Clatterbridge Centre for Oncology NHS
NHS Foundation Trust

Cavity Theory, Stopping-Power Ratios, Correction Factors.

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AAPM Summer School, CLINICAL DOSIMETRY FOR RADIOTHERAPY,
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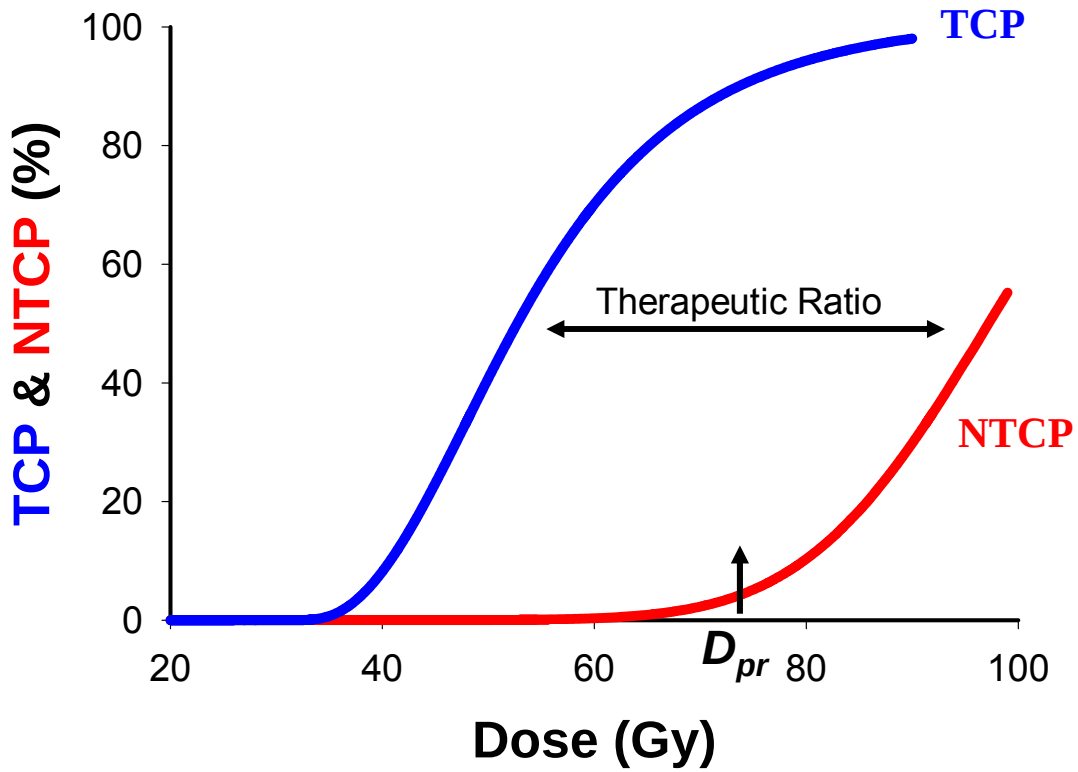
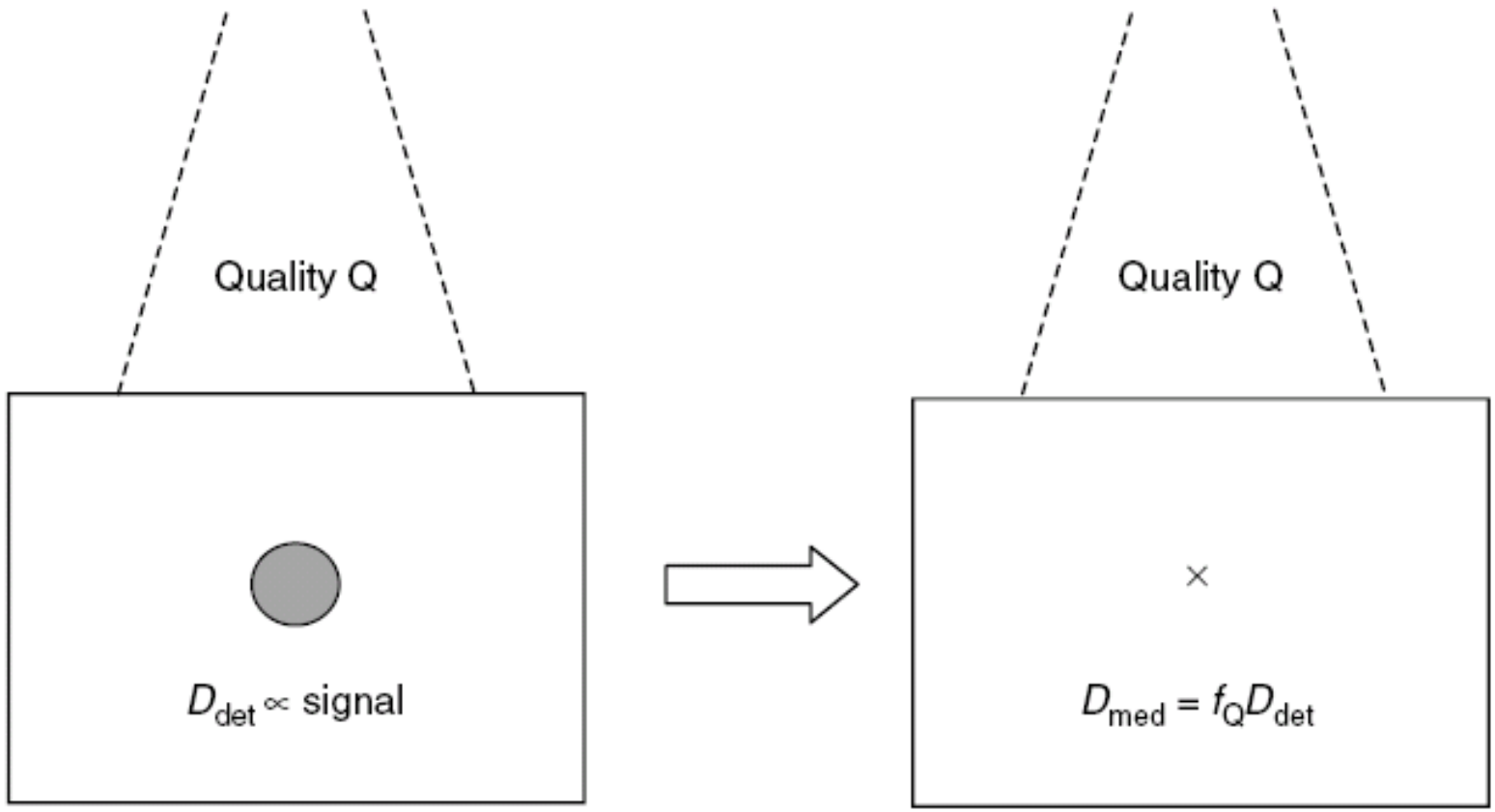
Accurate knowledge of the (patient) dose in radiation therapy is crucial to clinical outcome

For a given fraction size



Detectors almost never measure *dose to medium* directly.

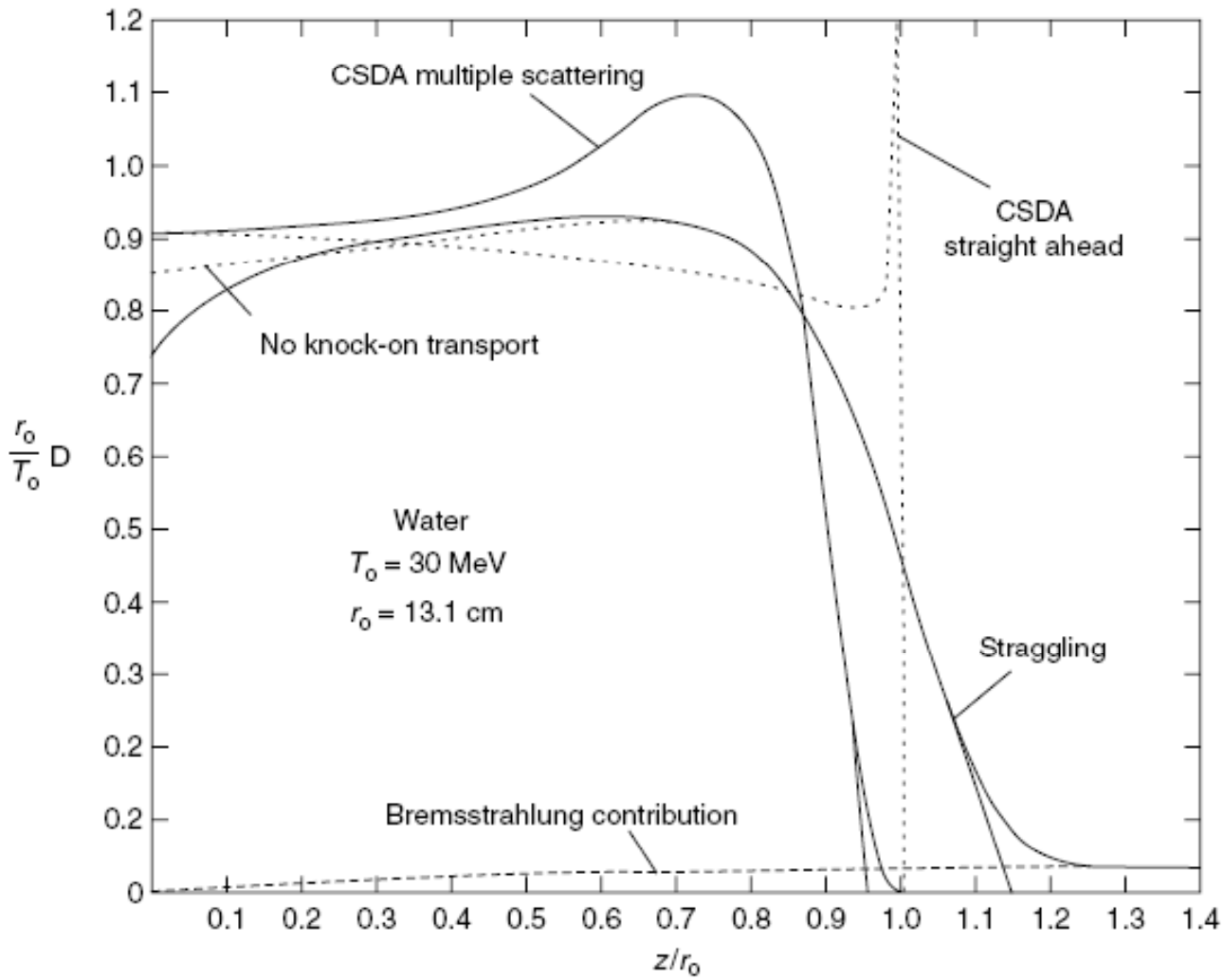
Therefore, the interpretation of detector reading requires dosimetry theory - “cavity theory”



$$f(\mathrm{Q}) = \left(\frac{D_{\mathrm{med}}}{D_{\mathrm{det}}} \right)_{\mathrm{Q}}$$

