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Dosimetry electron beams

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Physics Raport 277

$$D_{water} = M_{cor} \cdot N_{D,Air} \cdot \left(\frac{S_{col}}{\rho}\right)_{water} \Big/ \left(\frac{S_{col}}{\rho}\right)_{air} \cdot p_u$$

$N_{D,Air}$	callibration factor in terms of dose to Air; independent on energy
$\left(\frac{S_{col}}{\rho}\right)_{water} \Big/ \left(\frac{S_{col}}{\rho}\right)_{air}$	ratio of dose to water and dose to air of mass stopping powers
$p_u = p_{wall} \cdot p_{dis} \cdot p_{cav} \cdot p_{cel}$	perturbation correction factor; ratio for Energy Q
M_{cor}	signal we measure; corrected for the actual conditions (temperature and preassure)

$$D_{water} = M_{cor} \cdot N_{D,Air} \cdot \left(\frac{L_{\Delta}}{\rho}\right)_{water} \Big/ \left(\frac{L_{\Delta}}{\rho}\right)_{air} \cdot p_u$$

$\left(\frac{L_{\Delta}}{\rho}\right)_{water} \Big/ \left(\frac{L_{\Delta}}{\rho}\right)_{air}$

restricted mass stopping collision power

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Raport 398

$$D_{water} = M_{cor} \cdot N_{D,water} \cdot k_{Q,Q_0}$$

$N_{D,water}$	callibration factor in terms of dose to water; dependent on energy
k_{Q,Q_0}	factor which converts calibration factor from reference energy to user energy
M_{cor}	signal we measure; corrected for the actual conditions (temperature and preassure)

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$k_{Q,Q0}$ from Raport 398

$$k_{Q,Q_0} = \frac{\left(\dfrac{S_{col}}{\rho}\right)^{w}_{air,Q} \cdot p_{u,Q}}{\left(\dfrac{S_{col}}{\rho}\right)^{w}_{air,Q_0} \cdot p_{u,Q_0}}$$

$$p_u = p_{wall} \cdot p_{dis} \cdot p_{cav} \cdot p_{cel}$$

$$\left(N_{D,water}\right)_Q = \left(N_{D,water}\right)_{Q_0} \cdot k_{Q,Q_0}$$

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Energy of electron beams

The most probable Energy Ep,0 on the Surface is given by

$E_{p,0} = 0,22 + 1,98 \cdot R_p + 0,0025 \cdot R_p \cdot R_p$

(Ep,0 is in MeV, R_p is in cm, R_p is the practical range)

The mean electron Energy $E_{0,mean}$ at the Phantom Surface is given by

$E_{0,mean} = 2.33\ MeV/cm \cdot R_{50,dose}$,

R_{50} is the depth of 50% of dose which is obtained from R_{50} ionization (be given later)

