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Principles of Quality Assurance in Radiotherapy

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Principles of Quality Assurance in Radiotherapy

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

Quality assurance consist of a series of tests to evaluate the performance of various machine parameters and of dosimetric procedures.
The previous ones have been treated in another lecture and will not be treated here.

The precision uncertainty in delivering a dose in any point in a patient is generally accepted to be ±%5: This value (assumed to represent 2 standard deviation) seems clinically acceptable and technically achievable.

The problem of characterizing the result of a set of measurements by an overall uncertainty, combining random and non random uncertainties has been resolved suggesting that the two uncertainties are combined in quadrature 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 approximately a 95% or 99% confidence interval, respectively.

Fig.1 shows how uncertainties of components of the radiotherapic chain may interact.

In fig.2 the sequence of dosimetry procedures to deliver a planned absorbed dose to a patient is shown.

To obtain the required accuracy procedures for the dosimetry of high energy photon and electron beam are recommended by National and International Organization.

A block diagramm of the general organization of calibration protocol is shown in fig.3.

The commonest procedure for absorbed dose determination is based on the use of a calibrated ionization chamber.

The applied formalism is, in principle, the same in most dosimetry protocol.
The ionization chamber is calibrated in terms of exposure or air kerma at a primary Standard Laboratory.
Several interaction and correction factors have to be applied to determine the absorbed dose in the user beam.
Protocols giver numerical values and define the condition for which the coefficients are valid in terms of irradiation geometry and beam quality.

In fig.4 different steps in the calibration are shown. The symbol are those used in ICRU 35 and NACP:
The procedures of one of the most utilized protocol in the world, the IAEA protocol 1987, are shown in fig.5. Worksheet for calculating the absorbed dose to water, taken from the same protocol, are also reported.

The history of dosimetry protocol can be divided into three period summarized in fig.6.
All protocols had small inconsistencies, mainly in the stopping power values. Standard laboratories have revised their standard after the recommendation of CCEMRI in 1985 (Fig.7).
In addition more accurate data for some physical quantities become available(Fig.8, fig.9, fig.10).
In fig.11 basic equations utilized in several protocol for photon and electron beam are presented.

The overall uncertainty, corresponing to one standard deviation, is given in fig.12 for the calibration of a ionization chamber and in fig.13 for the dose at a reference point.

The ratio Dw / M Nx is a constant, at a given energy and ionization chamber, for each protocol and can be determined by the parameters at the stated energy from each protocol.. In fig.14 values of the ratio Dw/MNx are presented for several old and new protocols. Homogeneous protocol differ only in the last significative digit which has not been represented..

Data are taken from Mijnheer 1992, Almond 1987, Andreo 1989, IAEA 1987, AAPM Rep.n.13