<u>especially</u> when converting from calibration at Q_1 to measurement at Q_2

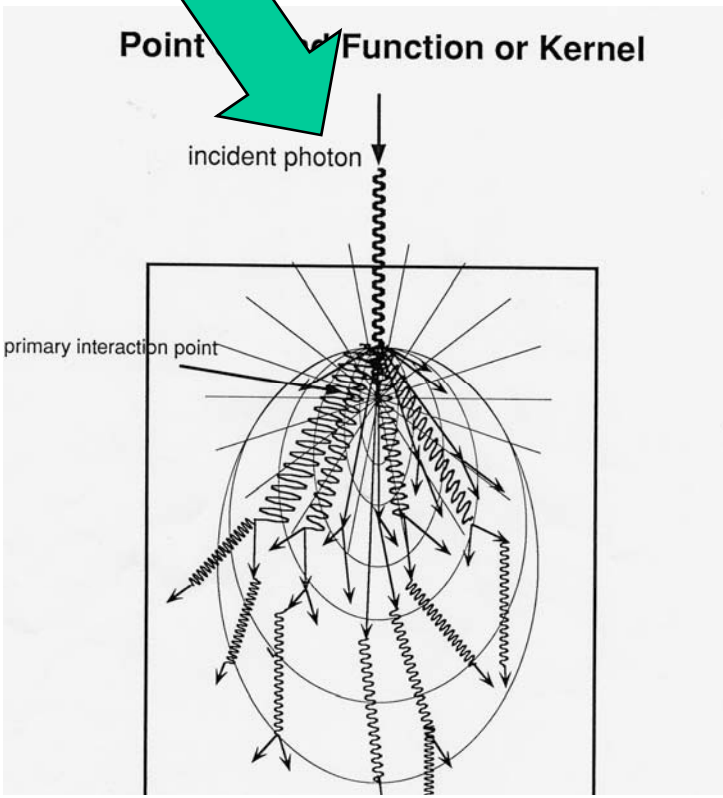
Also the “physics” of depth-dose curves:



Dose computation in a TPS

$$D(x, y, z) = \iiint \frac{\mu}{\rho} \Psi(x', y', z') K(x - x', y - y', z - z') \, dV'$$

Terma
cf. Kerma



First we will remind ourselves of two key results which relate the particle fluence, Φ, to energy deposition in the medium.

Under charged-particle equilibrium (CPE) conditions, the absorbed dose in the medium, D_{med}, is related to the <u>photon</u> (energy) fluence in the medium, $\mathrm{h}\nu\,\Phi_{\text{med}}$, by

$$D_{\text{med}} \overset{\text{CPE}}{=} \left(K_{\text{c}}\right)_{\text{med}} = \mathrm{h}\nu\,\Phi_{\text{med}} \left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{med}}$$

for monoenergetic photons of energy $\mathrm{h}\nu$, and by

$$D_{\text{med}} \overset{\text{CPE}}{=} \int_0^{h\nu_{\max}} h\nu \, \frac{\mathrm{d}\Phi_{\text{med}}}{\mathrm{d}\mathrm{h}\nu} \left(\frac{\mu_{\text{en}}(\mathrm{h}\nu)}{\rho}\right)_{\text{med}} \mathrm{d}\mathrm{h}\nu$$

for a spectrum of photon energies, where $(\mu_{\text{en}}/\rho)_{\text{med}}$ is the mass-energy absorption coefficient for the medium in question.

For <u>charged particles</u> the corresponding expressions are:

$$D_{\text{med}} \overset{\delta-\text{eqm.}}{=} \Phi_{\text{med}} \left(\frac{S_{\text{col}}}{\rho} \right)_{\text{med}}$$

where $(S_{col}/\rho)_{med}$ is the (unrestricted) electron mass collision stopping power for the medium.

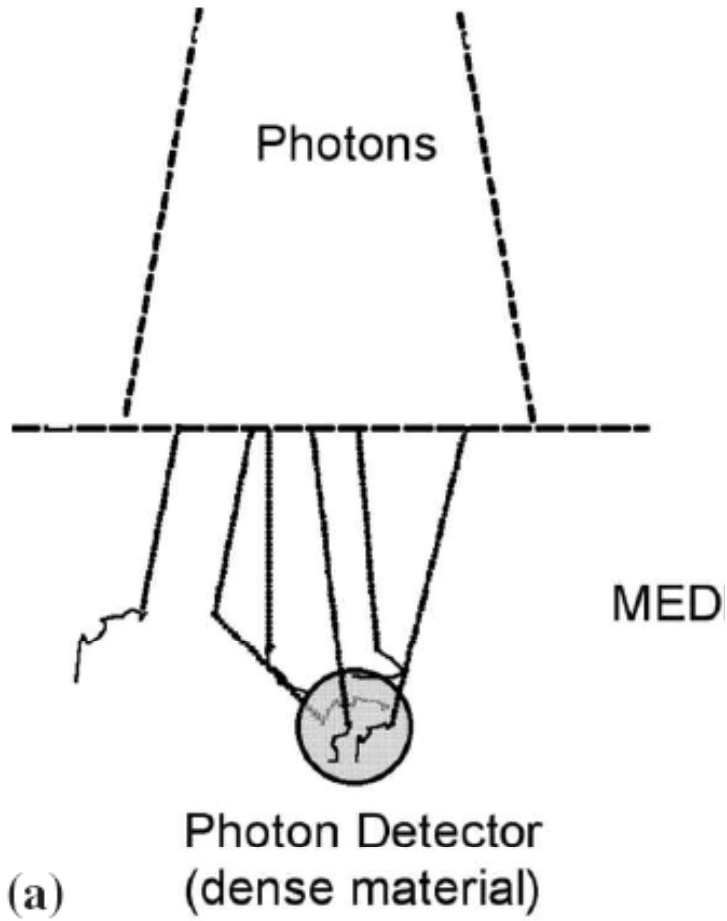
and for a spectrum of electron energies:

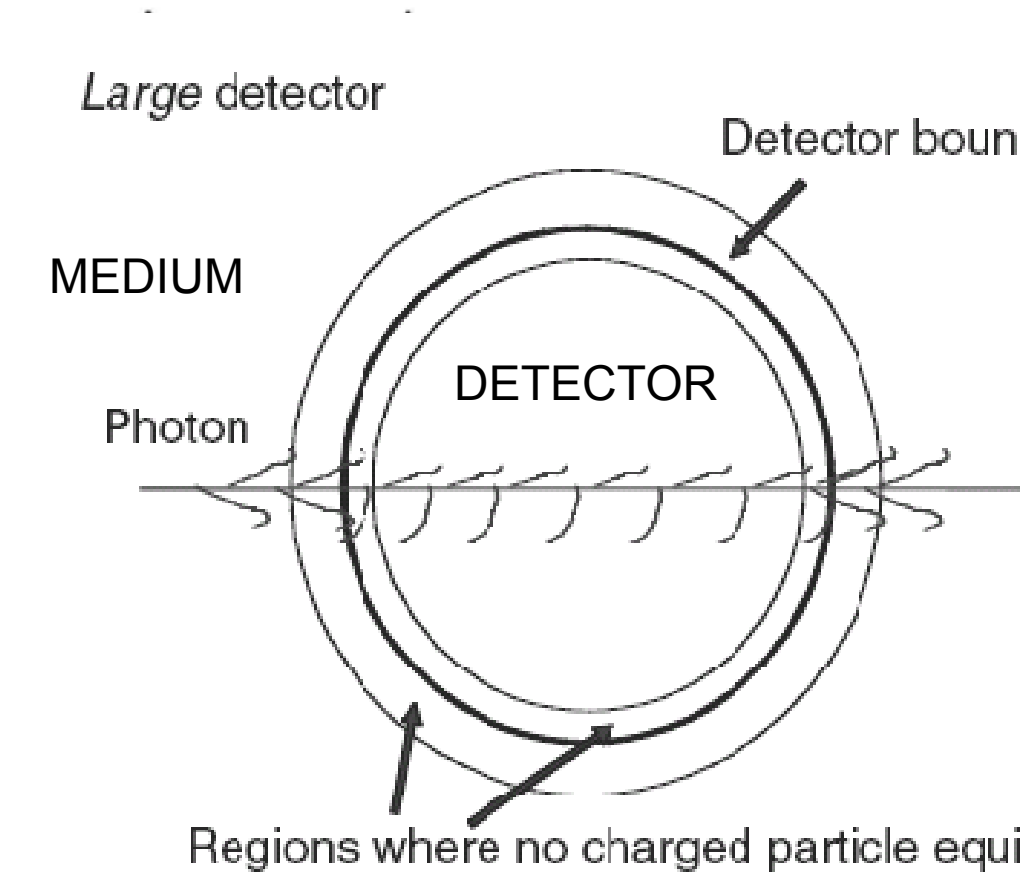
$$D_{\text{med}} \overset{\delta-\text{eqm.}}{=} \int_0^{E_{\max}} \frac{\mathrm{d}\Phi_{\text{med}}}{\mathrm{d}E} \left(\frac{S_{\text{col}}(E)}{\rho} \right)_{\text{med}} \mathrm{d}E$$

Note that in the charged-particle case the requirement is:

δ–ray equilibrium

"Photon" Detectors





$$D_{\mathrm{det}} \overset{\mathrm{CPE}}{=} \left(K_{\mathrm{c}}\right)_{\mathrm{det}} = \mathrm{h}\nu\,\Phi_{\mathrm{med}} \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{det}}$$