The mean electron Energy $E_{z,mean}$ at depth z is given by

$E_{z,mean} = E_{0,mean} \cdot (1 – z/R_p)$

Energy of electron beams ionization curve

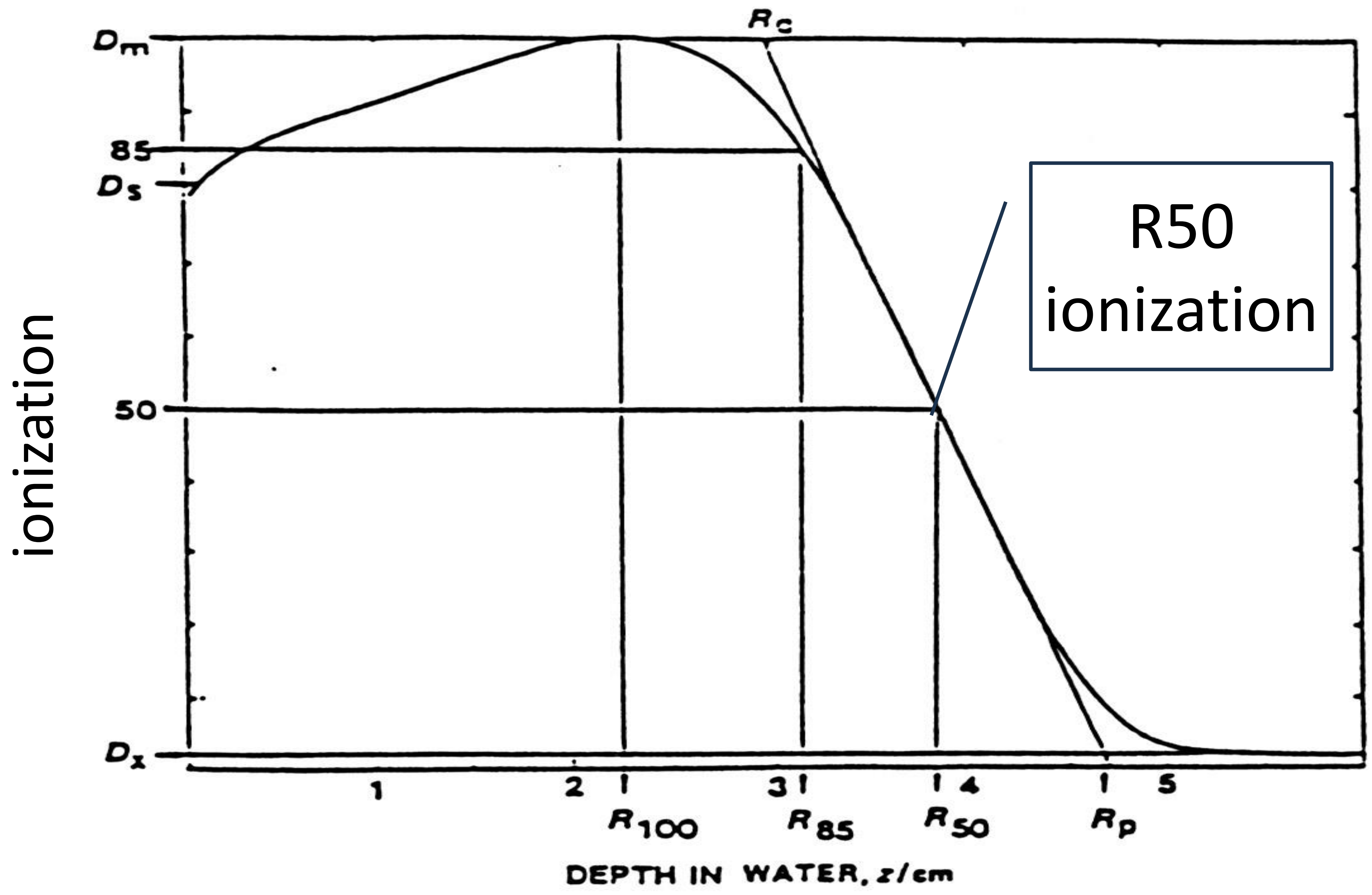

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TABLE 16. REFERENCE CONDITIONS FOR THE DETERMINATION OF ELECTRON BEAM QUALITY (R_{50})

Influence quantity	Reference value or reference characteristics
Phantom material	For $R_{50} \geq 4$ g/cm^2, water
	For $R_{50} < 4$ g/cm^2, water or plastic
Chamber type	For $R_{50} \geq 4$ g/cm^2, plane parallel or cylindrical
	For $R_{50} < 4$ g/cm^2, plane parallel
Reference point of the chamber	For plane parallel chambers, on the inner surface of the window at its centre.
	For cylindrical chambers, on the central axis at the centre of the cavity volume
Position of the reference point of the chamber	For plane-parallel chambers, at the point of interest For cylindrical chambers, 0.5 r_{cyl} deeper than the point of interest
SSD	100 cm
Field size at phantom surface	For $R_{50} \leq 7$ g/cm^2 , at least 10 cm × 10 cm
	For $R_{50} > 7$ g/cm^2, at least 20 cm × 20 cm[a]

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Construction of plane parallel chambers

	Window thickness	Electrode spacing	Collecting electrode diameter	Guard ring width	Recommended phantom material
NACP01 (Scanditronix) Calcam-1 (Dosetek)	90 mg/cm^2 0.5 mm	2 mm	10 mm	3 mm	Polystyrene Graphite Water (with water-proof housing)
NACP02 (Scanditronix) Calcam-2 (Dosetek)	104 mg/cm^2 0.6 mm	2 mm	10 mm	3 mm	Water, PMMA

Construction of plane parallel chambers

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	Window thickness	Electrode spacing	Collecting electrode diameter	Guard ring width	Recommended phantom material
Markus chamber PTW 23343 NA 30-329 NE 2534	102 mg/cm^2 0.9 mm (incl. cap)	2 mm	5.3 mm	0.2 mm	Water, PMMA
Scdx-Wellhöfer PPC 05	176 mg/cm^2 1 mm	0.5 mm	10 mm	3.5 mm	Water
Holt chamber (Memorial) NA 30-404	416 mg/cm^2 4 mm	2 mm	25 mm	5 mm	Polystyrene (phantom integr.)

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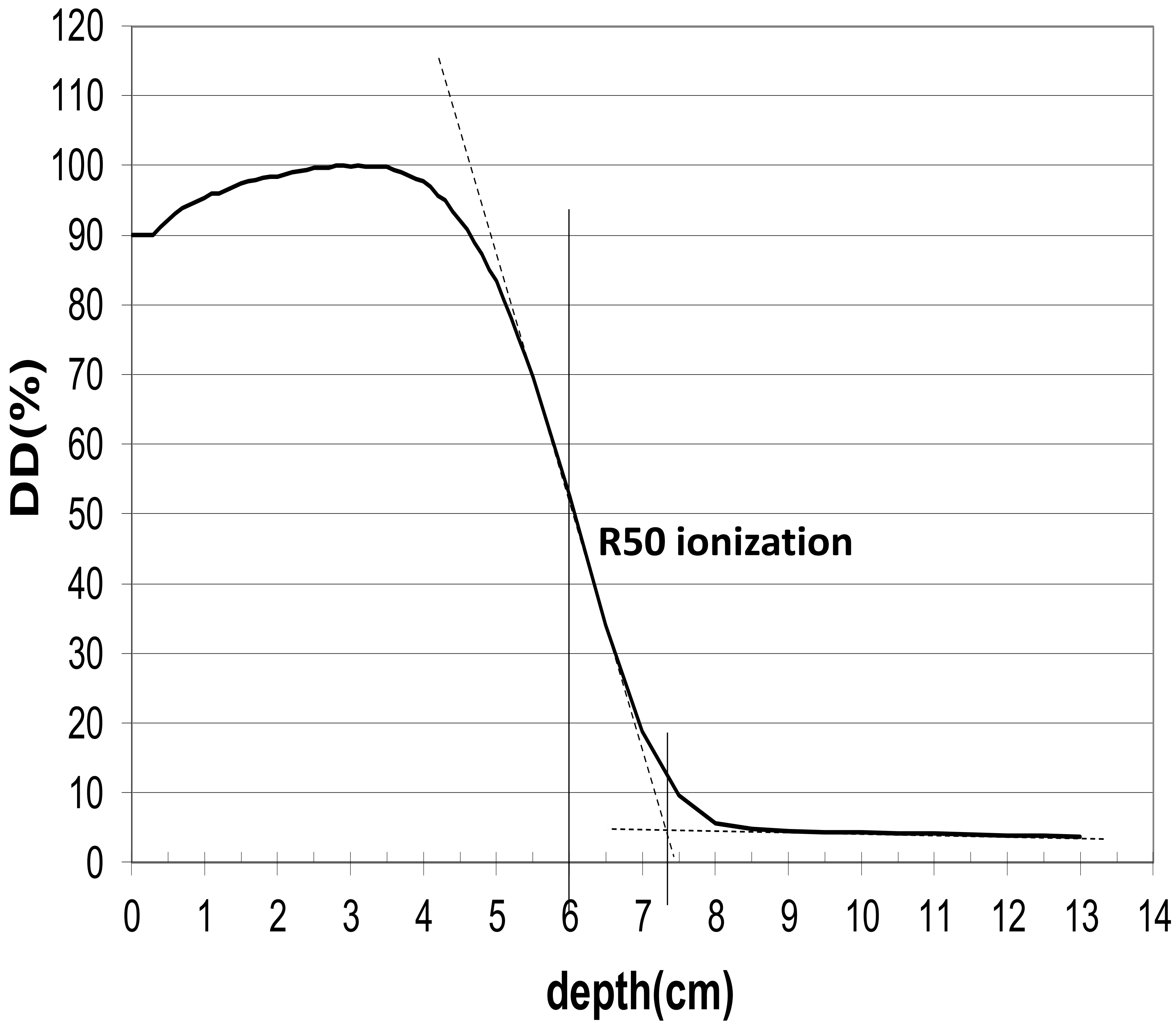
Size of the beam for output factor

