapy is a method of radiation therapy in which encapsulated sources are utilized to deliver radiation within a distance of a few centimeters by surface, intracavitary, or interstitial applications. The focus of this therapy is to enhance tumor sterilization while minimizing damage to normal tissue structures. There are, of course, many complex, multi-variate factors that affect tumor and normal tissue response. However, a number of advantages are provided by brachytherapy applications. These include more. precise localization of dose, attaining distributions which conform to irregular tumor shapes, and potentially lover morbidity. In addition, the development of new techniques, the use of radium substitutes, and the improvement of after-loading devices have stimulated renewed interest in brachytherapy.

It is the purpose of this chapter to establish basic criteria for the description and calibration of sealed sources, to suggest procedural policies for the development of a quality assurance program, to comment on approaches to treatment planning, and to discuss general aspects of radiation protection. This chapter discusses use of radium and its substitutes for temporary or permanent interstitial or intracavitary applications. The use of internally administered radionuclides or strontium-90 eye applicators is not described in this chapter but can be studied elsewhere [57].

SEALED SOURCES

A. Description

The accuracy of source calibration and of absorbed dose calculations in brachytherapy applications depends, in part, on a detailed description of the radioactive sources. Therefore, it is incumbent upon the user to obtain this information and to evaluate the potential implications for clinical dosimetry. In general, this information is available from the manufacturer or from the literature.

1. Physical and Chemical Form

The chemical composition of the radionuclide (e.g., Cs-137 adsorbed onto ceramic microspheres, radium sulfate, etc.) and inert filler material should be known along with information on the physical characteristics of the material (e.g., density, effective mass energy-absorption coefficient, etc.). This information is useful for a number of reasons. First, although chemical instability and physical changes within a source are unlikely and are the responsibility of the manufacturer, the possibility of such changes and the potential effects on patient treatments during the useful life of a source should not be ignored. Second, dose correction for attenuation due to the self-absorption within a source may be desired although the effect is generally quite small [119]. Third, the presence of radioactive impurities should also be known. Some sources (e.g., Ir-192) require a storage period after initial production to allow the decay of abort-lived impurities [127]; users should ask the manufacturer if such procedures are followed. Finally, if the source should rupture, knowledge of the chemical form may aid in radiation safety considerationa.

2. Source Encapsulation

Since the source encapsulation can influence source calibration, dose distribution, and source integrity. detailed knowledge of its configuration and composition is important for the overall accuracy of clinical dosimetry. Such information should be available from the manufacturer. Encapsulation designs may vary for the same radionuclide for different manufacturers as well as for different radionuclides. Most long-lived sources (Ra-226, Cs-137) are doubly encapsulated; other sources (Au-198) are singly coated, and others have a unique capsule design (I-125). The effect of the encapsulation on dose distributions of various sources has been investigated by a number of authors both experimentally and theoretically and are available in the literature [35,40,67,73,119].

3. Radionuclide Distribution and Source Uniformity

The distribution of radioactive material within the encapsulation may be continuous or in compartments or cells [119]; the loading of radionuclide along a source may be uniform or non-uniform, by design or otherwise; the active length may or may not be centrally located along the source [123]; the wall thickness of the casing may be non-uniform in different areas. There intricacies need to be considered for each type of source and their implications relative to source calibration and dose distribution carefully assessed. Autoradiography of a source is a simple and informative test; gross non-uniformity of the radionuclide within the source is easily visualized. For radioactive seeds or grains, the uniformity of activity among seeds needs to be assessed [74]. The spacing of seeds in ribbons as provided by the manufacturer may require monitoring.

4. Source Identification

Correct identification of sources of the same radionuclide and capsule design but of different activities is essential. Ease in such identification will prevent errors rod reduce the level of personnel exposure and anxiety. At present, markings on sources are frequently difficult to read; color coding fades or disintegrates with tire, and repeated handling of color sutures tied to needles causes loss of effectiveness with age. The user must work with the manufacturer to devise an acceptable identification system which is simple, easy to read and long lasting.

B. Calibration of Brachytherapy Sources

1. Introduction

Unlike external beam radiation therapy, where the physicist relies on a properly calibrated radiation measuring device (ion chamber) for his standard, in brachytherapy the physicist should rely on a properly calibrated standard radioactive source and only to a lesser extent upon his radiation measuring device. Clinical sources are then calibrated by intercomparison with a standard source. This concept may differ from present practice, which tends to rely upon the source manufacturer's calibration, or upon calibration factors of a well ionization chamber provided by the chamber manufacturer.