Thus for the “photon” detector:

$$D_{\text{det}} \overset{\text{CPE}}{=} \Psi_{\text{det}} \left(\frac{\mu_{\text{en}}}{\rho} \right)_{\text{det}}$$

and for the medium:

$$D_{\text{med}} \overset{\text{CPE}}{=} \Psi_{\text{med}} \left(\frac{\mu_{\text{en}}}{\rho} \right)_{\text{med}}$$

and therefore we can write:

$$f(\text{Q}) = \frac{D_{\text{med},z}}{\overline{D}_{\text{det}}} \overset{\text{CPE}}{=} \frac{\Psi_{\text{med},z} \left(\mu_{\text{en}} / \rho \right)_{\text{med}}}{\Psi_{\text{det}} \left(\mu_{\text{en}} / \rho \right)_{\text{det}}}$$

The key assumption is now made that the photon energy fluence in the detector is *negligibly different from that present in the undisturbed medium at the position of the detector* i.e. $\Psi_{\text{det}} = \Psi_{\text{med},z}$ and thus:

$$f\left(\mathrm{Q}\right) = \frac{D_{\text{med},z}}{\overline{D}_{\text{det}}} = \frac{\left(\mu_{\text{en}} / \rho\right)_{\text{med}}}{\left(\mu_{\text{en}} / \rho\right)_{\text{det}}}$$

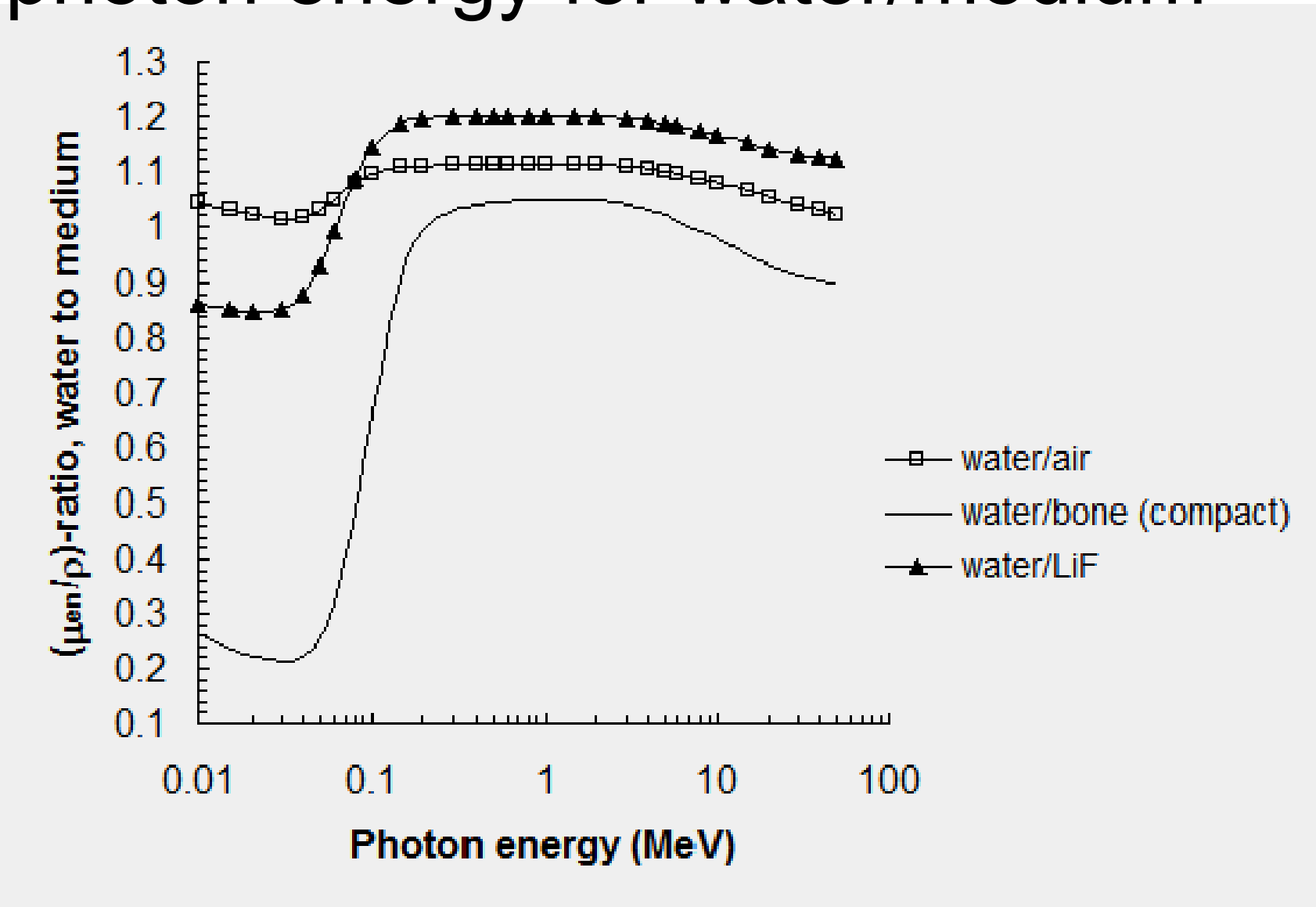
which is the well-known μ_{en}/ρ -ratio usually written as

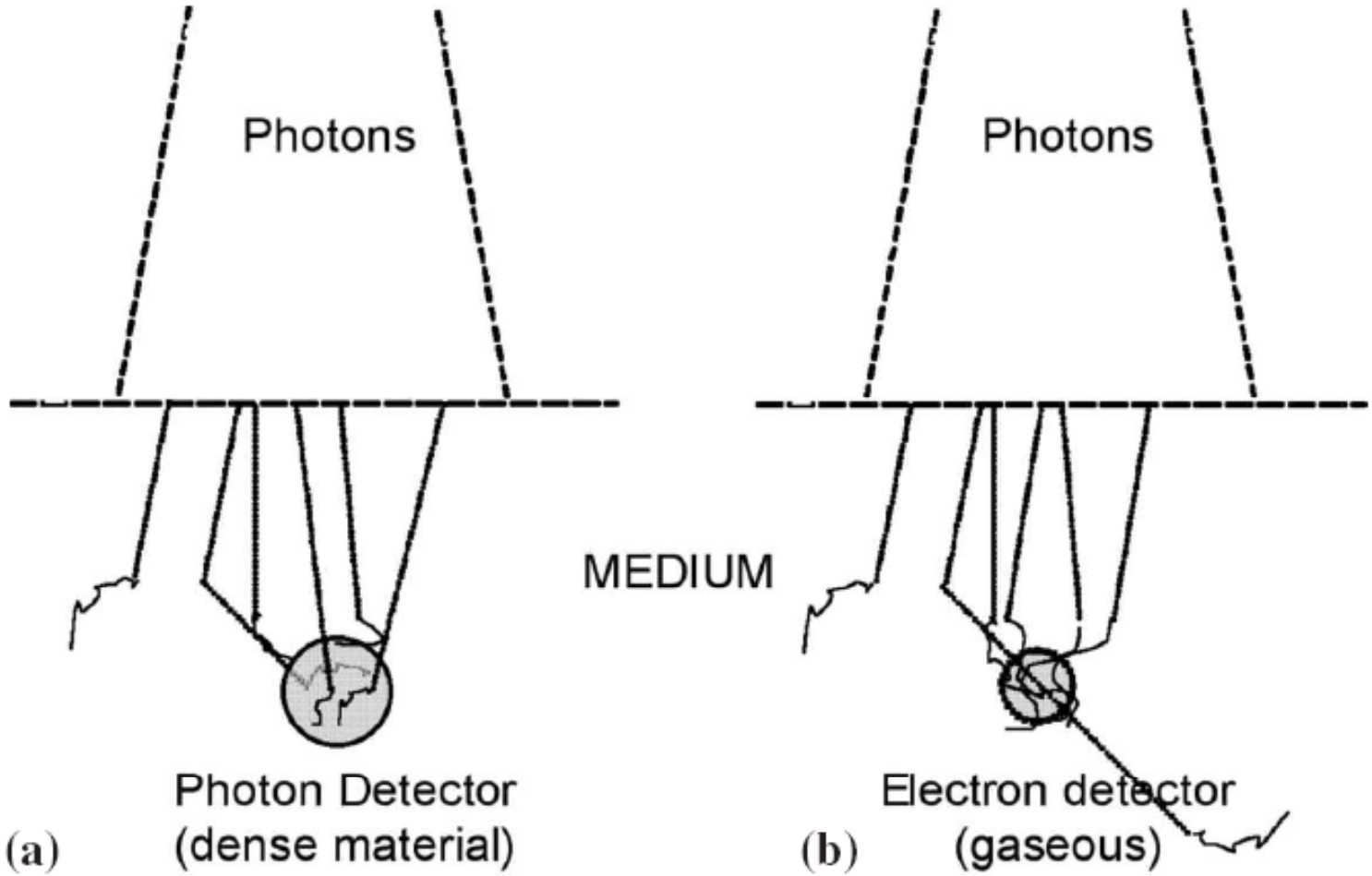
$$f\left(\mathrm{Q}\right) = \left(\frac{\overline{\mu}_{\text{en}}}{\rho}\right)_{\text{det}}^{\text{med}}$$

and finally for a spectrum of photon energies:

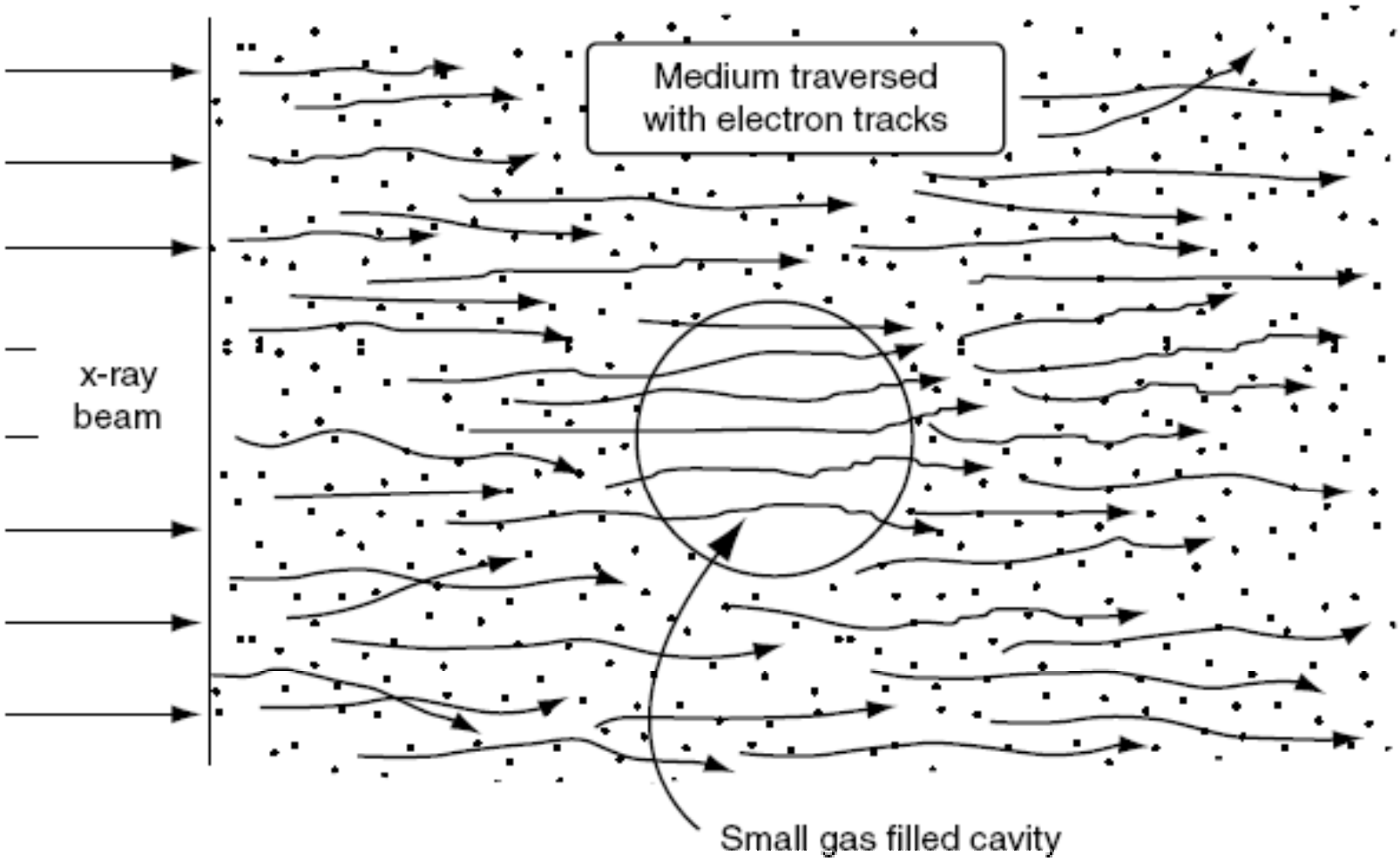
$$\left(\frac{\overline{\mu}_{\text{en}}}{\rho}\right)_{\text{det}}^{\text{med}} = \frac{\int_0^{E_{\max}} E_{\text{h}\nu} \frac{\mathrm{d}\Phi_{\text{med},z}}{\mathrm{d}E} \left(\frac{\mu_{en}(E)}{\rho}\right)_{\text{med}} \mathrm{d}E}{\int_0^{E_{\max}} E_{\text{h}\nu} \frac{\mathrm{d}\Phi_{\text{med},z}}{\mathrm{d}E} \left(\frac{\mu_{en}(E)}{\rho}\right)_{\text{det}} \mathrm{d}E}$$

The dependence of the μ_{en}/ρ -ratio on photon energy for water/medium

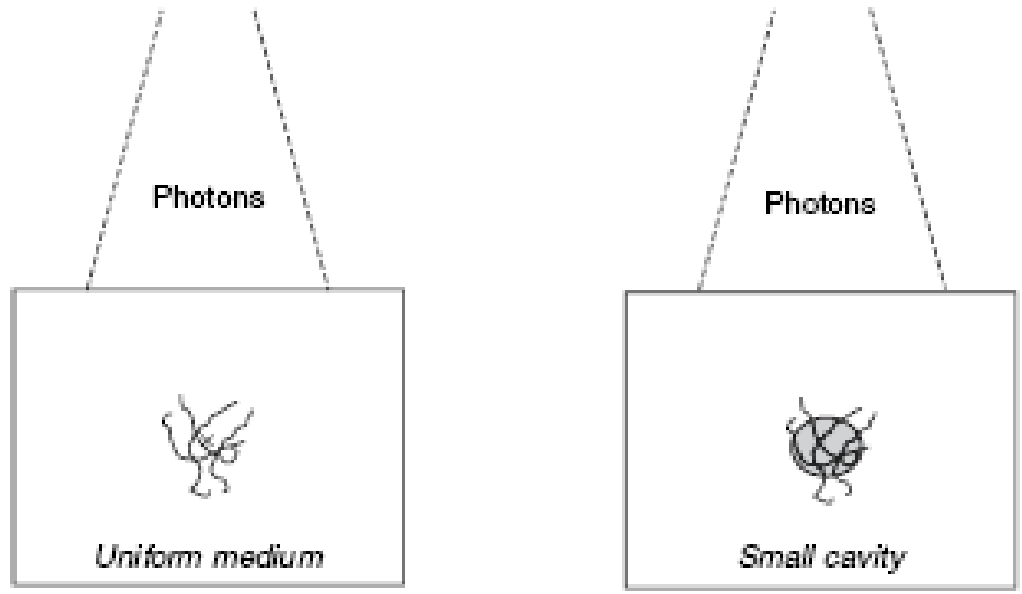




“Electron” detectors (Bragg-Gray)


Medium traversed
with electron tracks
x-ray
beam
Small gas filled cavity

BRAGG-GRAY CAVITY THEORY



We have seen that in the case of detectors with sensitive volumes large enough for the establishment of CPE, the ratio D_{med}/D_{det} is given by $(\mu_{en}/\rho)_{med,det}$ for the case of indirectly ionizing radiation. In the case of charged particles one requires an analogous relation in terms of stopping powers. If we assume that the electron fluences in the detector and at the same depth in the medium are given by Φ_{det} and Φ_{med} respectively, then according to Equ. 43 we must be able to write

$$\frac{D_{med}}{\overline{D}_{det}} = \frac{\Phi_{med}(S_{col}/\rho)_{med}}{\Phi_{det}(S_{col}/\rho)_{det}} \tag{45}$$

From equation (3.3a), the ratio of dose in the medium at some depth z, $D_{med,z}$, to dose in the detector (gas) can be written as

$$\frac{D_{med\,z}}{\overline{D}_{gas}} = \frac{\Phi^{e^-}_{med\,z}\left(S_{col}\ /\ \rho\right)_{med\,z}}{\Phi^{e^-}_{gas}\left(S_{col}\ /\ \rho\right)_{gas}}. \tag{3.9}$$

Assuming now that the detector is a *Bragg-Gray cavity* then

$$\Phi^{e^-}_{gas} = \Phi^{e^-}_{med,z} \tag{3.10}$$

and the dose ratio f(Q) becomes

$$\frac{D_{med\,z}}{\overline{D}_{gas}} = \frac{\left(S_{col}\ /\ \rho\right)_{med,z}}{\left(S_{col}\ /\ \rho\right)_{gas}}, \tag{3.11}$$

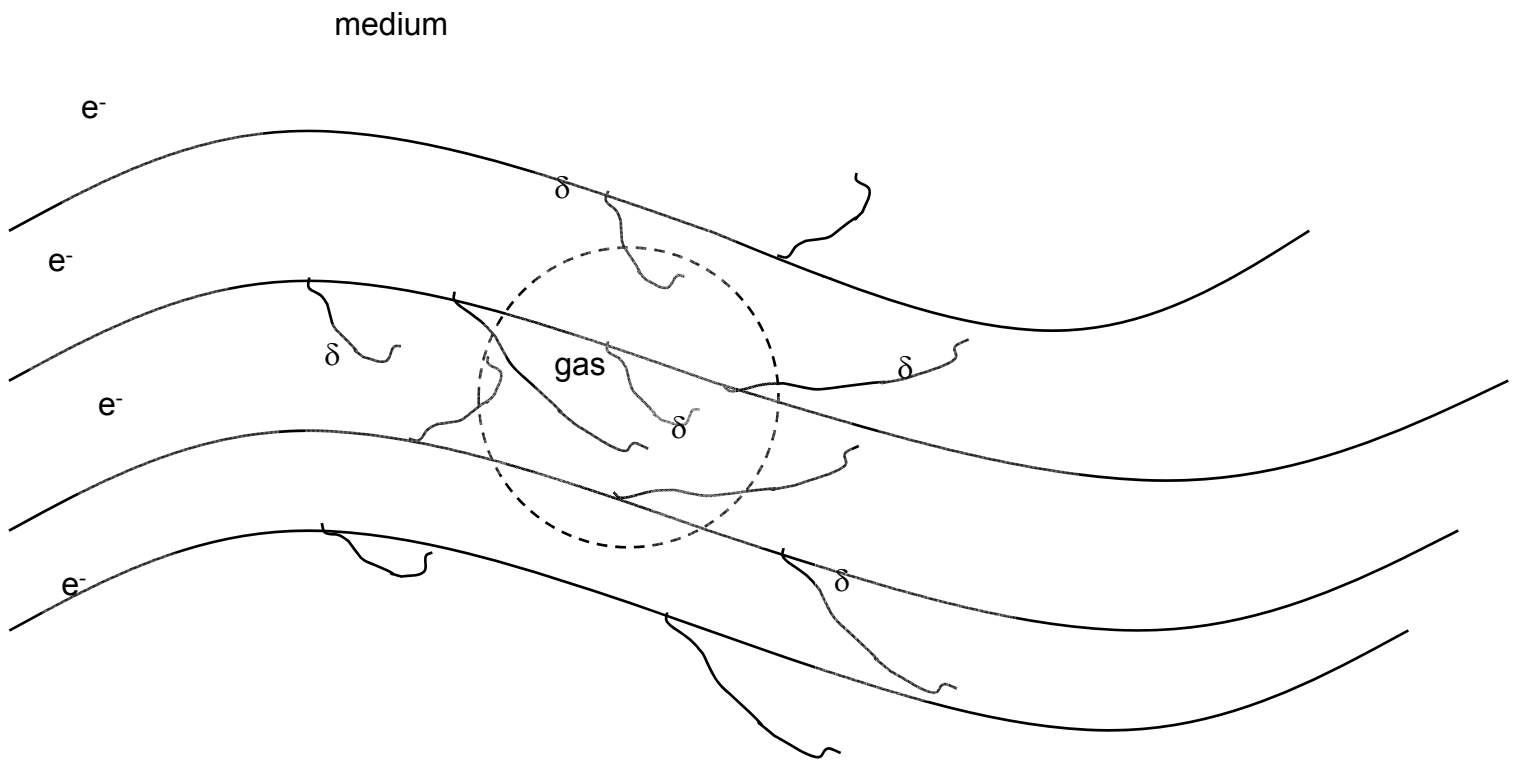
which is known as the (mass) *stopping-power ratio (SPR)*, written simply as $\left(\overline{S}_{col}\ /\ \rho\right)^{med}_{gas}$ or alternatively as $s_{med,gas}$. In practice the secondary electrons at depth