Rigorously

Field size at phantom surface	For $R_{50} \leq 7$ g/cm^2 , at least 10 cm × 10 cm
	For $R_{50} > 7$ g/cm^2, at least 20 cm × 20 cm[a]

The precise choice of field size is not critical, a convenient choice for the reference field size is that which is used for the normalization of output factors, usually 10 cm × 10 cm at the phantom surface. Never < 10 x 10 cm!

R50 ionization -15 MeV



Depth of measurement

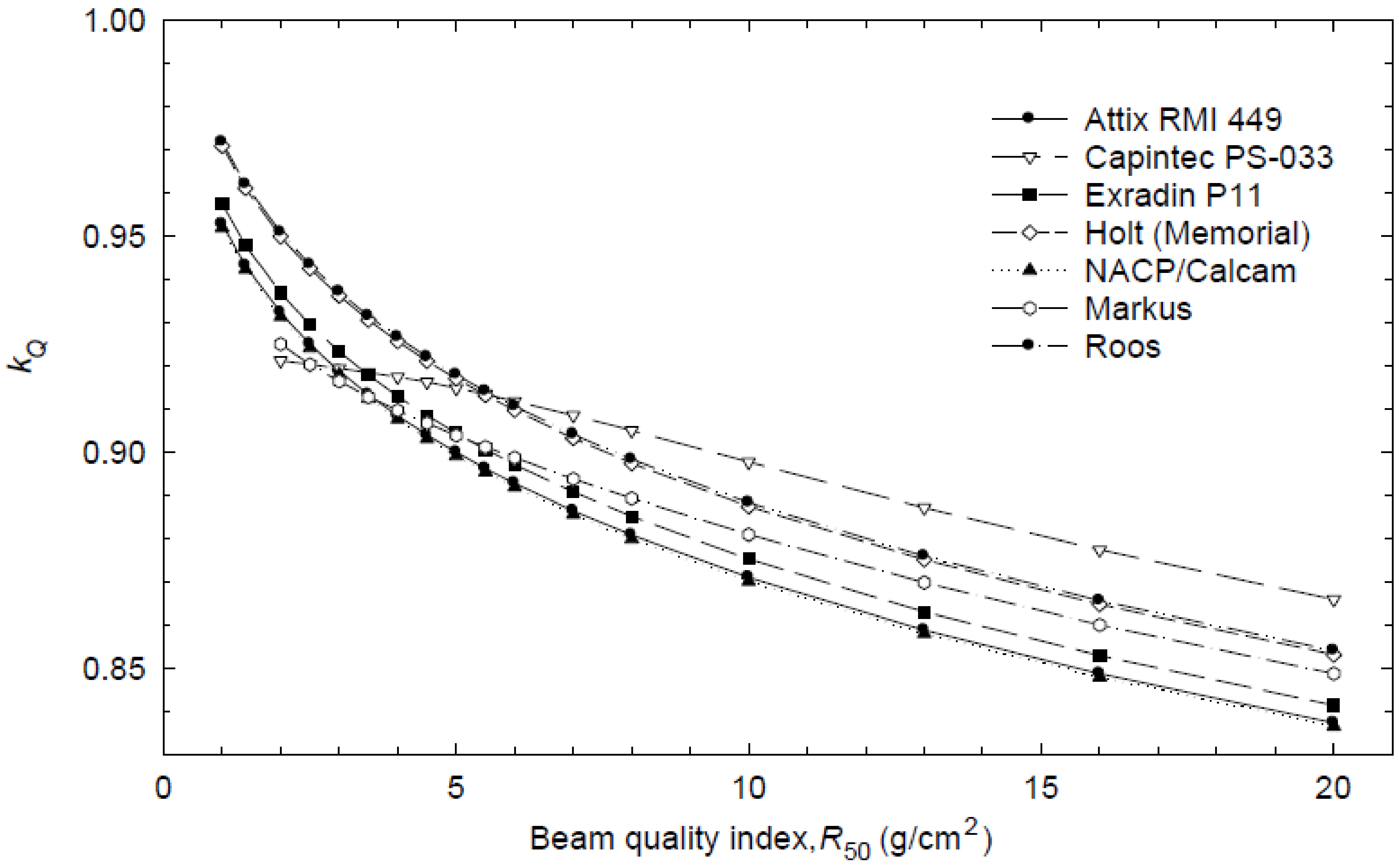
$$R_{50} = 1.029\ \mathrm{R}_{50,\mathrm{ion}} - 0.06\ \mathrm{g/cm}^2 \quad (R_{50,\mathrm{ion}} \leq 10\ \mathrm{g/cm}^2)$$
$$R_{50} = 1.059\ \mathrm{R}_{50,\mathrm{ion}} - 0.37\ \mathrm{g/cm}^2 \quad (R_{50,\mathrm{ion}} > 10\ \mathrm{g/cm}^2)$$

zref = 0.6 · *R*50 – 0.1 g/cm2 (*R*50 in g/cm2)