2. Calibration Instrument

Since the radioactive source is the standard, almost any reliable radiation detector will serve as a calibration device. The most common device used is a well ionization chamber (re-entrant chamber) commonly known as an isotope calibrator, found in virtually every nuclear medicine department. The second alternative is to use a large volume (preferably 100 cm^3 or larger) air ionization chamber to measure the radiation intensity at some distance (preferably 25 cm or greater) from the source. Other detectors or techniques might also be usable.

The reproducibility of this measuring device should be better than $\pm 2\%$. The signal-to-noise ratio should not, therefore, be less than 100:l. This may not be obtainable when trying to measure at a distance of 25 cm or more with a large-volume ion chamber. In addition, it is essential to be able to accurately reproduce the positioning of the standard source and all clinical sources to be measured. For such measurements it is obvious that the relative distance from the source to the center of the detector must be maintained (at 25 cm distance, a 2 mm positioning error translates to a 1.6% error in dose). In addition, because of oblique transmission through the wall of the source and the fact that most large volume ion chambers experience significant directional dependence, the relative orientation of the source axis and chamber axis is also important. Plastic devices can be used to rigidly hold the chamber and the source in a fixed orientation at a fixed distance from each other. Such devices made from plastic form minimize scatter and are convenient to fashion. Devices made from rigid plastics on the other hand provide greater structural integrity.

The sensitivity of a well-type chamber is also dependent upon the position of the source within the well and upon the orientation of the source [136]. It is essential, therefore, to devise a source holder which will reproduce the positioning of a particular type of source from day to day and/or from source to source. A device frequently used is a small diameter plastic tube (perhaps 6 mm OD) cemented perpendicular to the center of a plastic plate which site on top of the well and is designed to center the tube in the well. The source is confined then to stand on end along the axis of the well with the bottom end preferably a small distance (several cm) from the bottom of the well. Flexible sources such as seed assemblies or wire can be confined by a helix situated equidistant from the wall of the well a short distance from the bottom.

3. Chamber Characteristics

Since a well-type chamber is the preferred measurement device, further discussion is specific for a well-type chamber. Similar problems exist for at-a-distance devices; the solutions, however, may differ.

The physicist should identify a single chamber system that will be used for brachytherapy calibration. This need not be the role use of this chamber. Prior to using this chamber for source calibration the electrical and radiologic characteristics of the chamber must be established, including:

   a. Scale factors and linearity: In order to minimize the potential for undetected changes in the electrical characteristics of the chamber system, it is recommended that a single scale and/or a single radionuclide setting be used at all times irrespective of the number and types of radionuclides calibrated, even for those devices where a radionuclide can be selected by plug modules, dial setting, or push button. When it is necessary to change scales or electrometer settings, the various scales and other settings must be referenced to the usual setting by comparison with the same source for the two settings. The linearity of all scales used should be verified.

   b. Ion collection efficiency: Since all of these devices have large volumes, the ionization collection efficiency of the chamber should be determined using the highest intensity source expected to be calibrated. Techniques using measurements at two or more polarizing potentials should be used [39].

   c. Geometry and length dependence: The dependence of the sensitivity of the chamber on the position of the source within the chamber and on the length of the source must be measured. A source should be moved about in the active volume of the chamber to verify and quantitate the extent of the sensitivity change. Two techniques to determine the dependence on source length have been described [17]. They involve either moving a short source throughout the region to be occupied by longer sources and integrating the sensitivity over these rub-regions or obtaining a long source (wire or seed assembly) and making measurements as the source is physically shortened.

   d. Thickness of the wall of the source: Sources of the same radionuclide with significantly different encapsulation should not be considered equivalent. The sensitivity of the chamber may change as a result of different thickness or type of wall around the source. This is due primarily to differences in the oblique filtration [137].

   e. Energy Dependence: The sensitivity of a chamber will probably show significant dependence (>10%) on the energy of the photons even for "air-equivalent" or "tissue-equivalent" chambers. This dependence is apparently due to absorption of photons in the walls of the chamber, forward and backscattering of the photons and electrons from the walls of the chamber, and oblique transmission through the source.