For the more practical case of a spectrum of electron energies, the stopping-power ratio must be evaluated from

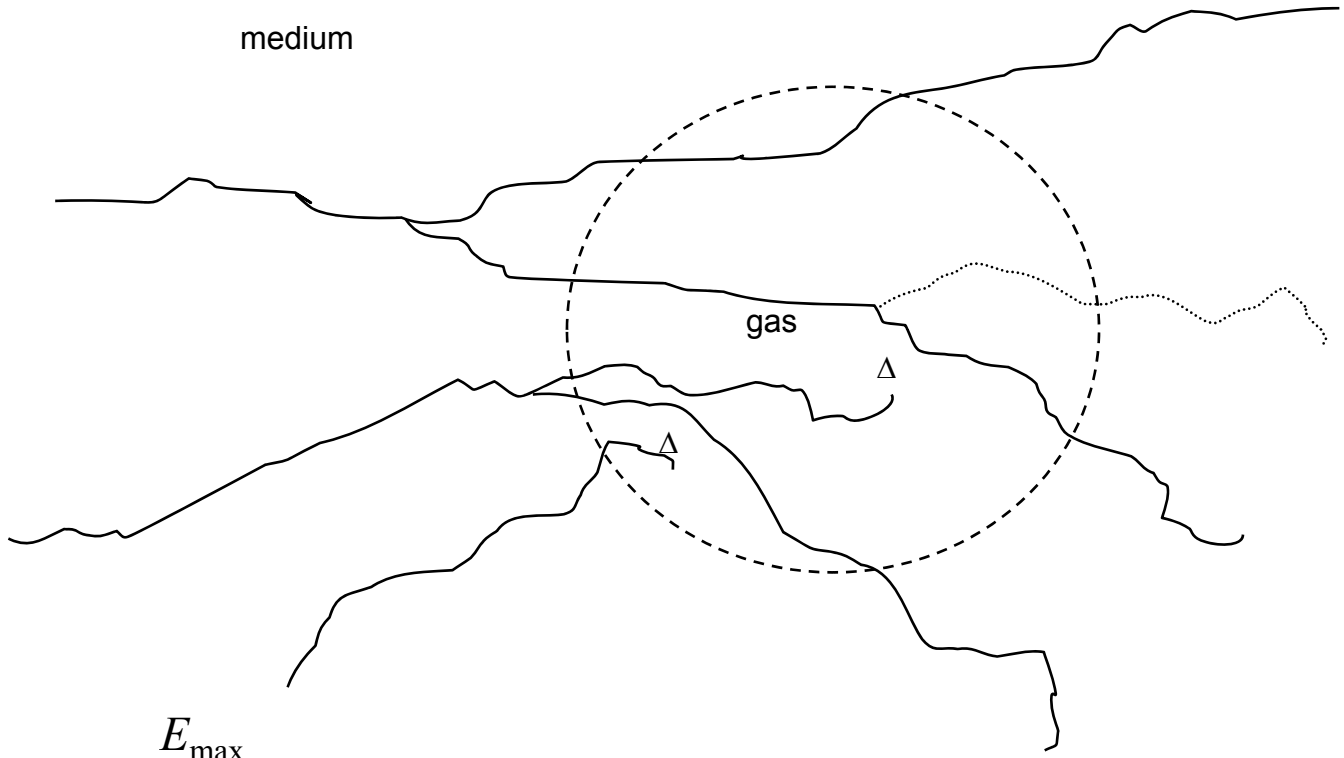
$$\frac{D_{\mathrm{med}}}{\overline{D}_{\mathrm{det}}} = \frac{\int_{0}^{E_{\max}} \Phi_E \, (S_{col}(E) / \rho)_{\mathrm{med}} \, \mathrm{d}E}{\int_{0}^{E_{\max}} \Phi_E \, (S_{col}(E) / \rho)_{\mathrm{det}} \, \mathrm{d}E} \tag{48}$$

where the energy dependence of the stopping powers have been made explicit and it is understood that Φ_E refers to the undisturbed medium in both the numerator and the denominator. It must be stressed that this is the fluence of **primary** electrons only; no delta rays are involved (see next section). For reasons that will become apparent in the next paragraph, it is convenient to denote the stopping-power ratio evaluated according to Equ. 48 by $s^{BG}_{\mathrm{med,det}}$ [12].

The problem with δ-rays



The Spencer-Attix "solution"



$$\frac{D_{\mathrm{med}}}{\overline{D}_{\mathrm{det}}} = \frac{\int_{\Delta}^{E_{\max}} \Phi_E^{\delta}\,(L_{\Delta}(E)/\rho)_{\mathrm{med}}\,\mathrm{d}E + \left[\Phi_E(\Delta)(S_{col}(\Delta)/\rho)_{\mathrm{med}}\,\Delta\right]}{\int_{\Delta}^{E_{\max}} \Phi_E^{\delta}\,(L_{\Delta}(E)/\rho)_{\mathrm{det}}\,\mathrm{d}E + \left[\Phi_E(\Delta)(S_{col}(\Delta)/\rho)_{\mathrm{det}}\,\Delta\right]}$$

In the previous section we have neglected the question of delta-ray equilibrium, which is a pre-requisite for the strict validity of the stopping-power ratio as evaluated in Equ. 43. The original Bragg-Gray theory effectively assumed that all collision losses resulted in energy deposition within the cavity. Spencer and Attix proposed an extension of the Bragg-Gray idea that took account, in an approximate manner, of the effect of the finite ranges of the delta rays [11]. All the electrons above a cutoff energy Δ, whether primary or delta rays, were now considered to be part of the fluence spectrum incident on the cavity. All energy losses below Δ in energy were assumed to be local to the cavity and all losses above Δ were assumed to escape entirely. The *local* energy loss was calculated by using the collision stopping power restricted to losses less than Δ, L_Δ (see lecture 3). This 2-component model leads to a stopping-power ratio given by [12,13]:

$$\left(\frac{\overline{L_\Delta}}{\rho}\right)_{gas}^{med} = \frac{\int_\Delta^{E_{\max}} \left(\Phi_E^{tot}(E)\right)_{med} \left[L_\Delta(E)/\rho\right]_{med} \mathrm{d}E + \left\{\Phi_E^{tot}(\Delta)\left[S_{col}(\Delta)/\rho\right]_{med}\Delta\right\}}{\int_\Delta^{E_{\max}} \left(\Phi_E^{tot}(E)\right)_{med} \left[L_\Delta(E)/\rho\right]_{gas} \mathrm{d}E + \left\{\Phi_E^{tot}(\Delta)\left[S_{col}(\Delta)/\rho\right]_{gas}\Delta\right\}}$$

BRAGG-GRAY CAVITY

The Stopping-Power Ratio $s_{med,\,det}$:

$$\frac{D_{\mathrm{med}}}{\overline{D}_{\mathrm{det}}} = \frac{\int_{\mathrm{o}}^{E_{\max}} \Phi_E \, (S_{col}(E)/\rho)_{\mathrm{med}} \, \mathrm{d}E}{\int_{\mathrm{o}}^{E_{\max}} \Phi_E \, (S_{col}(E)/\rho)_{\mathrm{det}} \, \mathrm{d}E}$$

The Spencer-Attix formulation:

$$\frac{D_{\mathrm{med}}}{\overline{D}_{\mathrm{det}}} = \frac{\int_{\Delta}^{E_{\max}} \Phi_E^{\delta} \, (L_{\Delta}(E)/\rho)_{\mathrm{med}} \, \mathrm{d}E + \left[\Phi_E(\Delta)(S_{col}(\Delta)/\rho)_{\mathrm{med}} \Delta\right]}{\int_{\Delta}^{E_{\max}} \Phi_E^{\delta} \, (L_{\Delta}(E)/\rho)_{\mathrm{det}} \, \mathrm{d}E + \left[\Phi_E(\Delta)(S_{col}(\Delta)/\rho)_{\mathrm{det}} \Delta\right]}$$

When is a cavity "Bragg-Gray?

In order for a detector to be treated as a Bragg–Gray (B–G) cavity there is really only one condition which must be fulfilled:

– *The cavity must not disturb the charged particle fluence (including its distribution in energy) existing in the medium in the absence of the cavity.*

In practice this means that the cavity must be <u>small</u> compared to the electron ranges, and in the case of photon beams, only gas-filled cavities, i.e. ionisation chambers, fulfil this.

A second condition is generally added:

The absorbed dose in the cavity is deposited entirely by the charged particles crossing it.

This implies that any contribution to the dose due to *photon* interactions in the cavity must be negligible. Essentially it is a corollary to the first condition. If the cavity is small enough to fulfil the first condition then the build-up of dose due to interactions in the cavity material itself must be negligible; if this is not the case then the charged particle fluence will differ from that in the undisturbed medium for this very reason.

A third condition is sometimes **erroneously** added:

Charged Particle Equilibrium must exist in the absence of the cavity.

Greening (1981) wrote that Gray's original theory required this. In fact, this "condition" is **incorrect** but there are historical reasons for finding it in old publications.

CPE is **not** required but what *is* required, however, is that the stopping-power ratio be evaluated over the charged-particle (i.e. electron) spectrum in the medium at the position of the detector.

Gray and other early workers invoked this CPE condition because they did not have the theoretical tools to evaluate the electron fluence spectrum (Φ_E in the above expressions) unless there was CPE. (but today we can do this using MC methods).