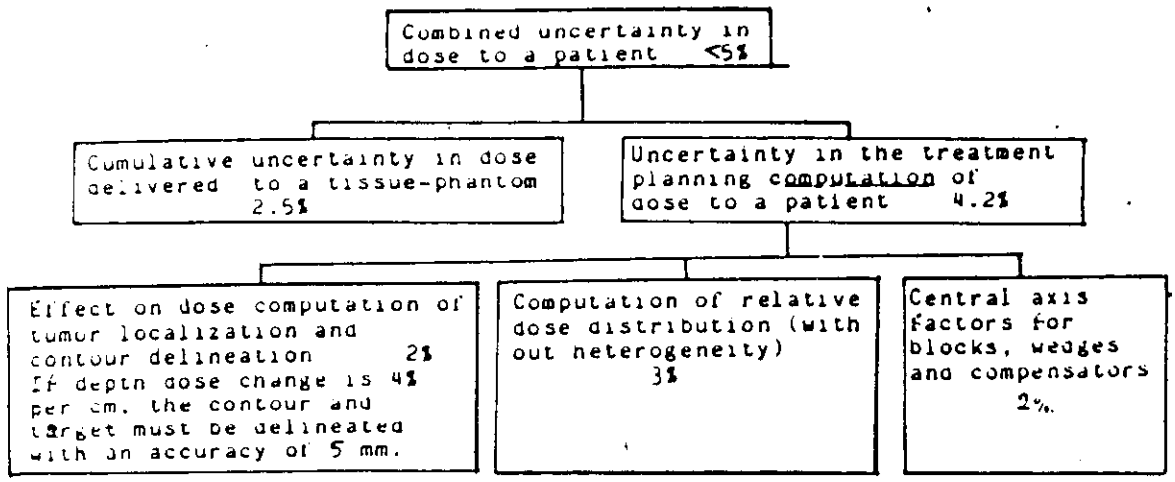
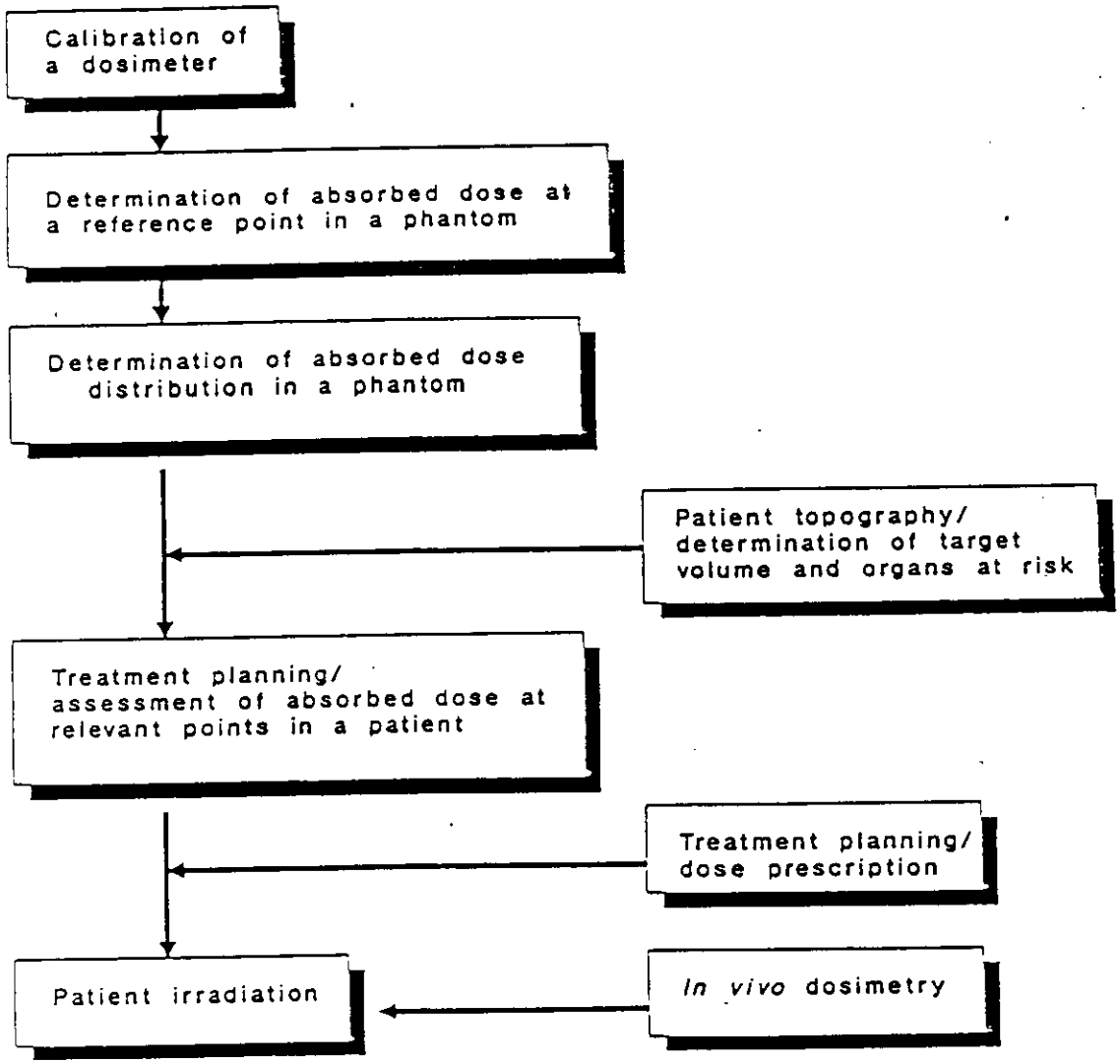
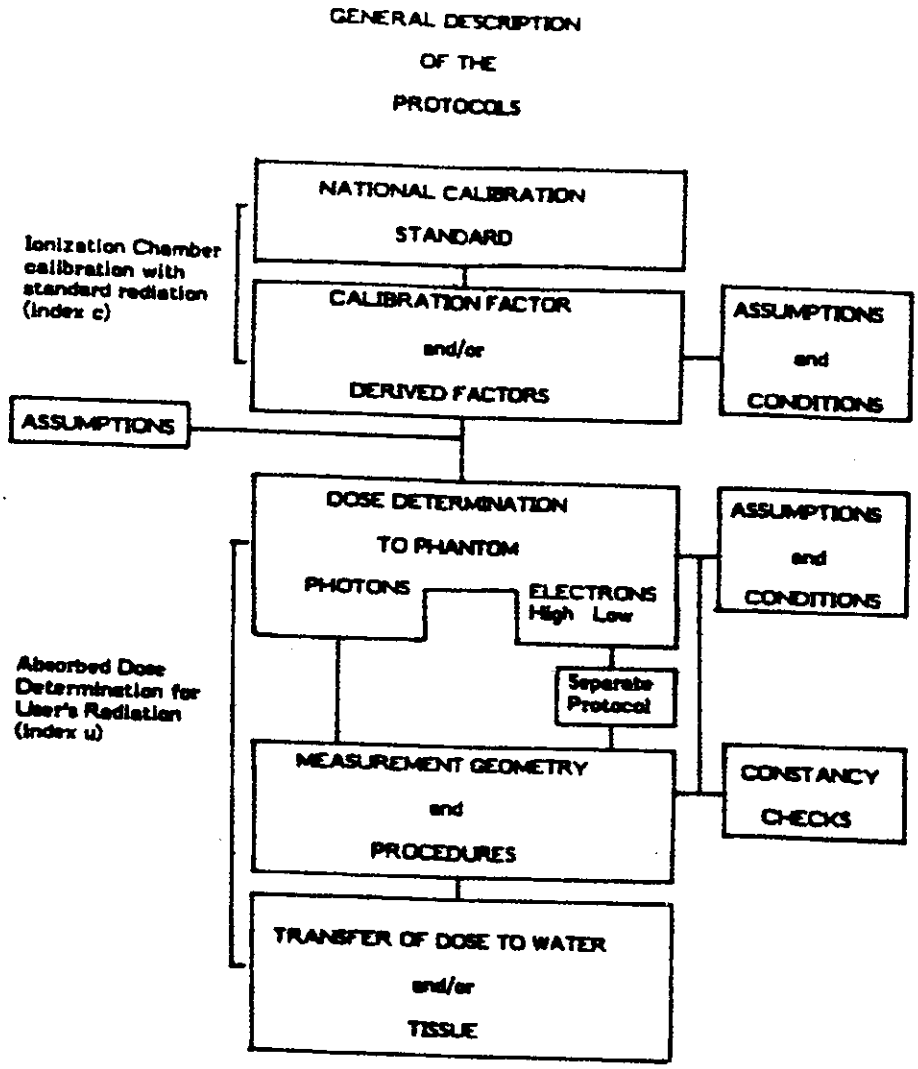


Figure 1 Example of dosimetric uncertainties in the radiation therapy process. The uncertainties represent approximately the 95% confidence level.



Sequence of dosimetry procedures to deliver a planned absorbed dose to a patient.