   4. Calibration of Sources

      a. Long-lived sources (Ra-226, Cs-137. Co-60, etc.):

         i) For each radionuclide (and encapsulation) to be measured, one source should be identified as the standard source. The source should be marked or otherwise identified so that it can be recognized at a later date. It is not necessary to remove this source permanently from clinical use.

ii) Send this standard source to an appropriate calibration laboratory for calibration. At the present time, only the National Bureau of Standards (NBS) provides these calibrations. However, efforts by the AAPM to establish other calibration centers are underway.

iii) Use the standard to calibrate all other similar sources. Calibration should be by sequential placement of the standard source and the sources to be calibrated in the same geometry within the chamber and comparing readings. Although this technique minimizes the hazards of chamber failure, it is advisable to predict the intensity of the standard source from previous measurements and compare the predicted measurement with that actually observed. Serious deviations might suggest equipment malfunction.

b. <u>Short-lived sources</u> (Ir-192, Au-198, <u>etc</u>.):

i) Identify a long-lived source as your reference source. This source should be marked or otherwise identified so it can be identified at a later date. This source may be a standard source for another radionuclide.

ii) Obtain a standard source of the appropriate short-lived isotope. The standard source should be compared with the reference source by sequential placement within the chamber with identical chamber settings in the two cases. This intercomparison will be used to establish a baseline comparison of the relative sensitivity of the system to the two sources.

iii) Submit the standard source to a suitable calibration laboratory for calibration.

iv) There are two techniques commonly used then to transfer the calibration.

(1) The chamber is calibrated with the standard source and the reference source is used to verify that the chamber is operating properly after the standard source has decayed away. This requires temperature and pressure corrections to reference conditions if unpressurized, ambient air chambers are used.

(2) A correction factor defined as the ratio of two measurements of chamber response using the standard source and reference source is calculated. The correction factor relates the response of the chamber to the abort-lived standard source in terms of the response to the reference source.

v) In either case, the reference source is measured every time the chamber is used to calibrate the short-lived sources.

vi) The standard source need not be replaced when it decays to a level much that it can no longer be used to calibrate the chamber.

C. Routine Surveillance Program

Treatment with sealed sources necessitates a quality assurance program which is
quite different from an external beam program.   For brachytherapy, the quality
assurance program must address the two components of the treatment objective: (1)
achieving an optimal therapeutic effect while, (2) minimizing unwanted exposure to
the patient, radiologic personnel, and the general public.   With regard to the
latter, many documents have been established for the safe use of sealed sources in
cancer management.   It is imperative that the medical physicist be aware of the
existence and importance of local, state, federal, and international guidelines and
regulations.   Many of these are referenced in Chapter 7.

One cannot, of course, clearly separate the above two components in a quality
assurance program.   However, with regard to optimizing the desired therapeutic
effect in brachytherapy, the program should primarily address the following broad
categories:

1.   source integrity
2.   source calibration
3. implantation equipment
4:   treatment planning and evaluation

The precise details should be tailored to the facility, to the type of
radionuclide, and to the clinical application.   The following list provides a focus
about which the physicist can formulate an appropriate routine surveillance program.

1.   Order information and source acquisition
2.   Receipt of radioactive materials
     a. package monitoring
     b.   review and corroboration of shipping memo
3.   Assay of sources (see Section above on sealed source calibration)
4.   Leak testing as required [98]
5.   Maintenance and inspection of implanting equipment
6.   Sterilization of equipment and sources as necessary [98]
7.   Control of source movement in and out of the radioactivity storage area
8.   Review of implant procedures and techniques
9.   Source removal from patient and return to storage
10.   Implant dosimetry (see Section III)
11.   Source inventory and disposal
12.   Education of personnel

In addition, less frequent review of the work facility, transport devices.
mechanical and electrical stability of calibration and surveying equipment, and the
details of the implanting procedures themselves are also required.

TREATMENT PLANNING AND DOSE EVALUATION

A.   Planning

The medical physicist must be prepared to advise the radiotherapist regarding
brachytherapy source configurations which will achieve the specified dose distri-
bution.   He should encourage the radiotherapist to develop clinical objectives in
terms of dose distribution and to make use of physics assistance in treatment
planning.