Do air-filled ionisation chambers function as Bragg-Gray cavities at KILOVOLTAGE X-ray qualities?

Ma C-M and Nahum AE 1991 Bragg-Gray theory and ion chamber dosimetry for photon beams *Phys. Med. Biol.* **36** 413-428

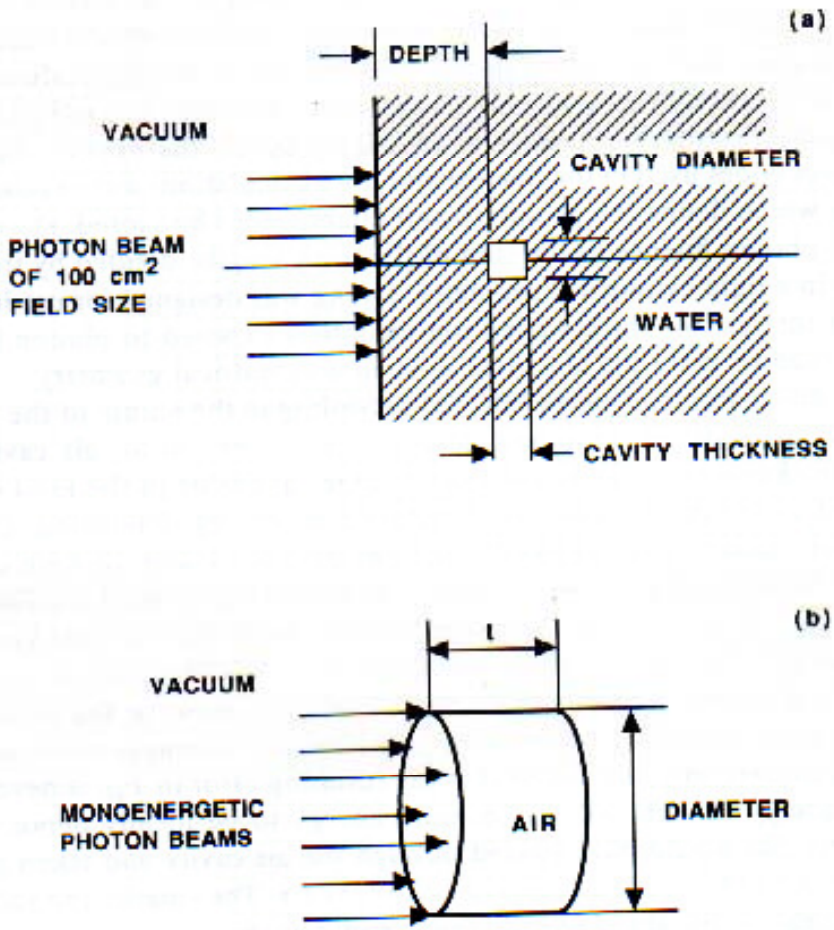


Figure 2. Schematic illustration of the geometry for the Monte Carlo calculation of the absorbed dose in a small air cavity placed (*a*) in water and (*b*) in vacuum. The thickness of the water volume is 40 cm and the field size of the incident photon beam is confined to 100 cm². The thickness of the air cavity is *t* and the diameter is 6 mm.

Table 1. The dose ratio, F_{air}^{spec}, for an air cavity of 6 mm thickness and 6 mm diameter in vacuum and at a depth of 5 cm in water for some clinical photon beams. The photon beams are characterized by both tube potential and first half-value layer (HVL).

Incident Beam			
Tube potential	HVL (mm Al)	In vacuum	5 cm depth in water
50 kV	1.62	0.26	0.18
150 kV	5.01	0.27	0.29
240 kV	7.30	0.27	0.27
240 kV	17.4	0.18	0.23
^{60}Co		0.0037	0.0060
4 MV		0.0014	0.0098

The commonly used air-filled ionization chamber irradiated by a megavoltage photon beam is the clearest case of a Bragg-Gray cavity. However for typical ion chamber dimensions for kilovoltage x-ray beams, the percentage of the dose to the air in the cavity due to photon interactions in the air is far from negligible as the Table, taken from [9], demonstrates:

Ma C-M and Nahum AE 1991 Bragg-Gray theory and ion chamber dosimetry for photon beams *Phys. Med. Biol.* **36** 413-428

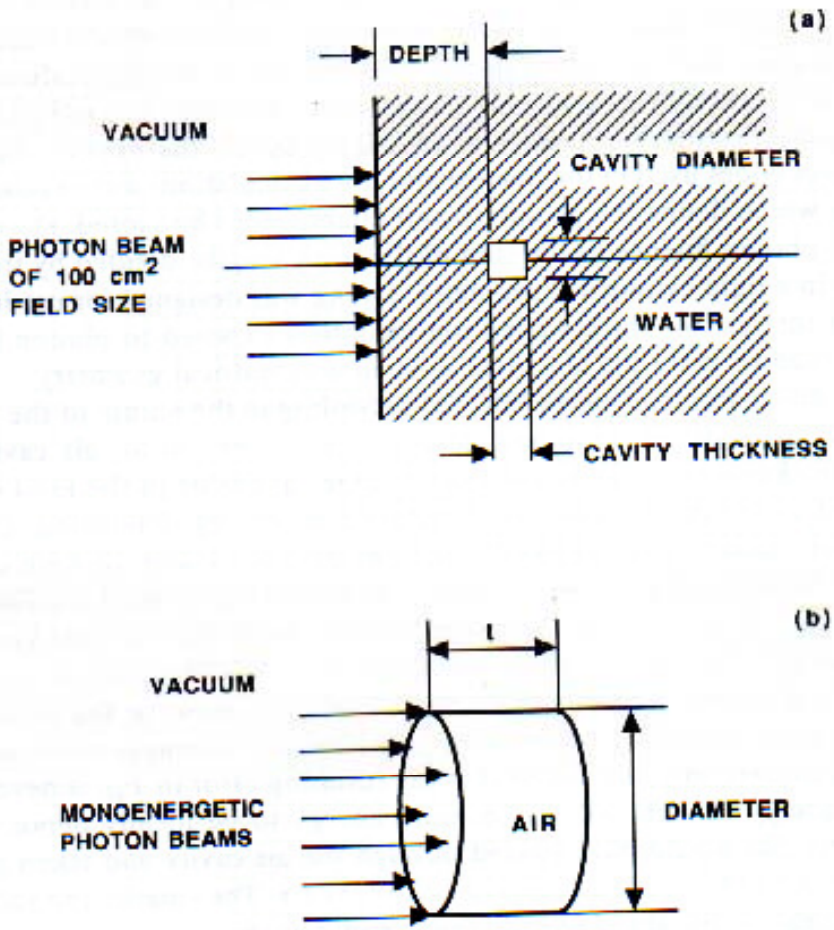
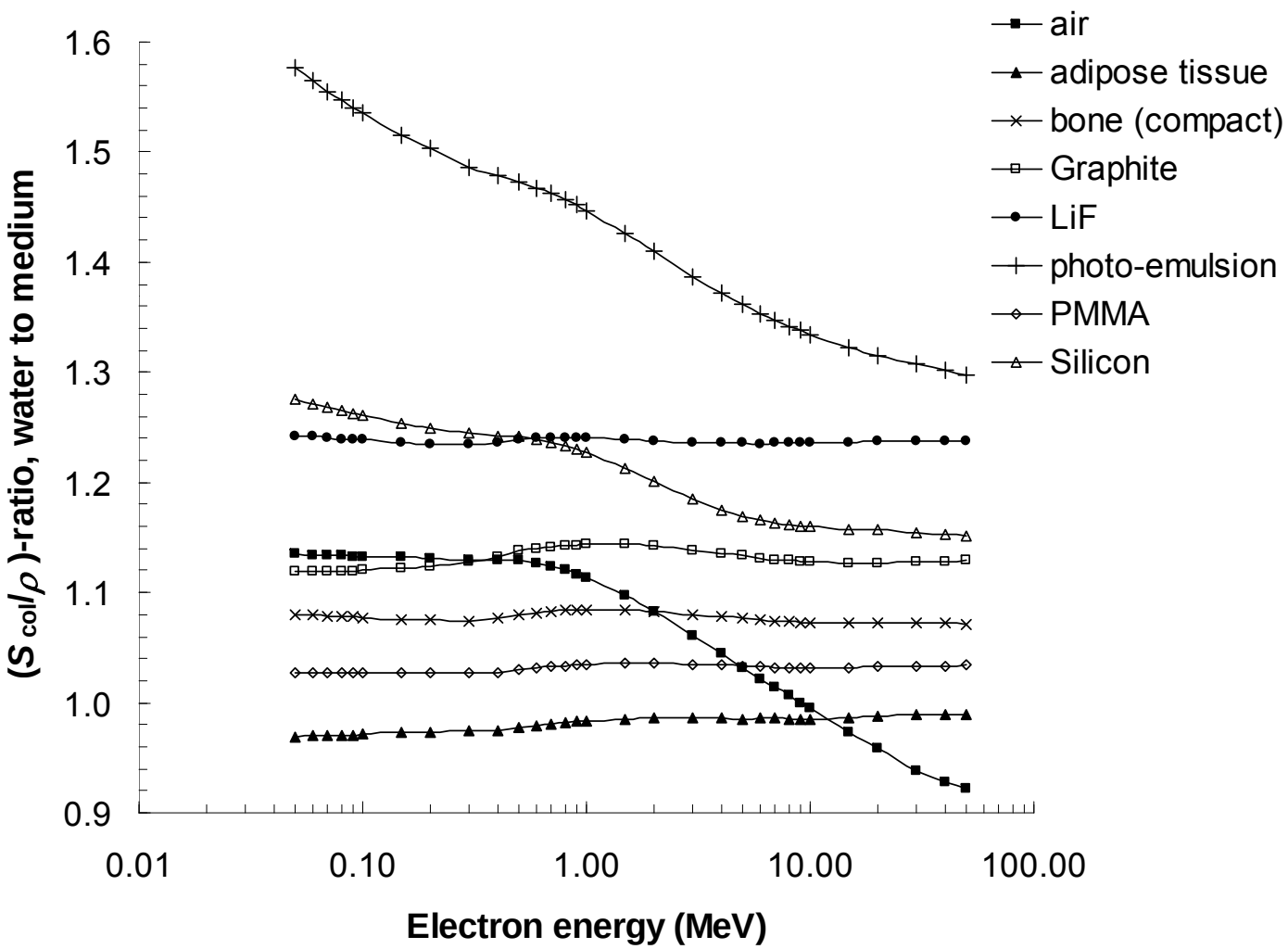
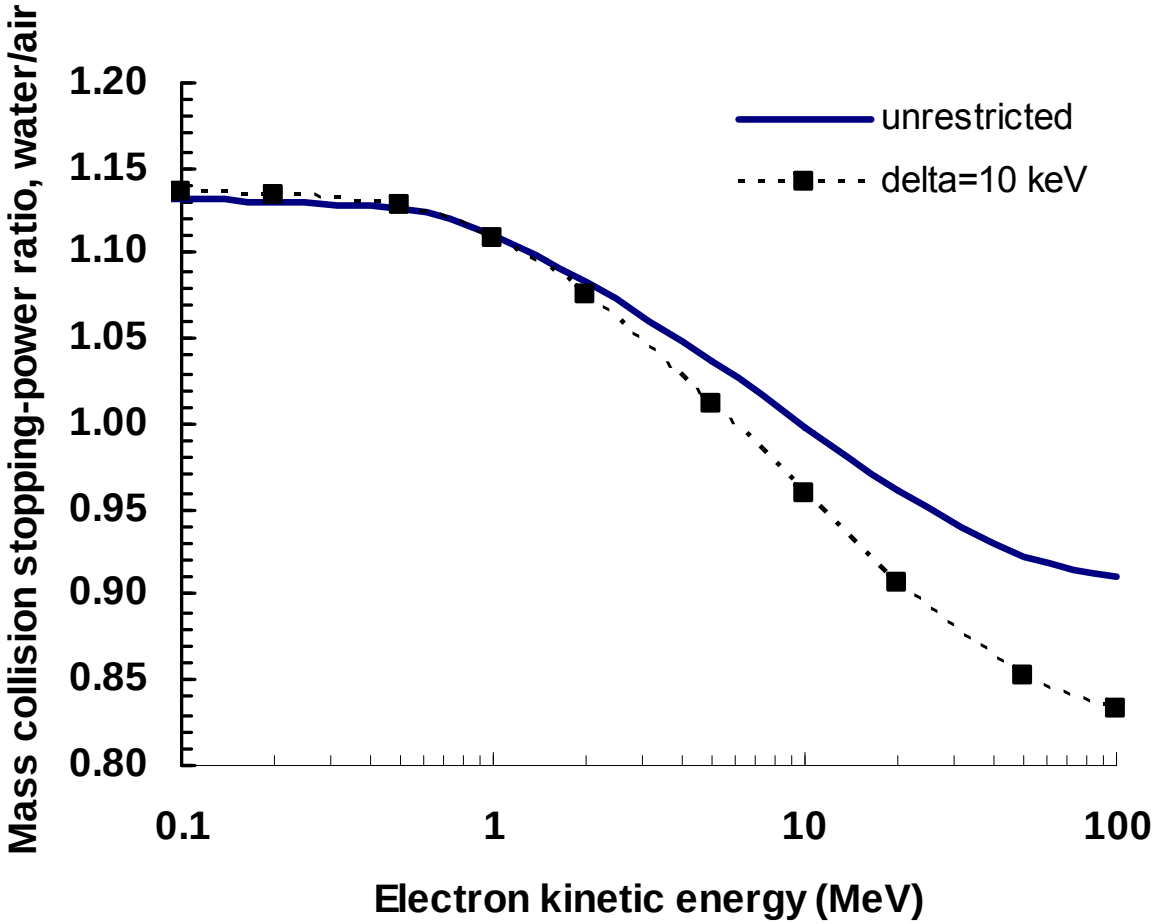