Fig 2



Block diagram of the general organization of calibration protocols.

Fig 3

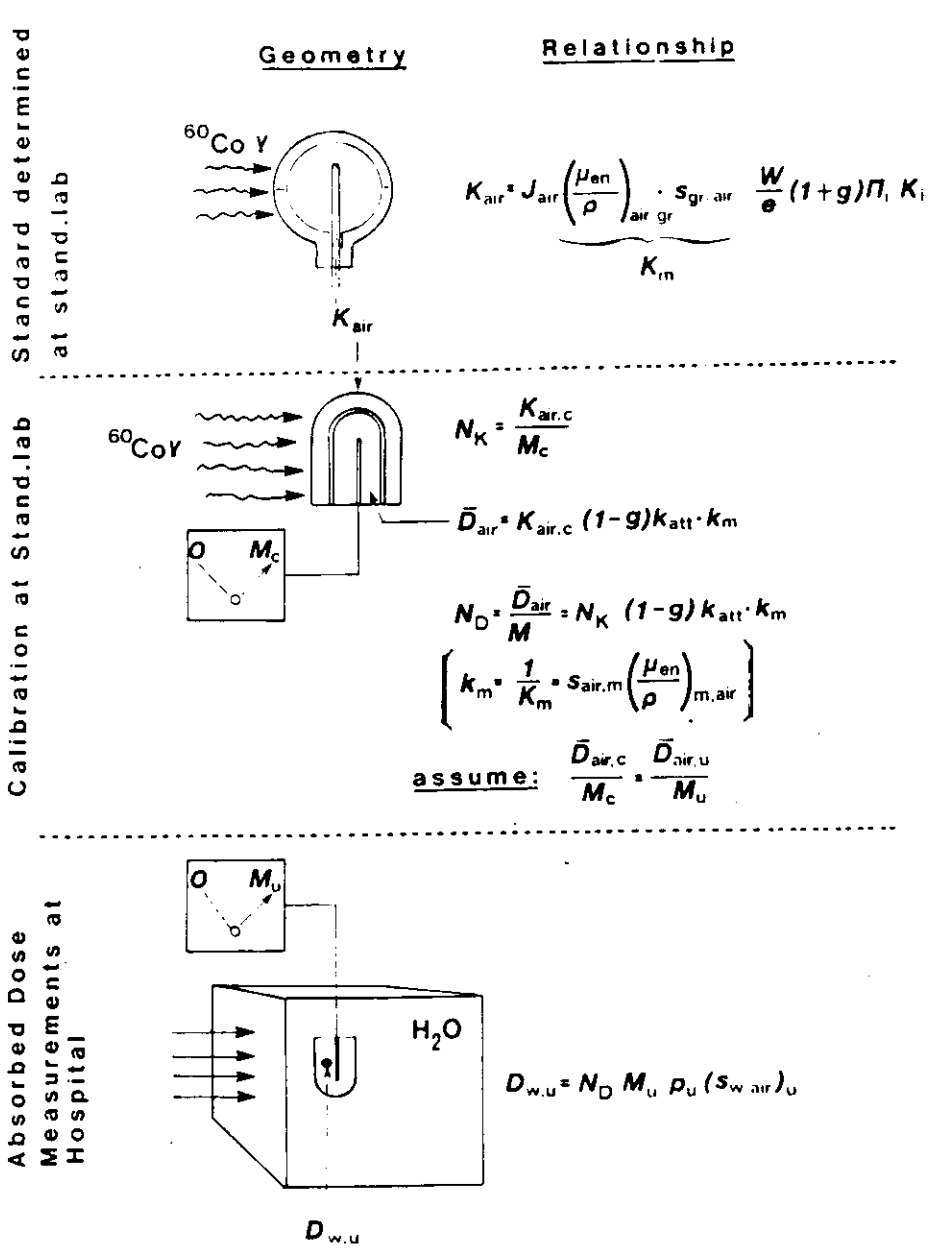


Fig. 4 The different steps in the calibration chain. The symbols are those used in ICRU Report 35 [4] and NACP [8]. At the Standards Laboratory a pure graphite chamber is used. The hospital chamber may instead be made of other materials and the build-up cap may be made of a different material to the wall. The equation for the material correction factor k_m can only be used for one pure material, m. The perturbation correction factor used in electron dosimetry, p_u, for cylindrical chambers, is reported in both the protocols under assumptions that the absorbed dose is determined at the "effective point of measurement". For photon radiation instead, NACP [8] uses the centre of the chamber as the measuring point. In this case p_u includes a correction factor for the replacement of water by air.

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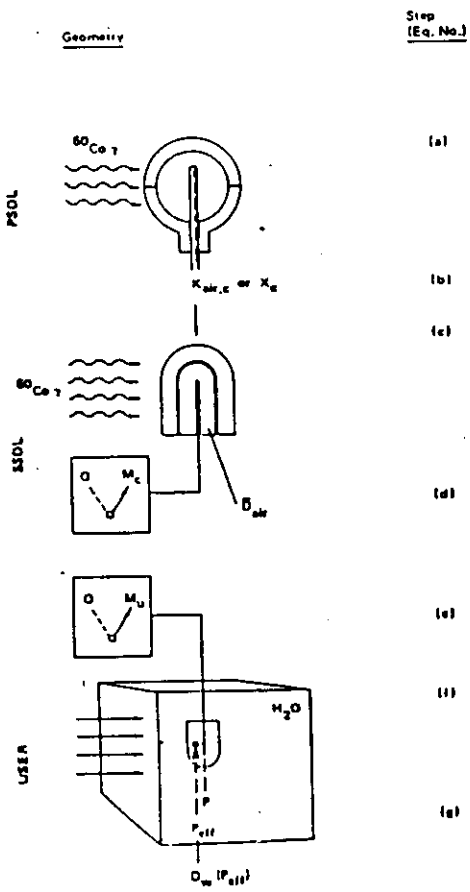

The calibration chain for electron radiation and high energy photons from PSDL to SSDL to user. It is recommended that the solid line is followed. The air kerma or exposure calibration of the user's chamber can be utilized in this chain; s_m and K_i are correction factors applied when determining exposure or air kerma in standard laboratories. The rest of the symbols are explained in the text.