This depth is close to the depth of the absorbed dose maximum zmax at beam qualities *R*50 < 4 g/cm2 (*Eo* 10 MeV), but at higher beam qualities is deeper than zmax.

k_{QQ0} for calibration in Co60 k_Q

Table 18 (TRS 398)



Calibration in electron beam

Chambers my be calibrated in Co60 or in electron beam (very seldom).
If in electron beam set of calibration factors are needed.

One calibration factor is valid only for one energy (for one quality index).

To measure for another energy the cross calibration procedure may be applied.

Report 398 – beam qulity index (for k_{QQ0})

R50 for depth dose curve (g/cm^2)

PDD measurements (ionization depth dose)

SSD = 100 cm

field size at the phantom surface at least:

10 cm × 10 cm for *R*50 < 7 g/cm2 (*Eo* 16 MeV),

20 cm × 20 cm for *R*50 > 7 g/cm2 (*Eo* 16 MeV).

Corrections for influence quantities

$$D_{water} = M_{cor} \cdot N_{D,water} \cdot k_{Q,Q_0}$$

for preassure and temperature

$$k_{T,P} = \frac{(273.2 + T)}{(273.2 + T_0)} \cdot \frac{P_0}{P}$$

T_0, P_0 are the temperature and preassure used for callibration

for humidity
no corrections for humidity are needed if the calibration factor was reffered to a relative humidity of 50% and is used in a relative humidity between 20 and 80%

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Corrections for influence quantities

$$D_{water} = M_{cor} \cdot N_{D,water} \cdot k_{Q,Q_0}$$

Polarity effect

The influence of polarization on the chamber reading should be accounted for.

Correction factor

$$k_{pol} = \frac{|M_+| + |M_-|}{2M}$$

M+, M- are reading obtained for positive and negative polarity
M reading for polarity used routinely

Corrections for influence quantities

(Rigorously) Ion recombination and polarity corrections are required at all depths, but these may be derived from a reduced set of representative measurements:

near the surface, the ionization maximum and the depths corresponding to 90% and 50% of the ionization maximum.

Corrections for influence quantities

$$D_{water} = \boxed{M_{cor}} \cdot N_{D,water} \cdot k_{Q,Q_0}$$

Polarity effect

User should inform teh callibration laboratory on the polarization potential and polarity used in daily measurements.

After changing polarity one should wait some time to obtain
a stable reading of the chamber. For some chambers it may be even 20 min.

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Corrections for influence quantities

$$D_{water} = \boxed{M_{cor}} \cdot N_{D,water} \cdot k_{Q,Q_0}$$

Ion recombination correction factor k_s

The two voltage method is used.

Reading is measured for two voltages V1 and V2. V1/V2 ≥ 3

Correction factor

$$k_s = a_0 + a_1 \cdot \left(\frac{M1}{M2}\right) + a_2 \cdot \left(\frac{M1}{M2}\right)^2$$

Corrections for influence quantities

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$$D_{water} = M_{cor} \cdot N_{D,water} \cdot k_{Q,Q_0}$$

$$k_s = a_0 + a_1 \cdot \left(\frac{M1}{M2}\right) + a_2 \cdot \left(\frac{M1}{M2}\right)^2$$

V_1/V_2	Pulsed		
	a_0	a_1	a_2
2.0	2.337	–3.636	2.299
2.5	1.474	–1.587	1.114
3.0	1.198	–0.875	0.677
3.5	1.080	–0.542	0.463
4.0	1.022	–0.363	0.341
5.0	0.975	–0.188	0.214

Coefficients from Table 9
Report 398
Two sets of data for pulsed
and pulsed-scanned dose.
Almost all beams are pulsed.

Signal M is always corrected signal!

Cross calibration
reference chamber calibrated in Co60

Cylindrical ion chamber *ref* calibrated in Co60 beam: $N_{ref,D,water,Q}$

There is no calibration factor for plane paralel chamber X.

We do measurements with both chambers in the electron beam of the energy with quality index Q_0 higher > 7.5 g/cm^2.

Corrected readings were M_{ref}, M_X

Cross calibration C060 beam

measurements in energy Q0 > 7.5 g/cm^2

For M_{ref} and M_X:

$$M_{ref} \cdot N_{ref,D,water,Q} \cdot k_{ref,Q,Q0} = M_X \cdot N_{x,D,water,Q} \cdot k_{X,Q,Q_0}$$

From this equation we have $N_{X,D,water,Q}$

From Table 18 we have $k_{chamber,Q,Q0}$ correction k factors for other energies.