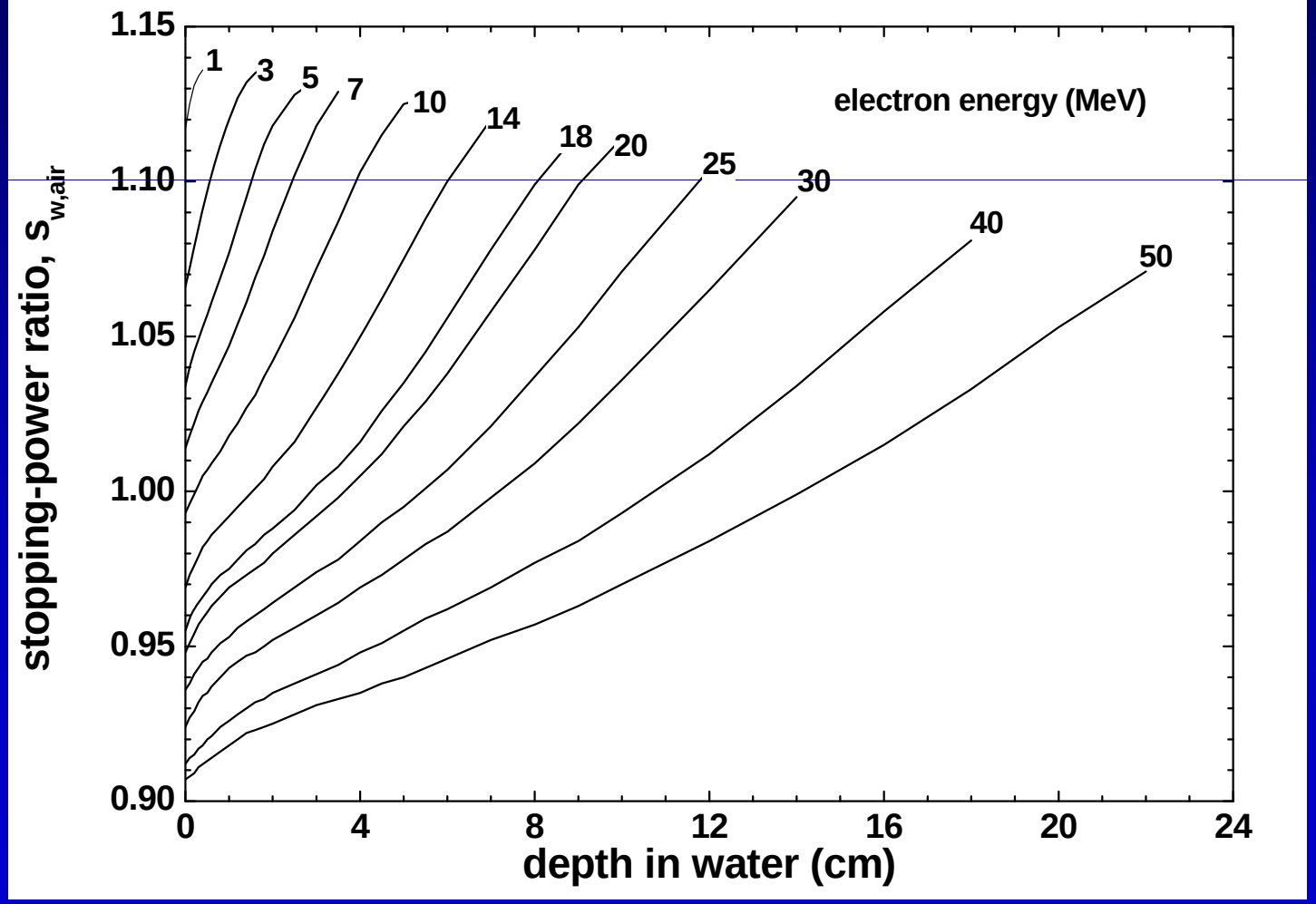
Figure 2. Schematic illustration of the geometry for the Monte Carlo calculation of the absorbed dose in a small air cavity placed (*a*) in water and (*b*) in vacuum. The thickness of the water volume is 40 cm and the field size of the incident photon beam is confined to 100 cm². The thickness of the air cavity is *t* and the diameter is 6 mm.