ABSORBED DOSE DETERMINATION
IN PHOTON AND ELECTRON BEAMS

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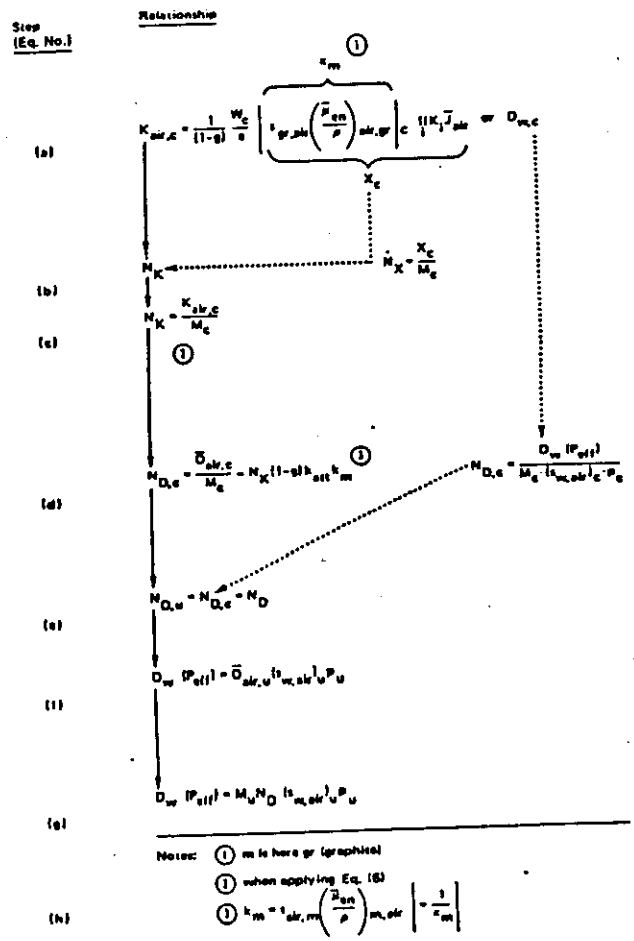

(From IAEA, 1987)

Fig 5

WORKSHEET 1 FOR CALCULATING THE ABSORBED DOSE TO AIR CHAMBER FACTOR N_D

Name: *User* Date:

1. Ionization chamber

Chamber model and serial number: *NE 2505/3A, No. 4075*

Cavity inner radius: *3.14* mm

Wall material: *Graphite (ρ = 1.82 g/cm^3)*, thickness: *0.0655* g/cm^2

Buildup cap material: *PMMA (ρ = 1.18 g/cm^3)*, thickness: *0.543* g/cm^2

total thickness: *0.6085* g/cm^2

2. Calibration laboratory data

Calibration laboratory and date: *SSDL, 860808*

Calibration factor (kerma in air)[1], N_K = *9.08 × 10^{-3}* Gy/scale div
given at P_0 = *101.3* kPa, T_0 = *20* °C and *50* % R.H.
Polarizing voltage: *−250* V, field size: *10 × 10* cm^2
Source chamber distance: *100* cm

3. Constants

W/e = 33.97 J/C, and g = 0.003 (for ^{60}Co gamma radiation).

4. Determination of k_{att} k_m[2]

Fraction of ionization due to electrons from chamber wall (Fig. 15),

α = *0.53*

Stopping power ratio air/wall (Table XVII),

$s_{air,wall}$ = *0.998*

Energy absorption coefficient ratio wall/air (Table XVII),

$(\bar{\mu}/\rho_{en})_{wall,air}$ = *1.001*

Fraction of ionization due to electrons from buildup cap,

$(1-\alpha)$ = *0.47*

Stopping power ratio air/cap (Table XVII), $s_{air,cap} = 0.908$

Energy absorption coefficient ratio cap/air (Table XVII), $(\bar{\mu}_{en}/\rho)_{cap,air} = 1.081$

$$k_m = \alpha\, s_{air,wall}\, (\bar{\mu}_{en}/\rho)_{wall,air} + (1-\alpha)\, s_{air,cap}\, (\bar{\mu}_{en}/\rho)_{cap,air} = 0.991$$

$k_{att} = 0.990$

$k_{att}\, k_m = 0.981$

5. Absorbed dose to air calibration factor

$N_D = N_K\,(1-g)\,k_{att}\,k_m = 0.888 \times 10^{-2}$ Gy/div, obtained at *101.3* kPa, *20* °C, *50%* R.H.

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[1] If N_x instead of N_K is known, N_K is given by

$$N_K = N_X \frac{W}{e} \frac{1}{1-g}$$

N_X should be in C/kg per division. If N_X is in R/div:
N_X (C/kg div) = N_X (R/div) 2.58×10^{-4} (C/kg·R)

[2] If the chamber is included in Table XVIII it is recommended to use the product $k_{att}\, k_m$ given there.

WORKSHEET 2 FOR CALCULATING THE ABSORBED DOSE TO WATER UNDER REFERENCE CONDITIONS USING ELECTRON BEAMS

Name: *User* Date:

1. Radiation treatment unit: *Sagittaire*

Nominal energy: *19* MeV

Depth of the effective point of measurement: *3* cm, $(z_{P_{eff}} - z_P = 0.5r)$[1]

Field size: *10* × *10* cm^2 at SSD = *100* cm

Nominal dose rate of the accelerator: *200* monitor units/min

2. Ionization chamber

Model and serial number: *NE 2505/3A, No. 4075*

Inner radius[1]: *3.14* mm, wall material and thickness: *Graphite, 0.0655* g/cm^2

Absorbed dose to air chamber factor:

N_D = *0.888* × *10^{-2}* Gy/div given at P_0 = *101.3* kPa, T_0 = *20* °C, *50* % R.H.