TABLE 18. CALCULATED VALUES FOR k_Q FOR ELECTRON BEAMS, FOR VARIOUS CHAMBER TYPES CALIBRATED IN ^{60}Co GAMMA RADIATION, AS A FUNCTION OF BEAM QUALITY R_{50}

(the data are derived using values for stopping-power ratios and perturbation factors, as given in Appendix II)

Ionization chamber type[a]	Beam quality R_{50} (g/cm^2)																
	1.0	1.4	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	13.0	16.0	20.0
Plane-parallel chambers																	
Attix RMI 449	0.953	0.943	0.932	0.925	0.919	0.913	0.908	0.904	0.900	0.896	0.893	0.886	0.881	0.871	0.859	0.849	0.837
Capintec PS-033	—	—	0.921	0.920	0.919	0.918	0.917	0.916	0.915	0.913	0.912	0.908	0.905	0.898	0.887	0.877	0.866
Exradin P11	0.958	0.948	0.937	0.930	0.923	0.918	0.913	0.908	0.904	0.901	0.897	0.891	0.885	0.875	0.863	0.853	0.841
Holt (Memorial)	0.971	0.961	0.950	0.942	0.936	0.931	0.926	0.921	0.917	0.913	0.910	0.903	0.897	0.887	0.875	0.865	0.853
NACP / Calcam	0.952	0.942	0.931	0.924	0.918	0.912	0.908	0.903	0.899	0.895	0.892	0.886	0.880	0.870	0.858	0.848	0.836
Markus	—	—	0.925	0.920	0.916	0.913	0.910	0.907	0.904	0.901	0.899	0.894	0.889	0.881	0.870	0.860	0.849
Roos	0.965	0.955	0.944	0.937	0.931	0.925	0.920	0.916	0.912	0.908	0.904	0.898	0.892	0.882	0.870	0.860	0.848
Cylindrical chambers																	
Capintec PR06C (Farmer)	—	—	—	—	—	—	0.916	0.914	0.912	0.911	0.909	0.906	0.904	0.899	0.891	0.884	0.874
Exradin A2 (Spokas)	—	—	—	—	—	—	0.914	0.913	0.913	0.913	0.912	0.911	0.910	0.908	0.903	0.897	0.888
Exradin T2 (Spokas)	—	—	—	—	—	—	0.882	0.881	0.881	0.881	0.880	0.879	0.878	0.876	0.871	0.865	0.857
Exradin A12 (Farmer)	—	—	—	—	—	—	0.921	0.919	0.918	0.916	0.914	0.911	0.909	0.903	0.896	0.888	0.878
NE 2571 (Guarded Farmer)	—	—	—	—	—	—	0.918	0.916	0.915	0.913	0.911	0.909	0.906	0.901	0.893	0.886	0.876
NE 2581 (Robust Farmer)	—	—	—	—	—	—	0.899	0.898	0.896	0.894	0.893	0.890	0.888	0.882	0.875	0.868	0.859

Cross calibration for chamber X reference chamber calibrated in electron beam

It is allowed to calibrate a chamber with a calibrated chamber **ref** in the secondary sandard laboratory in electron energy **cross**.

Chambers are compared by alternately placing the chambers at z_{ref} for energy **cross**.

$$N_{D,w,Qcross}^{X} = \frac{Mref}{M_X} \cdot N_{D,w,Q_{Cross}}^{ref}$$

Cross calibration in energy Q_0

To obtain calibration factor for energy *Int*

$$M_{ref,Q_0} \cdot N^{ref}{}_{D,w,Qcro_{ss}} \cdot k_{ref,Q_0,Q_{cross}} = M_{X,Q_0} \cdot N_{x,D,w,Q_0}$$

$$N^{X}_{D,w,QInt} = \frac{N^{X}_{D,w,Q_0}}{k_{X,Q_0,QInt}}$$

From this equation we have $N_{X,D,w,QInt}$

From Table 19 for energy *Int* we have $k_{X,QInt,Q}$

correction k factors for other Q energies.

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TABLE 22. ESTIMATED RELATIVE STANDARD UNCERTAINTY[a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR AN ELECTRON BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure		Relative standard uncertainty (%)	
	User chamber type:	Cylindrical	Plane parallel
	Beam quality range:	$R_{50} \geq 4$ g/cm^2	$R_{50} \geq 1$ g/cm^2
Step 1: Standards laboratory			
$N_{D,w}$ calibration of secondary standard at PSDL		0.5	0.5
Long term stability of secondary standard		0.1	0.1
$N_{D,w}$ calibration of user dosimeter at SSDL		0.4	0.4
Combined uncertainty of step 1[b]		*0.6*	*0.6*
Step 2: User electron beam			
Long term stability of user dosimeter		0.3	0.4
Establishment of reference conditions		0.4	0.6
Dosimeter reading M_Q relative to beam monitor		0.6	0.6
Correction for influence quantities k_i		0.4	0.5
Beam quality correction k_Q (calculated values)		1.2	1.7
Combined uncertainty of step 2		*1.5*	*2.0*
Combined standard uncertainty of $D_{w,Q}$ (steps 1+2)		**1.6**	**2.1**

TABLE 23. ESTIMATED RELATIVE STANDARD UNCERTAINTY[a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR AN ELECTRON BEAM, BASED ON A CHAMBER CALIBRATION IN A HIGH ENERGY ELECTRON BEAM

Physical quantity or procedure		Relative standard uncertainty (%)	
	User chamber type:	Cylindrical	Plane parallel
	Beam quality range:	$R_{50} \geq 4$ g/cm^2	$R_{50} \geq 1$ g/cm^2
Step 1: PSDL			
$N_{D,w}$ calibration of user dosimeter at PSDL		0.7	0.7
Combined uncertainty in step 1		*0.7*	*0.7*
Step 2: User electron beam			
Long term stability of user dosimeter		0.3	0.4
Establishment of reference conditions		0.4	0.6
Dosimeter reading M_Q relative to beam monitor		0.6	0.6
Correction for influence quantities k_i		0.4	0.5
Beam quality correction k_{Q,Q_o} (calculated values)		0.9	0.6
Combined uncertainty in step 2		*1.3*	*1.2*
Combined standard uncertainty of $D_{w,Q}$ (steps 1+2)		**1.4**	**1.4**