Familiarity with traditional manual methods of dose calculation, e.g., the Hanchester (or Paterson-Parker) system [87] and the Quimby system [34], is essential for understanding basic treatment planning approaches and for a basis of communication with the physician. Also, computer calculated done-planning tables have been published which may be useful for interstitial seed implants [70,118].

In certain individual situations it is possible to perform pre-implant calculations for idealized source configurations proposed either by the physician or the physicist. While this approach is undoubtedly useful for special or unusual cases, it is generally not recommended as a routine treatment planning procedure for individual patients. A more efficient application of computers to implant treatment planning involves performing calculations and dose evaluations for a wide range of idealized implants defined by systematic variations in dimensional and activity parameters [12,107]. Dose as a function of these parameters can then be presented in the form of a table, graph or nomogram for individual treatment planning.

Definitive permanent implants with I-125 seeds require special consideration, because their planning, from the time of early clinical trials, has involved making the implanted activity a function of the average dimension of the treatment region [37]. Specialized planning is also required for boost therapy applications of I-125 [13].

For intracavitary brachytherapy, source locations are generally determined by the geometry of the applicator, and treatment planning connotes selection of a source-strength configuration which minimizes dose to normal tissue for a given dose to specified treatment location*. Optimization of this sort may be attempted by trial and error or on the basis of intuition and clinical experience, but it is greatly facilitated by computer calculations using appropriate algorithms [114].

B. Localization

Orthogonal films afford greater localization accuracy than films at other angles. Certain precautions are required, however, to realize the potential accuracy. It is important that the origin of the coordinate system for each film be selected at a point such that the line joining it to the x-ray source is perpendicular to the film. Otherwise, an "origin offset" error results, which has a shearing effect on implant shape and may easily translate extreme source positions by several millimeters for implant dimensions of a few centimeters.

For implants having source positions at significantly different distances from the x-ray tube target, demagnification calculations will distort the source configuration if a single magnification value is assumed. Individual magnification corrections at source positions are desirable for such implants and are made possible by an "enhanced" ring method [88], in which the ring must be in the same position on the patient for both the AP and the lateral film and must, of course, be completely imaged in both films.

For I-125 seed implants, it generally has not been practical to use orthogonal film localization if computerized isodose distribution6 are required. In most cases, the seeds are too numerous and too close together to permit accurate identification of seeds between orthogonal films. Therefore, a method often used has been stereo-shift localization, in which either the x-ray tube or the patient is shifted (usually longitudinally) a measured distance between two AP films [11].

Three-film localization, in which seed coordinates from an intermediate-angle film are used to assist in identifying images between two orthogonal films, is showing promise of improved accuracy for both localization and identification [10,115,126]. Patient motion between films, for any localization method, is probably the greatest source of error; it can be reduced by improving patient comfort and by shortening the time between films.

C. Dose Calculation

Several computational options exist for the basic dose calculation involving one point of interest rod one source. In one option the dose in the source vicinity is obtained by evaluating l II analytical expression involving the accumulated activity (integral of activity over tine of treatment), the exposure rate constant, the f-factor (for converting exposure to dose), encapsulation filtration corrections, geometric attenuation, and a (usually polynomial) functional representation of scattering buildup and exponential attenuation by tissue [120]. The filtration corrections for linear sources would employ Sievert integral calculations, and the tissue attenuation buildup corrections may be taken from either measured or calculated data. In another option, one may calculate the absorbed dose rate from the measured exposure rate at unit distance. In a third option, one can use the results of direct measurements of the dose rate per unit exposure at unit distance, or dose rate per unit nominal activity, for the source type of interest within an appropriate phantom. For the two last options, information about the exposure rate constant and the activity are unnecessary. Greater confidence results from more than one approach, provided acceptable agreement is obtained in the region of interest. A reasonable goal is ±5% uncertainty in the data at points less than 2 cm from the source, where accuracy is of greater inportance than at more distant points.

Whether calculated or measured data are used, one has the further option of assessing the data either by evaluating a (perhaps fitted) analytical expression or by interpolating from a table. Formula evaluation may involve regions of poor fit to the data and tends to require more computer time, whereas table look-up either requires an inconveniently large table for direct look-up or tile-consuming interpolation formulas if the table is to be small. An approach intermediate between there extremes is to use linear interpolation of a small table from which geometric variation has been removed. The geometric attenuation is re-inserted in the calculation following table look-up [88].