Polarizing voltage: *−250* V

Response change as compared to calibration date derived from checking against a radioactive source: *O.K. within 0.2%*

3. Electrometer reading correction

Reading[2], M_u^0 = *0.9976* div/m.u., monitor setting: *200* m.u.

Pressure, P = *100.3* kPa

Temperature, T = *24.3* °C $\quad p_{TP} = \frac{P_0}{P}\frac{(273.2 + T)}{(273.2 + T_0)} = 1.025$

Humidity correction, k_h = *1.000*

Recombination correction (Table VIII or IX)

V_1 = *250* V, V_2 = *83.33* V, M_1/M_2 = *1.095* , $\quad p_s$ = *1.054*

$M_u = M_u^0\, p_{TP}\, k_h\, p_s$ = *1.078* div/m.u.

Electron fluence correction plastic to water (Table XII),[3] h_m = *1.0*

$M_{u,w} = M_u\, h_m$ = *1.078* div/m.u.

4. Absorbed dose to water

Ranges obtained by measurement at SSD = 1 m with absorbed dose curves

R_{50} = *7.4* cm, R_p = *9.0* cm

Phantom material (plastics can only be used if $\bar{E}_0 < 10$ MeV)
a) *water* b) plastic

Ranges converted to ranges in water (Eq. (1), Table III)

R_{50} = cm, R_p = cm

Most probable energy at the surface

$E_{p,0} = 0.22 + 1.98\, R_p + 0.0025\, R_p^2$, $E_{p,0}$ = *18.24* MeV

Mean energy at the surface (Table IV), $\bar{E}_0$ = *17.56* MeV 17.2

z/R_p = *0.333* , $\bar{E}_z/\bar{E}_0$ (Table V) = *0.596*

Mean energy at depth (z = *3* cm), $\bar{E}_z$ = *10.47* MeV

Stopping power ratio water/air (Table X), $s_{w,air}$ = *0.999*

Perturbation factor (Table XI)[4], p_u = *0.981*

$D_w\,(P_{eff}) = M_u\, N_D\, s_{w,air}\, p_u$ = *0.938* × *10*$^{-2}$ Gy/m.u.

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[1] For plane parallel chambers, P_{eff} is situated in the front surface. Data regarding radius are therefore not needed.

[2] Averaged value of readings corrected for leakage and polarity.

[3] Equal to 1 if a water phantom is used.

[4] Equal to 1 for plane parallel chambers.

WORKSHEET 3 FOR CALCULATING THE ABSORBED DOSE TO WATER UNDER REFERENCE CONDITIONS USING HIGH ENERGY PHOTON BEAMS

Name: *User* Date:

1. Radiation treatment unit: *Theratron 80,* ^{60}Co

Nominal accelerating potential: MV

Depth in water of the effective point of measurement: *5* cm, ($z_{P_{eff}} - z_P = 0.5$ r, Fig. 11)

Field size: *10* × *10* cm^2 at SSD = *80* cm

Nominal dose rate of the accelerator: monitor units/min

2. Ionization chamber

Model and serial number: *NE 2505/3A, No. 4075*

Inner radius: *3.14* mm, wall material and thickness: *Graphite, 0.0655* g/cm^2

Absorbed dose to air chamber factor:

N_D = *0.888* × 10^{-2} Gy/div given at P_0 = *101.3* kPa, T_0 = *20* °C, *50* % R.H.

Polarizing voltage: *−250* V

Response change as compared to calibration date derived from checking against a radioactive source: *O.K. within 0.1%*

3. Electrometer reading correction

Reading[1], M_u^0 = *76.43* div/min^2, monitor setting: — $\frac{min^2}{m.u.}$

Pressure, P = *100.7* kPa

Temperature, T = *23.8* °C

$$p_{TP} = \frac{P_0}{P}\frac{(273.2 + T)}{(273.2 + T_0)} = 1.019$$

Humidity correction, k_h = *1.000*

Recombination correction (Table VIII or IX, or Fig. 13)

V_1 = *250* V, V_2 = *83.3* V, M_1/M_2 = *1.001* , p_s = *1.000*

$$M_u = M_u^0\, p_{TP}\, k_h\, p_s = 77.88 \text{ div/min}^2$$

4. Absorbed dose to water

Quality of the beam, TPR_{10}^{20} (or D_{20}/D_{10}) = — for 10 × 10 cm^2
at SCD = 1 m (SSD = 1 m)

Stopping power ratio water/air (Table XIII), $s_{w,air} = 1.133$

Perturbation factor (Fig. 14)[3], $p_u = 0.991$

$$D_w (P_{eff}) = M_u N_D s_{w,air} p_u = 77.65 \times 10^{-2} \text{ Gy/min}^2$$

---

[1] Average value of readings corrected for leakage and polarity.

[2] Corrections for the effective irradiation time in gamma therapy beams should be accounted for.

[3] The perturbation factor can also be obtained from Eq. (25). Fraction of ionization due to electrons from chamber wall (Figs 15 and 16), $\alpha = 0.53$