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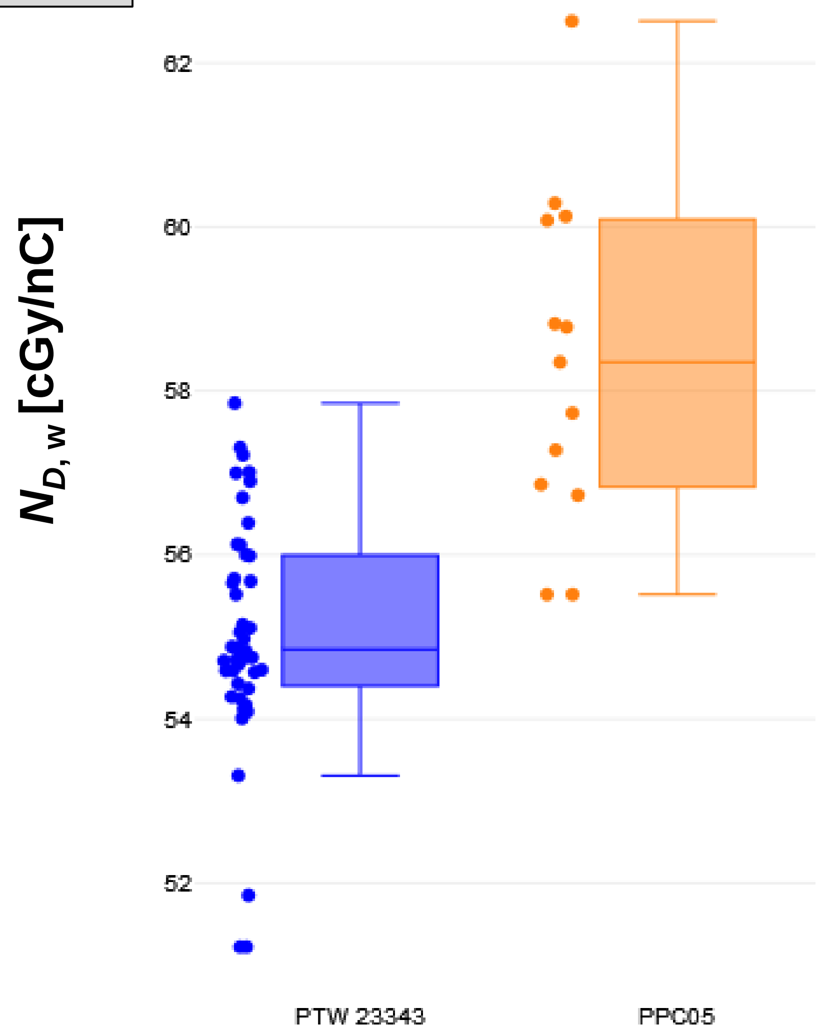
Results

Calibration coefficients for PTW 23343 and PPC05 ionization chambers

Box plot



Type of plane parallel ionization chambers

Descriptive statistics

Type of chambers	PTW 23343	PPC05
Sample size: n	44	13
Arithmetic mean value of $N_{D,w}$ [cGy/nC]	55.03	58.35
Median value of $N_{D,w}$ [cGy/nC]	54.85	58.35
Standard deviation value of $N_{D,w}$ [cGy/nC]	1.44	2.04
Standard deviation value of $N_{D,w}$ expressed as a percentage of the arithmetic mean value of $N_{D,w}$ [%]	2.61	3.50
Q_1 [cGy/nC]	54.40	56.86
Q_3 [cGy/nC]	55.99	60.08
$N_{D,w\ max}$ [cGy/nC]	57.85	62.51
$N_{D,w\ min}$ [cGy/nC]	51.22	55.52
$N_{D,w\ max}$ / $N_{D,w\ min}$	1.13	1.13
Outliers	51.22, 51.85, 51.22	none

Central axis depth dose distribution

The measurement of a central axis depth dose distribution should follow the procedure given in Section 7.3.2 for the measurement of R_{50}. If an ionization chamber is used, the measured depth ionization distribution must be converted to a depth dose distribution.[32] For a beam of quality R_{50}, this is achieved by multiplying the ionization current or charge at each measurement depth z by the stopping-power ratio $s_{w,air}$ at that depth. Values for $s_{w,air}$ are given in Table 20 as a function of R_{50} and the relative depth z/R_{50}. Linear interpolation between table entries is sufficient. These stopping-power ratios are calculated using Eq. (66) in Appendix II [91].[33]

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TABLE 20. SPENCER-ATTIX STOPPING-POWER RATIOS (Δ = 10 keV) WATER TO AIR ($s_{w,air}$) FOR ELECTRON BEAMS, AS A FUNCTION OF BEAM QUALITY R_{50} AND RELATIVE DEPTH z/R_{50} IN WATER

(the data are derived using Eq. (66) in Appendix II [91])