In multiple source dose calculations at an array of points, it is highly desirable to be able to calculate dose on a rectangular mesh (e.g., 0.5 cm width) in any plane of interest passing through the implant. One should be able to obtain multiple parallel planes at specified separations at any given orientation.

It is also helpful for some purposes to be able to calculate both the volume and the integral dose enclosed by isodose contours in three dimensions.

In implementing new or unfamiliar computer programs for brachytherapy dose calculations, it is advisable: (1) to compare results for an idealized (e.g., single source) configuration with the results of band calculations, and (2) to compare results for one or more typical clinical applications with those obtained using an established computing system, perhaps at another institution.

D. Evaluation

The items to be included in a typical evaluation will depend strongly on clinical requirements. However, it is essential that appropriate labelling of isodose rate curves, date and time of implant, patient orientation and other patient demographic information be clearly indicated. It may also be useful to superimpose isodose rate contours on AP and lateral films of the implant to indicate anatomical relationships.

If dose objectives have been specified for the treatment, the physics evaluation should report a comparison of the doses desired at certain points of interest with those actually achieved. With respect to intracavitary applications for cervix cancer, for example, comparison might be made at treatment points representing the cervix and the obturator nodes, in addition to specific reference points and various tissue-tolerance points. Isodose contours for cervix treatments should be displayed in planes intersecting, as nearly as possible, the centerline of the uterus.

For removable interstitial implants of wires or reed in ribbons, it is useful to present isodose rate contours in regularly spaced planes perpendicular to the source lines. The radiotherapist can thus easily identify the dose rate for which the contour adequately encompasses the region to be treated.

For permanent seed implants, it may be useful to determine an average peripheral dose, i.e., the average dose on the surface containing the outermost seeds. This evaluation may not require computer isodose calculations and can be made from graphs showing activity per unit l absorbed dose as a function of volume dimensions [134]. Perhaps a more useful clinical evaluation is to determine a "matched peripheral dose (MFD)" - the dose for which the isodose contour volume equals the volume of the treatment region designated by the radiotherapist. If the treatment region has been specified by mutually perpendicular dimensions, its volume is usually calculated on the assumption of an ellipsoidal shape, since isodoses as well as implanted anatomical structures generally have rounded contours. Reporting this type of MPD as a quality control parameter has the virtues of (1) reducing a wealth of computer data to a single number, and (2) the clinical feedback element of relating the dote to direct anatomical measurements by the radiotherapist.

Finally, in any brachytherapy evaluation, a treatment summary should be included which specifies the relevant treatment parameters. The report should contain the basic physical aspects of the radioactive material (radionuclide, form, activity), source insertion and removal times or treatment dose rates for temporary implants, treatment volume and dome, high or low dose volumes, and critical tissue doses.

REMOTE CONTROLLED, HIGH-INTENSITY BRACHYTHERAPY IRRADIATORS

Low dose rate afterloading systems employ various radioactive source materials for the treatment of many gynecologic, head and neck, and soft tissue malignancies. However, this approach requires patient hospitalization during the procedure and also involves exposure to those attending the patient in the hospital room. These two problems are alleviated by a system which uses remotely controlled afterloading of high intensity sources. Because of the high activity of the sources (l-9 curies), these irradiators require special consideration with regard to their use.

A. Source position.

   1. Daily tests should be conducted to verify the operational condition of device. which indicate source location, e.g., light indicator. on the control panel and a radiation monitor within the treatment room.

   2. The reproducibility of physical positioning of the source within the catheter should be within ±l mm and checked daily. This check may be done with an autoradiographic technique.

   3. The treatment position of the source must be verified to be at the prescribed position for each treatment course. This is normally done by conventional x-ray localization.

B. Treatment time.

   1. Timer accuracy must be verified monthly. The timer should not result in an error greater than 1% of the desired dose to be delivered.

   2. The error in dose due to source travel time after occurrence of timer ON, and for complete return after timer OFF, should be determined initially and semi-annually. This correction should be used in all instances where an error of more than 1% might be introduced into the delivery of the prescribed dose.

   3. In those cases where a back-up timer is not a standard feature of the irradiator, an accessory back-up timer should be provided.