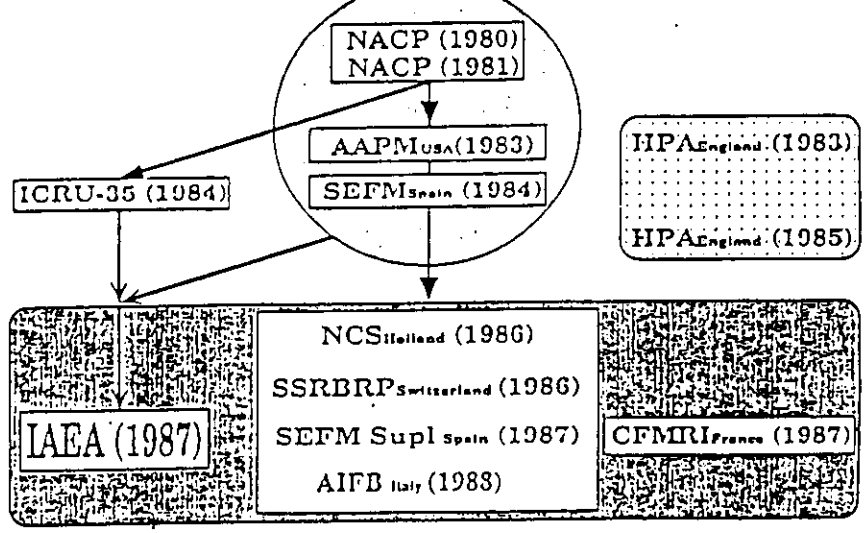
Stopping power ratio wall/air (Table XX), $s_{wall,air} = 1.002$

Energy absorption coefficient ratio water/wall (Table XXI), $(\bar{\mu}_{en}/\rho)_{w,wall} = 1.113$

Fraction of ionization due to electrons from water, $(1-\alpha) = 0.47$

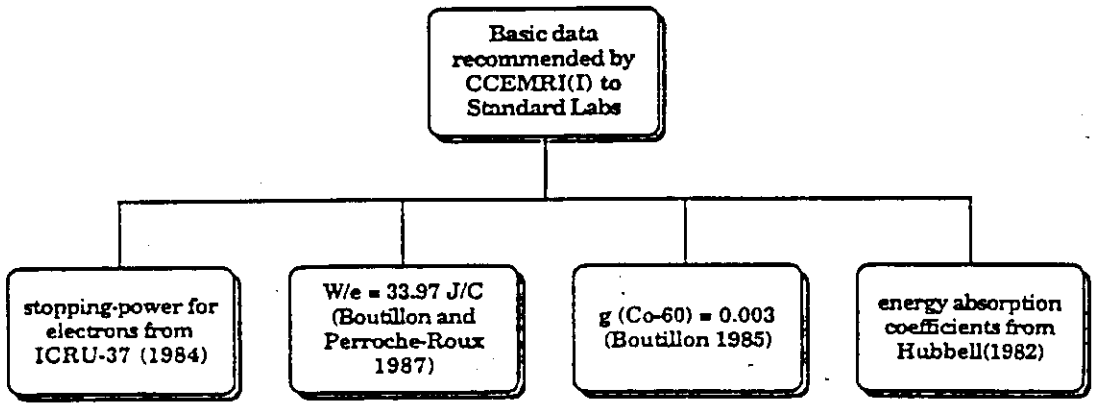
Stopping power ratio water/air (Table XIII), $s_{w,air} = 1.133$

$$p_u = \frac{\alpha\, s_{wall,air}\, (\bar{\mu}_{en}/\rho)_{w,wall} + (1-\alpha)\, s_{w,air}}{s_{w,air}} = 0.992$$



Older (upper part) and modern (large box in the lower part) dosimetry protocols and codes of practice (from Andreo, 1989).

Fig 6

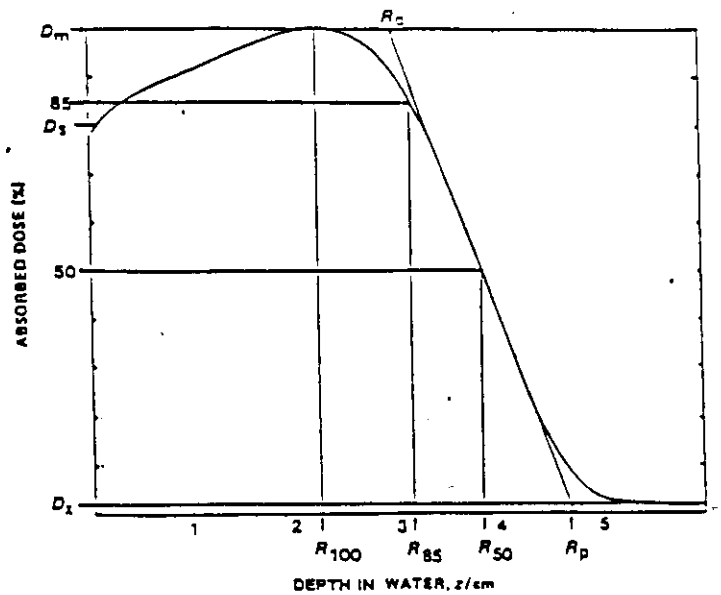


Basic data recommended by CCEMRI (1985).

Fig 7

Data for electron beam dosimetry

- beam quality given by $\bar{E}o$
- water/air s-ratios from Berger 1983 (cf also AAPM 1983)
- perturbation factors from Johansson et al 1978



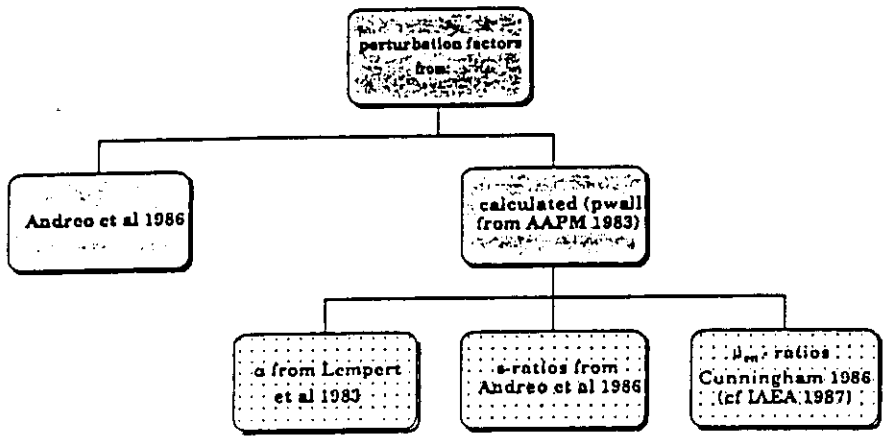
Characteristic central axis depth dose distribution in water of an electron beam showing the various parameters (taken from Brahme and Svensson (13)). R_{100} is the depth of the dose maximum, R_{85} and R_{50} are the depths of the 85 % and 50 % of the maximum dose, respectively, R_p is the practical range and R_q is the depth where the tangent at the steepest point intersects the maximum absorbed dose level (D_m).