	Beam quality R_{50} (g/cm^2)																
	1.0	1.4	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	13.0	16.0	20.0
z_{ref} (g/cm^2):	0.5	0.7	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.5	4.1	4.7	5.9	7.7	9.5	11.9
$s_{w,air}(z_{ref})$:	1.102	1.090	1.078	1.070	1.064	1.058	1.053	1.048	1.044	1.040	1.036	1.029	1.022	1.010	0.995	0.983	0.970
Relative depth in water z/R_{50}																	
0.02	1.076	1.060	1.042	1.030	1.020	1.012	1.004	0.997	0.991	0.986	0.980	0.971	0.963	0.950	0.935	0.924	0.914
0.05	1.078	1.061	1.044	1.032	1.022	1.014	1.006	1.000	0.994	0.988	0.983	0.974	0.965	0.952	0.937	0.926	0.916
0.10	1.080	1.064	1.047	1.036	1.026	1.018	1.010	1.004	0.998	0.992	0.987	0.978	0.970	0.957	0.942	0.931	0.920
0.15	1.083	1.067	1.050	1.039	1.030	1.022	1.014	1.008	1.002	0.997	0.992	0.983	0.975	0.961	0.946	0.935	0.924
0.20	1.085	1.070	1.053	1.043	1.034	1.026	1.019	1.012	1.006	1.001	0.996	0.987	0.979	0.966	0.951	0.940	0.929
0.25	1.088	1.073	1.057	1.046	1.037	1.030	1.023	1.017	1.011	1.006	1.001	0.992	0.984	0.971	0.956	0.945	0.933
0.30	1.091	1.076	1.060	1.050	1.041	1.034	1.027	1.021	1.016	1.010	1.006	0.997	0.989	0.976	0.961	0.950	0.938
0.35	1.093	1.079	1.064	1.054	1.045	1.038	1.032	1.026	1.020	1.015	1.011	1.002	0.995	0.982	0.966	0.955	0.943
0.40	1.096	1.082	1.067	1.058	1.049	1.042	1.036	1.030	1.025	1.020	1.016	1.007	1.000	0.987	0.972	0.960	0.948
0.45	1.099	1.085	1.071	1.062	1.054	1.047	1.041	1.035	1.030	1.025	1.021	1.013	1.006	0.993	0.978	0.966	0.953
0.50	1.102	1.089	1.075	1.066	1.058	1.051	1.046	1.040	1.035	1.031	1.027	1.019	1.012	0.999	0.984	0.971	0.959
0.55	1.105	1.092	1.078	1.070	1.062	1.056	1.051	1.045	1.041	1.036	1.032	1.025	1.018	1.005	0.990	0.977	0.964
0.60	1.108	1.095	1.082	1.074	1.067	1.061	1.056	1.051	1.046	1.042	1.038	1.031	1.024	1.012	0.996	0.984	0.970
0.65	1.111	1.099	1.086	1.078	1.072	1.066	1.061	1.056	1.052	1.048	1.044	1.037	1.030	1.018	1.003	0.990	0.976
0.70	1.114	1.102	1.090	1.082	1.076	1.071	1.066	1.062	1.058	1.054	1.050	1.043	1.037	1.025	1.010	0.997	0.983
0.75	1.117	1.105	1.094	1.087	1.081	1.076	1.072	1.067	1.064	1.060	1.057	1.050	1.044	1.033	1.017	1.004	0.989

$S_{w,air}$ for electron beams

$$s_{w,\mathrm{air}}(z) = \frac{a + bx + cx^2 + dy}{1 + ex + fx^2 + gx^3 + hy}$$

$x = \ln(R50)$ and $y = z/R50$

$a = 1.075$	$b = -0.5087$	$c = 0.0887$	$d = -0.084$
$e = -0.4281$	$f = 0.0646$	$g = 0.00309$	$h = -0.125$

Note that this procedure neglects any variation in the perturbation factor with depth. This is a good approximation for well guarded plane-parallel chamber types. For plane-parallel chambers that are not well guarded and for cylindrical chamber types, changes in the perturbation factor are significant and must be accounted for.

Guard ring

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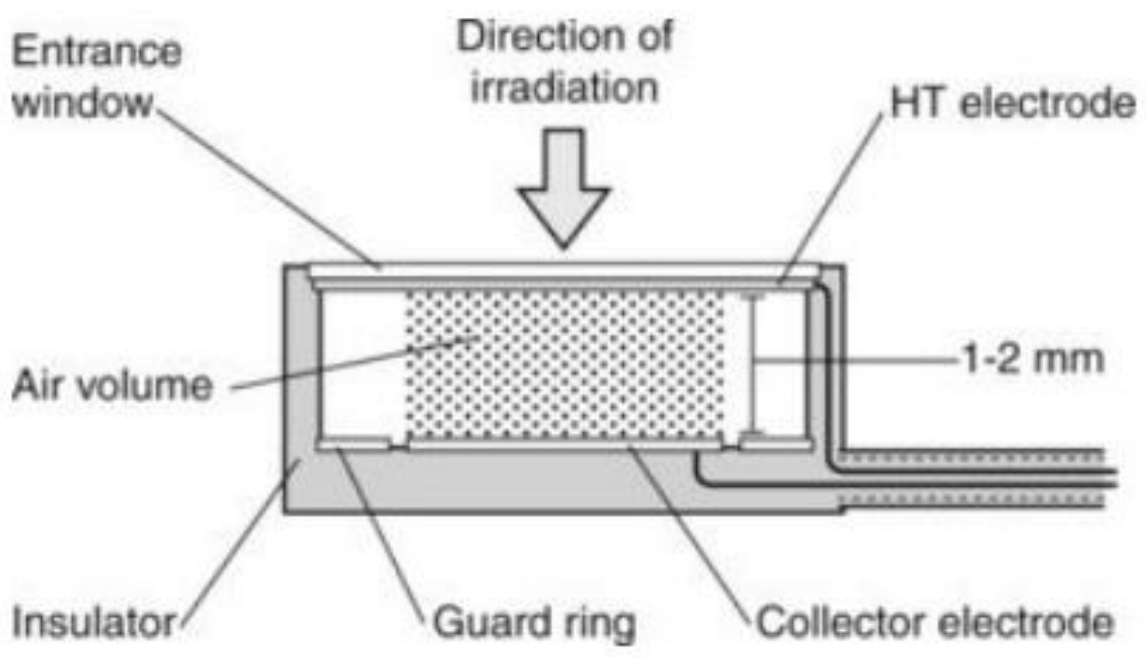

https://radiologykey.com/parallel-plate-ionization-chamber/

Guard ring (GR) is an annular ring surrounded the charge-collecting electrode. The voltage of guard ring is the same as chargé-collecting electrode.

GR ensures that the electric field lines near the edge of the collecting electrode remain straight. The collecting volume is accurately defined by the area of the collecting electrode and the electrode separation.

GR minimizes the extent of charge leakage from the volume outside of the collecting volume.

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Output factors measurement

OF should be measured at dose max (z_{max}).

We have to be aware of the variation of the depth of maximum, particularly for small beams.