   4. The calculation of the treatment time should be verified independently before the start of treatment.

   5. The dose prescription may have to be modified because of the higher dose rate.

C. Treatment confirmation.

   1. At the time of each treatment during the course of therapy, radiographic or fluoroscopic confirmation of the applicator position should be made. In vivo dosimetric confirmation is l also recommended.

   2. Constant patient viewing from the console must be available.

D. Emergency procedures.

   Each installation must have a permanently posted operation plan for emergency source retraction should power or mechanical failure of the apparatus require such action. In all such installations, a person who has been trained for and has practiced the required action should be on duty whenever this apparatus is used for patient treatment.

CHAPTER 7

RADIATION SAFETY

INTRODUCTION

The purpose of this section is to outline a quality assurance (QA) program pertinent to the establishment and maintenance of an adequate health physics program in radiation therapy. The established procedures for the safe use of therapeutic and diagnostic equipment in a radiation therapy departments are described in numerous documents published by both the ICRP and the NCRP. Furthermore, many of these guidelinea have been adopted as laws by federal and state authorities (such as rules from the Nuclear Regulatory Commission and Agreement State Regulations). It is thus imperative that the medical physicist in charge of installation planning, commissioning, mod maintenance of therapeutic equipment be aware of the existence and importance of these guidelines and regulations.

The radiation protection program should be designed to cover all sources of radiation and be consistent with regulatory requests and ALARA (As Low As is Reasonably Achievable) concepts [19,48,130,132]. The program should be reviewed by the administration on a periodic basis to determine if adequate resources are available for its implementation. All aspects of the program must be well documented.

For the purposes of this report, we have defined the quality assurance program to consist of all the health physics components requiring periodic action. The following areas have been identified.

Personnel Dosimetry

1. Calibration of dosimeters by suppliers
    a.   Instrument calibration
    b. Source calibration

2. Calibration checks by user
    a.   Instrument calibration
    b.   Source calibration

3. Distribution and use of badges
        Calibrations and tests

4. Record keeping, reporting and review

Radiation Survey: The calibration and operating conditions of importance for a radiation survey of a radiation therapy facility are as follows [49,95,100,101].

1. Consult facility design for orientation of the beam relative to
    permanent attenuating objects.

2. Working conditions.
   a) Restrictions of beam orientation
   b) Work load
   c) Occupancy factor, Use factor

3. Instrumentation
   a) Instrumentation calibration [51,101,130]
   b) Source calibration [99]

4. Interlock check

5. Reporting of survey results.
   a) Exposure rate versus location
   b) corrective measures required

The structural shielding and installation of external beam equipment should be planned and supervised by an expert knowledgeable in the methods of making shielding calculations. There must be related to the equipment specifications, radiation protection requirements and regulations.

Upon completion, an installation must have a radiation survey made by or under the supervision of a physicist familiar with health physics techniques. The parameters used for the shielding design must be fully understood by the surveyor for accurate assessment of the results. For example, if the exposure rate in an area occupied by personnel exceeds the maximum permissible value, recommendations for changes should be made with due regard to normal and extreme operating conditions. Therapy equipment, generating X-rays above 10 MeV, is a potential source of high energy neutrons, which are rnostly generated in the target and collimators in the treatment head. The neutron fluence can contribute significantly to the radiation levels in areas adjacent to the therapy machine. Radiation surveys of neutrons must therefore be considered around high energy therapy machines [51, 101]. The installation survey and following periodic surveys shall be documented and filed for future review and use.

A comprehensive review of maximum permissible organ doses and ALARA principles is given in references 19,48,99, and 130.

Radiation surveys should be repeated every time a change in the installation or the working conditions occurs. In particular, workload, use factor, and occupancy should be reviewed. Any changes should be documented and followed by a radiation survey. Periodic and frequent checks of door interlocks and beam orientation constraints must also be performed. The calibration of survey instruments is discussed in [51,101].

The surveying physicist shall report the results to the person in charge of the equipment and keep copies of such reports on file. It is important that procedures and adequate report and data forms be developed and documented to facilitate consistent and accurate periodic surveys.

Below is a suggestion of suitable documents which should be written by a qualified health, medical, or radiological physicist using the Bibliography. Such documents should give due regard to the unique working conditions of the particular radiation therapy department for which they are intended.