Data employed for electron beam dosimetry (from Andreo, 1989).

Fig 8

Data for photon beam dosimetry

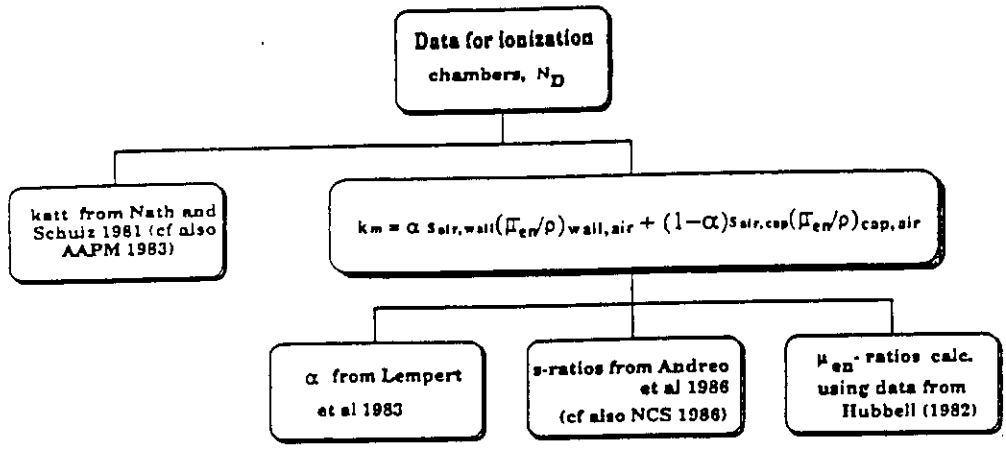
- beam quality given by dose ratio at 2 depths ("TPR")
- water/air s-ratios from Andreo and Brahme 1986
- perturbation factors from:



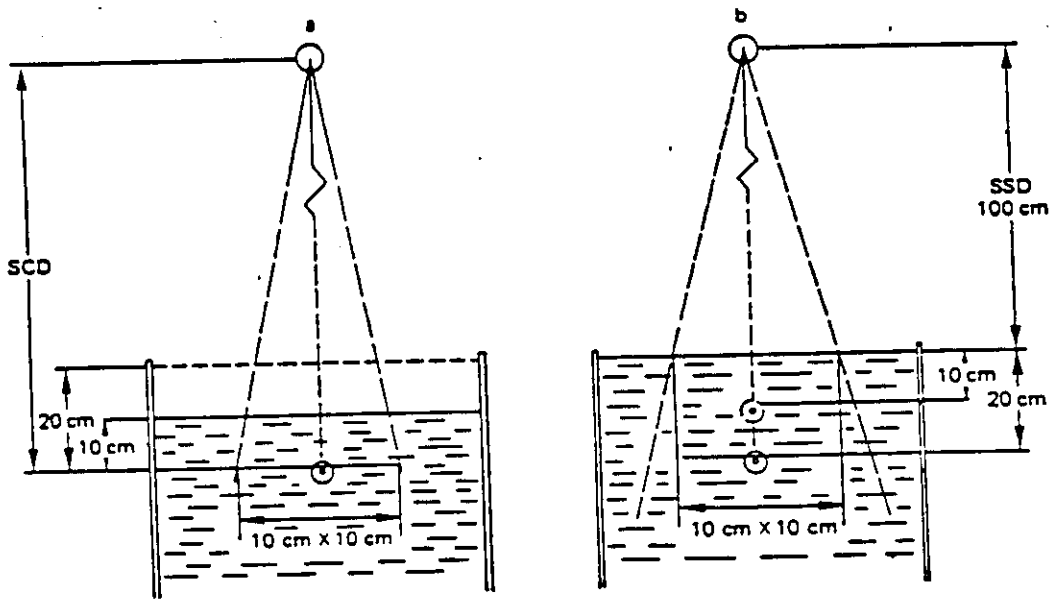
$$p_{wall} = \frac{\alpha\, s_{wall,air}(\bar{\mu}_{en}/\rho)_{w,wall} + (1-\alpha)\, s_{w,air}}{s_{w,air}}$$

Data employed for photon beam dosimetry (from Andreo, 1989).

Fig 9



Data employed for the computation of N_D, $C_{w,u}$ and F_X (F_E) (from Andreo, 1989).



The two experimental set-ups to determine the quality of photon beams. (a) The source-chamber distance (SCD) is kept constant and depth is changed by varying the amount of phantom material over the detector. TPR_{10}^{20} is measured (b) The sourece-surface distance (SSD) is kept constant and the chamber is moved to different depths. I_{20}/I_{10} is measured (from IAEA, 1987).

Fig 10

X-RAY BASIC EQUATIONS

DIN $\quad D_w = MN_x gk_c$

NACP $\quad D_w = MN_D \left(\left(\frac{S}{\rho}\right)_{w,air}\right)p$

$$= MN_x K_{att} K_m \left(\frac{W}{e}\right) K_1 \left(\left(\frac{S}{\rho}\right)_{w,air}\right)p$$

NCRP $\quad D_w = MN_x C_\lambda$

HPA $\quad D_w = 0.01\, MN_x C_\lambda$

AAPM $\quad D_w = MN_{gas}\left(\frac{\bar{L}}{\rho}\right)^w_{gas} P_{repl} P_{wall}$

$$= MN_x K_1 \left(\frac{W}{e}\right) \left[\frac{A_{ion} A_{wall} \beta_{wall}}{(\bar{L}/\rho)^{wall}_{gas} (\bar{\mu}_{en}/\rho)^{air}_{wall}}\right]_c \left(\frac{\bar{L}}{\rho}\right)^w_{gas} P_{repl} P_{wall}$$

NB: - At a given energy $\frac{D_w}{N_x M}$ = constant for each protocol.