Another problem is to define the OU for other SSD. There is a complicated dependence of OF on SSD particularly for small beams (virtual source). We encourage to measure additional sets of measurements for other SSDs, e.g. 110 cm, 115 cm.

Percent depth dose for electron beams dependence on the beam size

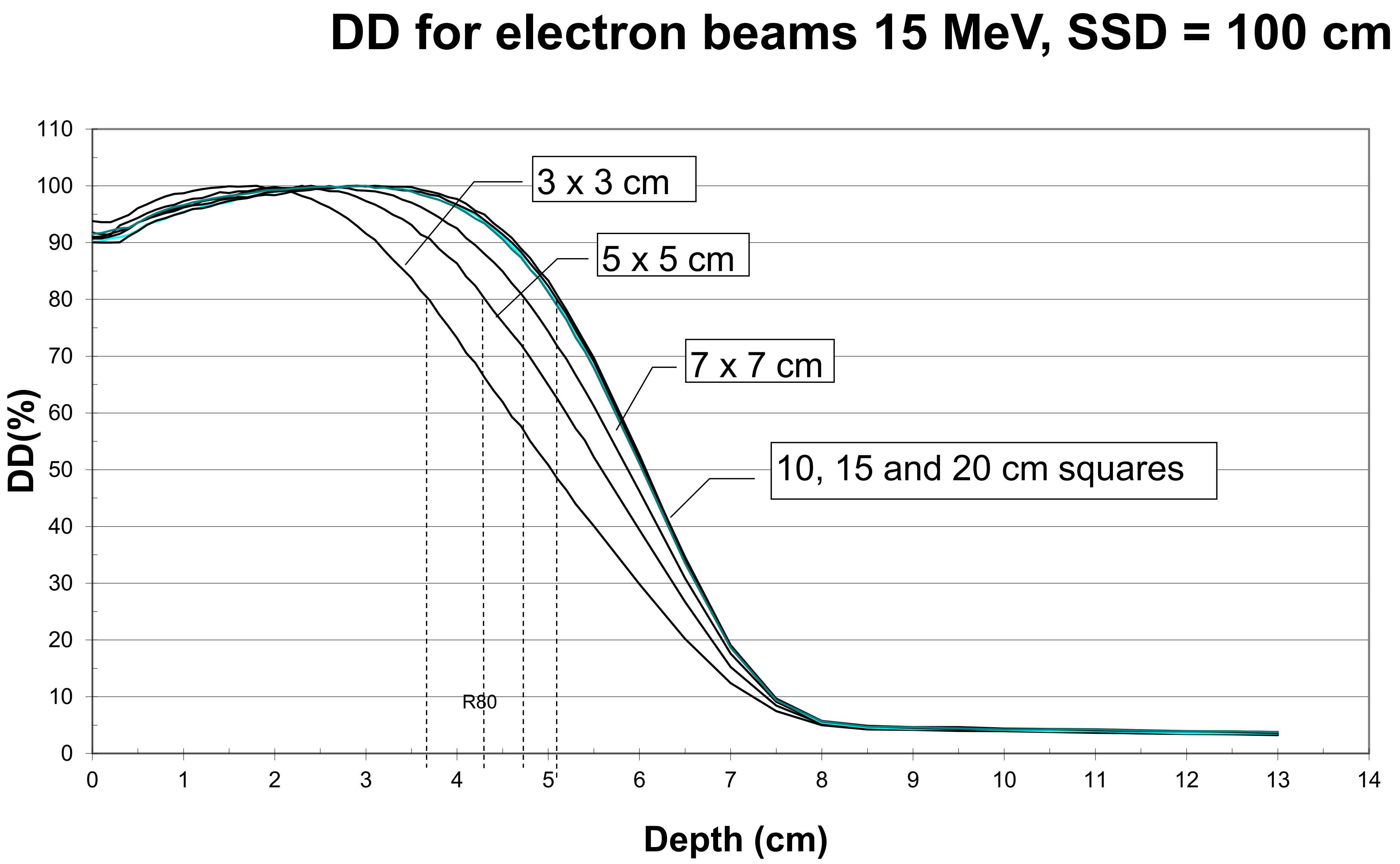

TABLE 6. ELEMENTAL COMPOSITION (FRACTION BY WEIGHT), NOMINAL DENSITY AND MEAN ATOMIC NUMBER OF COMMON PHANTOM MATERIALS USED AS WATER SUBSTITUTES *(for comparison, liquid water is also included)*

	Liquid water[a]	Solid water WT1[a]	Solid water RMI-457	Plastic water	Virtual water	PMMA[a,b]	Polystyrene[a]	Tissue equivalent plastic A-150[a]
H	0.1119	0.0810	0.0809	0.0925	0.0770	0.0805	0.0774	0.1013
C		0.6720	0.6722	0.6282	0.6874	0.5998	0.9226	0.7755
N		0.0240	0.0240	0.0100	0.0227			0.0351
O	0.8881	0.1990	0.1984	0.1794	0.1886	0.3196		0.0523
F								0.0174
Cl		0.0010	0.0013	0.0096	0.0013			
Ca		0.0230	0.0232	0.0795	0.0231			0.0184
Br				0.0003				
Density (g/cm^3)	1.000	1.020	1.030	1.013	1.030	1.190	1.060	1.127
$\bar{Z}$[c]	6.6	5.95	5.96	6.62	5.97	5.85	5.29	5.49

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USE OF PLASTIC PHANTOMS

it is strongly unrecommended

Plastic phantoms may only be used at beam qualities $R_{50} \leq 4$ g/cm^2 (approximately $E_0 \leq 10$ MeV).

Depth is scaled with: $z_{water} = z_{plastic} \cdot c_{pl}$ (g/cm^2)

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Summary

We use electron beams less and less.

Complicated dosimetry for electron beams has been replaced by no less complicated dosimetry of small fields.

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Thank you for your attention.