> Radiation safety rules
> ALARA radiation levels for radionuclide sources
> Shielding calculations
> Procedure for door and beam orientation interlock checks
> Inventory of radiation survey equipment
> Source inventory and disposal records

Calibration procedure for radiation survey monitors
Emergency procedure for 1) Co-60 equipment
                                     2) brachytherapy (breakage, loss)
                                     3) linacs and other types of teletherapy equipment

In relation to the above, the FDA Problem Reporting Program for Radiation Therapy Devices indicates that a Co-60 source which jams in the unshielded 'on', position in not an infrequent occurence. The emergency response should be practiced periodically so that the reaction to such an incident is instinctive.

Brachytherapy   (See also Chapter 6)

Categories requiring radiation safety measures in brachytherapy.

A. <u>Facility</u>

    1. Receipt and inventory of sources
    2. Storage and work areas (shielding, carrier design)
    3. Transportation (shielding, carrier design)

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    1. Inventory
    2. Source identification
    3. Cleaning (especially safety aspects)
    4. Leak tests
    5. Disposal

C. <u>Clinical Application</u>

    1. Preparation, l sterilization and transfer of l sources and
       source applicator
    2. Application to patient
    3. Removal of sources from patient (patient and room
       surveys)
    4. Return of sources to storage area
    5. Personnel monitoring
    6. Patient discharge

D. <u>Emergencies</u> and <u>Special</u> <u>Precautions</u>

    1. Source breakage and contamination
    2. Loss of source
    3. Cardiac or respiratory arrest
    4. Emergency surgery
    5. Death of patient (autopsy, cremation, embalming.)
    6. Notification of the location of radioactive sources to local fire
       department.

E. <u>Education and</u> <u>Training</u>, of <u>Personnel</u>

    1. Physician and nursing staff
    2. Ancillary personnel (including housekeeping)

In the present state of our knowledge, it is considered wise to avoid all unnecessary irradiation. Patients treated by brachytherapy techniques present the greatest potential radiation hazard since the sources used contain photon emitters of relatively high intensities and have the potential of being misplaced in an unshielded configuration. Reduction of radiation exposure to personnel from brachytherapy sources may be achieved by one or any combination of the following measures: (a) increasing the distance of the individual from the source, (b) reducing the duration of exposure and (c) using protective barriers between the individual and the source. The principle of keeping exposures as low as is reasonably achievable (ALARA) applies, of course, to the application of internally distributed radioactive waled sources.

There are many good references available on radiation safety in brachytherapy, most notably the reports of the National Council on Radiation Protection and Measurements [96,98,99]. The recommendations of these references are not repeated here, but the reader is provided with a list of procedures in brachytherapy where thought must be given to radiation safety. Naturally, any measure taken by the staff to reduce the risk to personnel and to maximize the benefit to the patient is not only radiation safety, but is intimately connected to the quality assurance program as well. Further, each facility must consult the agency regulations (Nuclear Regulatory Commission or State) for any specific requirements on radiation protection pertinent to its license to possess and use radioactive materials and radiation equipment.

Conclusion

The rationale of a radiation safety program in radiation therapy is adequately covered by the numerous reports issued by ICRU, ICRP, NCRP, federal and local agencies. The operational procedures discussed in this section and the extensive bibliography should facilitate the selection of the correct procedures, quality assurance items and frequency of procedures for most radiation safety problems.

The physicist in charge of the radiation safety program must document all procedures and the results of all surveys and checks. This assures consistency, safety, and accuracy. It gives credibility to the health physics program. However, it should be emphasized that radiation protection principles are undergoing a continuous review by many regulatory agencies and professional organizations. It is thus necessary for the physicist to follow there developments.

Furthermore, it should be emphasized that if a medical physicist finds himself involved into an area in which he is unqualified, for example, accelerator radiation safety, he should consult a qualified expert in that particular area for assistance.

QUANTITIES AND UNITS IN TELETHERAPY AND BRACHYTHERAPY

At the time of writing, the world of science is in the process of adopting the International System of Units (SI, for Systeme International). The International Commission on Radiation Units and Measurements (ICRU) now uses both SI and special radiation units in its reports and plans to discontinue the use of the special radiation unite by the end of 1985. The reason for changing to SI radiation units is that the special radiation units (rad, roentgen, curie) are not coherent with other units of the modernized meter-kilogrm-second-ampere system of units, i.e., their use introduces unnecessary numerical factors into the relationships between the numerical values of physical quantities. The most common physical quantities currently of importance in teletherapy and brachytherapy, with their SI and customary or special units, are given in the attached table, with some relevant conversion factors.