Account must be taken of absorbed dose and calibration units NACP, HPA, and AAPM express absorbed dose in gray. DIN and NCRP in rad. DIN, NCRP and HPA are for calibration factors related to exposure in terms of roentgens. NACP and AAPM allow for exposure in roentgens or Ckg^{-1} with $k_1 = 2.58 \times 10^{-4}$ or 1, respectively.

ELECTRON BEAM BASIC EQUATION

DIN $\quad D_w = MN_x gk_c$

NACP $\quad D_w = MN_D \left(\left(\frac{S}{\rho}\right)_{w,air}\right)p$

$$= MN_x K_{att} K_m \left(\frac{W}{e}\right) K_1 \left(S_{w,air}\right)p$$

AAPM $\quad D_w = MN_{gas}\left(\frac{L}{\rho}\right)^w_{gas} P_{repl} P_{wall}$

$$= MN_x K_1 \left(\frac{W}{e}\right) \left[\frac{A_{ion} A_{wall} \beta_{wall}}{(L/\rho)^{wall}_{gas} (\bar{\mu}_{en}/\rho)^{air}_{wall}}\right]_c \left(\frac{L}{\rho}\right)^w_{gas} P_{repl} P_{wall}$$

NB: - At a given energy $\frac{D_w}{N_x M}$ = constant for each protocol.

Account must be taken of absorbed dose and calibration units. NACP and AAPM express absorbed dose in gray and the exposure calibration in terms of roentgens or CKg^{-1} $K_1 = 2.58 \times 10^{-4}$ for exposure expressed roentgen and $k_1 = 1$ for exposure in terms of CKG^{-1}.

Fig 11

COMBINED UNCERTAINTIES IN THE DIFFERENT PHYSICAL QUANTITIES OR PROCEDURES

The values of the uncertainties correspond to one standard deviation.

Step 1 in the calibration procedure (from IAEA 1987)

Type of physical quantity or procedure	Uncertainty (%)
Interaction coefficients (W/e $s_{graphite,air}$ $(\mu_{en}/\rho)_{air,graphite}$)	0.4
Measurement of K_{air} with the standard chamber (belongs to PSDL)	0.3
Calibration of secondary instrument (belongs to SSDL)	0.3
Calibration of local reference instrument (belongs to Hospital)	0.3
Transfer of K_{air} to a reference point in the ^{60}Co γ-beam at the Hospital	0.5
Calibration of the field instrument at the Hospital	0.5
Combined uncertainty in step 1	**1.0**

$$X = J_{air}\, s_{graphite,air}\, (\mu_{en}/\rho)_{air,graphite} \prod_i k_i$$

$s_{graphite,air}$	1.5
$(\mu_{en}/\rho)_{air,graphite}$	0.2
Combined	**1.5**

$$K_{air} = X \frac{W}{e} \frac{1}{1-g}$$

W/e $s_{graphite,air}$	0.3
$(\mu_{en}/\rho)_{air,graphite}$	0.2
Combined	**0.4**

Air kerma standard has "higher accuracy" than exposure standard for ^{60}Co γ-ray beams.

(from Andreo, 1989)

Fig 12

Absorbed dose to water in the therapy beam

$$D_w(P_{eff}) = M\, N_D\, s_{w,air}\, p_u = M\, N_K(1-g)\, k_m\, k_{att}\, s_{w,air}\, p_u$$

COMBINED UNCERTAINTIES IN THE DIFFERENT PHYSICAL QUANTITIES OR PROCEDURES

The values of the uncertainties correspond to one standard deviation.

Step 2 in the calibration procedure

(from IAEA 1987 and App. III in Brahme *et al* 1988)

Type of physical quantity or procedure	Uncertainty (%)		
	^{60}Co	high-energy photons	high-energy electrons
$k_m\, k_{att}$	1.6	1.6	1.6
combination of ($k_m\, k_{att}$ experim):	$\sqrt{1.5^2+0.2^2+0.5^2}$		
$s_{w,air}$ (calculation of values)	1.5	1.5	1.5
$s_{w,air}$ (selection procedure by the user)	-	0.5	1.5
p_u	0.5	1.0	1.5
Combined in user factors	2.2	2.5	3.1
(in IAEA 1987	2.4	2.6	3.2)
Field instrument measurements in the therapy beam	0.5	1.0	1.0
Monitor of the therapy unit	0.5	1.5	1.5
Combined uncertainty in step 2	2.3	3.1	3.6
Step 1	1.0	1.0	1.0
Combined uncertainty	2.5	3.3	3.7

Main contributions come from factors for the user, especially s-ratios

(from Andreo, 1989)

Fig 13

The ratio D_W / M N_X is constant, at a given energy, for each protocol

	6 MV	8 MV	20 MV	25 MV
AAPM 1983	0.945	0.955	0.939	0.921
SEFM 1984		0.953	0.935	
NACP 1980	0.957	0.953	0.933	0.929
IAEA 1987		0.964	0.951	0.948
NCS 1986		0.964	0.951	0.948
AIFB 1987		0.964	0.951	0.948
SSRBRP 1986		0.964	0.951	0.948
DIN 1980	0.974			0.936
HPA 1983	0.95			0.919
NCRP 1981	0.94			0.900

	e 6 MeV	e 20 MeV
AAPM 1983	0.842	0.834
SEFM 1984	0.838	
NACP 1980	0.846	0.849
ICRU 1984	0.849	
DIN 1980		0.836
IAEA 1987	0.854	
AIFB 1987	0.854	
SSRBPR 1986	0.854	

Fig 14