The change to SI units will necessarily involve some inconvenience. For the quantity absorbed dose, the change from rads to grays is not difficult, and can be made even easier by using the convenient equality of the centigray (cGy) and the rad. The quantity exposure has the inconvenient SI unit coulomb per kilogram (C/kg), and the SI unit of exposure rate can take a variety of even more inconvenient forms. In order to facilitate the change to SI units, several European countries have changed from the quantity exposure to the quantity air kerma. The subject is under consideration in the U.S., and a recommendation whether to change from exposure to another quantity will presumably be made by suitable authorities. Until a decision has been made, it is probably advisable to continue use of the special unit of exposure, the roentgen (R), even when, as for example in teletherapy calculations, all other quantities are given in SI units.

In brachytherapy dosimetry, there will be still another inconvenient change. from the usual multiple of the special unit of activity, the millicurie (mCi), to a multiple of the SI unit of activity, the megabecquerel (MBq). However, in addition to problems associated with the change of units, a change has been proposed to wet still another problem in brachytherapy dosimetry. Brachytherapy sources other than radium have conventionally been specified in terms of exposure rate at a specified distance. (Radius sources are both specified and calibrated in terms of mass of radium, but radium now plays a decreasing role in brachytherapy.) Both the source activity A and the exposure rate constant Γ_δ enter into brachytherapy calculations, but in such a fashion that only the product $A \cdot \Gamma_\delta$ influences the calculated tissue dose rate. Since $A \cdot \Gamma_\delta$ is the exposure rate at unit distance, it is clear that the activity A and the exposure rate constant Γ_δ are variables whose separate values are irrelevant to source specification. As a result, it has been repeatedly suggested that brachytherapy sources be specified in the same terms in which they are calibrated, i.e., exposure rate at 1 meter [40,127].

Because of these impending changes, it is of great importance in brachytherapy calculations that all possible care be used in calculating tissue dose from the specified source strength. Methods of calculation now in use will almost certainly be changed to some extent in future years, and each change holds the possibility of serious error. Where methods of calculation are well established, it would seem prudent to continue without change until wide agreement has been reached on quantities, units, and methods of source specification for brachytherapy.

TABLE VII

Quantities and Units In Teletherapy and Brachytherapy

Quantity	SI Unit		usual multiple	Symbol of customary or special units
	Name	Symbol		
length	meter	m	mm, cm	cm
time	second	s	min,h,d	h
mass	kilogram	kg	g	g
energy	joule	J		MeV
absorbed dose	gray	Gy	cGy	rad, mrad
exposure	coulomb per kilogram	C/kg		R, mR
activity	becquerel	Bq	MBq	mCi
temperature	degree Celsius	°C		°F
pressure	pascal	Pa	kPa	mbar atm mmHg

CONVERSION FACTORS

1 rad = 1cGy   1 Gy = 100 rad

1 R = 0.258 mC/kg   1 C/kg ≈ 3.88 kR

1 mCi = 37 MBq   1 MBq ≈ 27.0 μCi

1 MeV ≈ 1.602 x 10⁻¹³ J   1 J ≈ 6.24 x 10¹² MeV

$1 \frac{R\ cm^2}{mCi\ h} \approx 1.937 \times 10^{-13} \frac{(C/kg)\ m^2}{MBq\ s}$ $1 \frac{(C/kg)\ m^2}{MBq\ s} \approx 5.16 \times 10^{12} \frac{R\ cm^2}{mCi\ h}$

$1 \frac{R\ cm^2}{mCi\ h} \approx 7.51 \times 10^{-10} \frac{R\ m^2}{MBq\ s}$ $1 \frac{R\ m^2}{MBq\ s} \approx 1.332 \times 10^{9} \frac{R\ cm^2}{mCi\ h}$

$t_C = (t_F - 32)/1.8$ $t_F = 1.8t_C + 32$

where t_C is the temperature in degrees Celsius and t_F is the temperature in degrees Fahrenheit.

760 mmHg ≈ 1 atm = 1013.25 mbar = 101.325 kPa

100 kPa = 1000 mbar ≈ 0.987 atm ≈ 750 mmHg

APPENDIX B

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