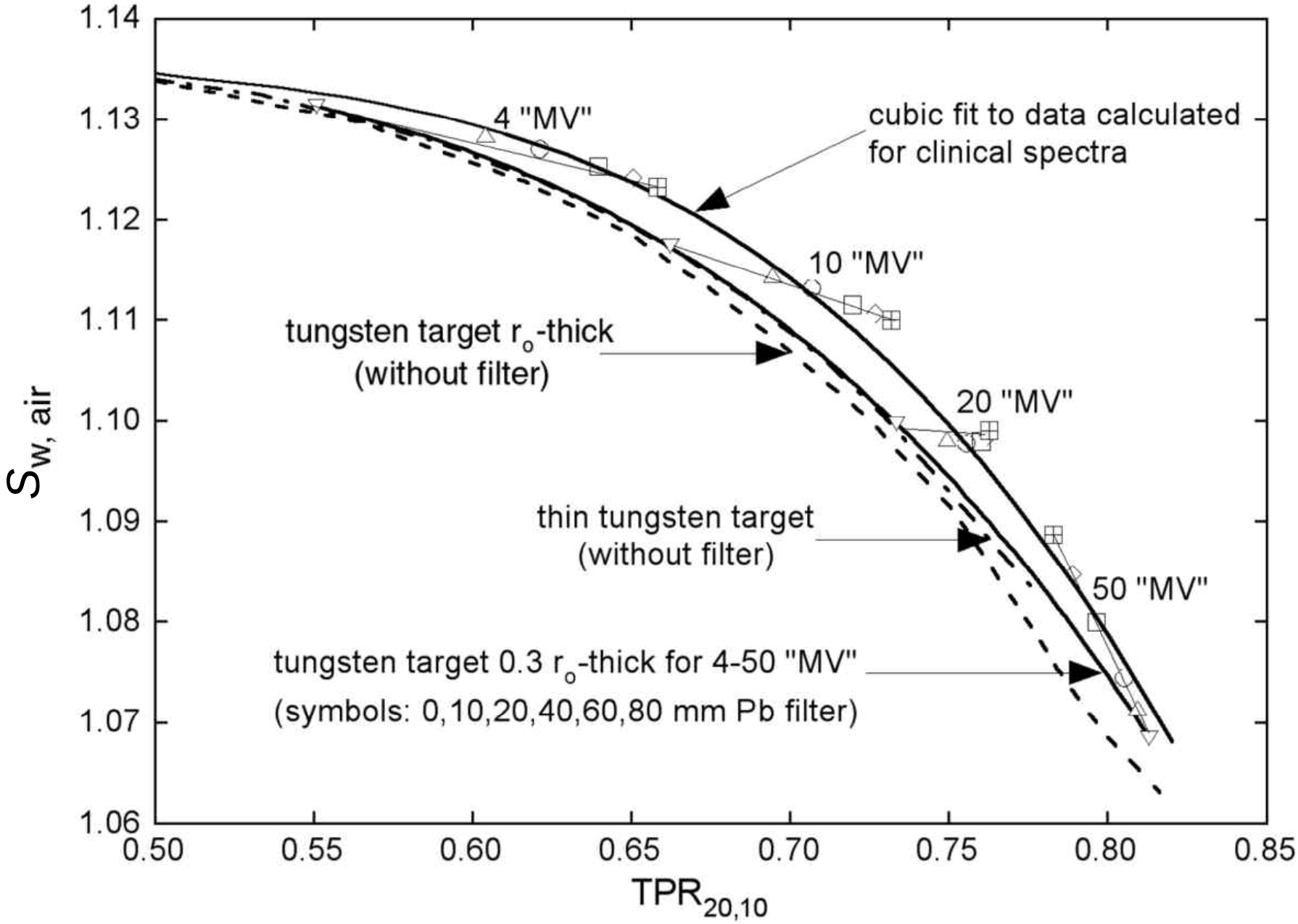
STOPPING-POWER RATIOS

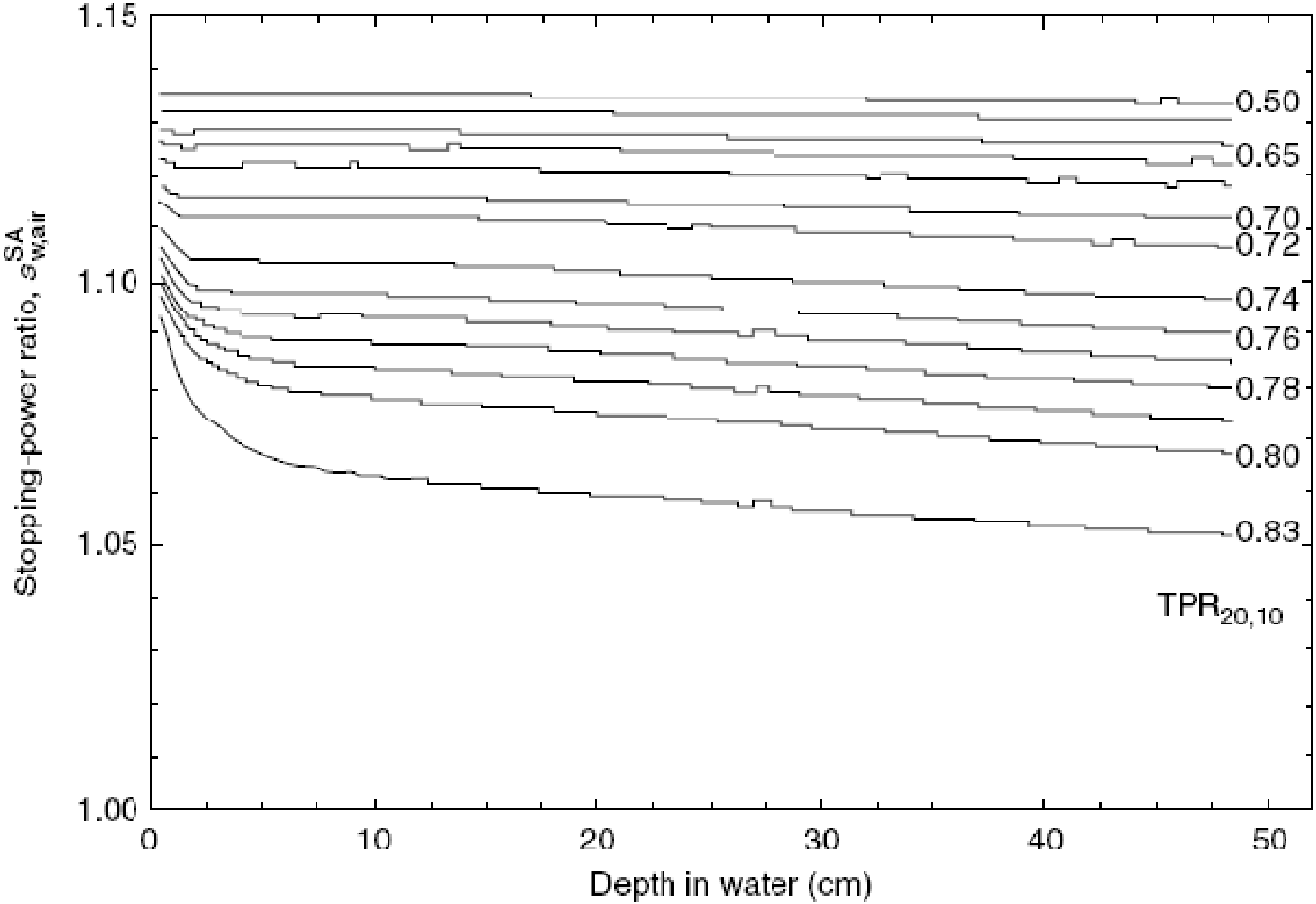

air
adipose tissue
bone (compact)
Graphite
LiF
photo-emulsion
PMMA
Silicon
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
(S col/ρ)-ratio, water to medium
0.01
0.10
1.00
10.00
100.00
Electron energy (MeV)


Mass collision stopping-power ratio, water/air
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.1
1
10
100
Electron kinetic energy (MeV)
unrestricted
delta=10 keV

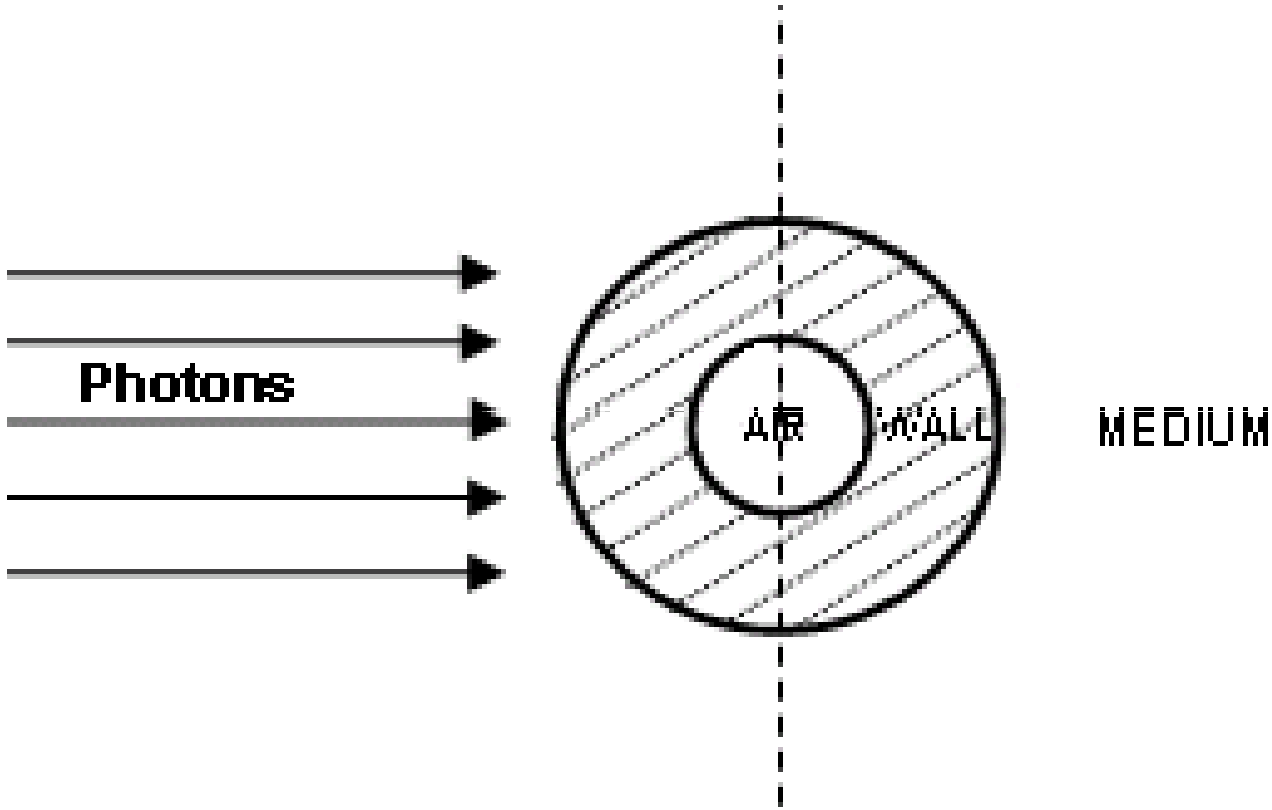
Depth variation of the Spencer-Attix water/air stopping-power ratio, $s_{w,air}$, for Δ=10 keV, derived from Monte Carlo generated electron spectra for monoenergetic, plane-parallel, broad electron beams (Andreo (1990); IAEA (1997b)).




1.14
1.13
1.12
1.11
1.10
1.09
1.08
1.07
1.06
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
$s_{w,\,air}$
$TPR_{20,10}$
4 "MV"
10 "MV"
20 "MV"
50 "MV"
cubic fit to data calculated for clinical spectra
tungsten target r_o-thick (without filter)
thin tungsten target (without filter)
tungsten target 0.3 r_o-thick for 4-50 "MV"
(symbols: 0,10,20,40,60,80 mm Pb filter)


1.15
1.10
1.05
1.00
0
10
20
30
40
50
Depth in water (cm)
Stopping-power ratio, $s^{SA}_{w,air}$
0.50
0.65
0.70
0.72
0.74
0.76
0.78
0.80
0.83
$TPR_{20,10}$

"THICK-WALLED" ION CHAMBERS



$$D_{med}(\mathrm{C}) \overset{\mathrm{CPE}}{=} D_{wall}(\mathrm{C})\left(\frac{\overline{\mu_{en}}}{\rho}\right)_{wall}^{med} \;\&\; D_{wall}(\mathrm{C}) = D_{air}(\mathrm{C})\left(\frac{\overline{L_{\Delta}}}{\rho}\right)_{air}^{wall}$$

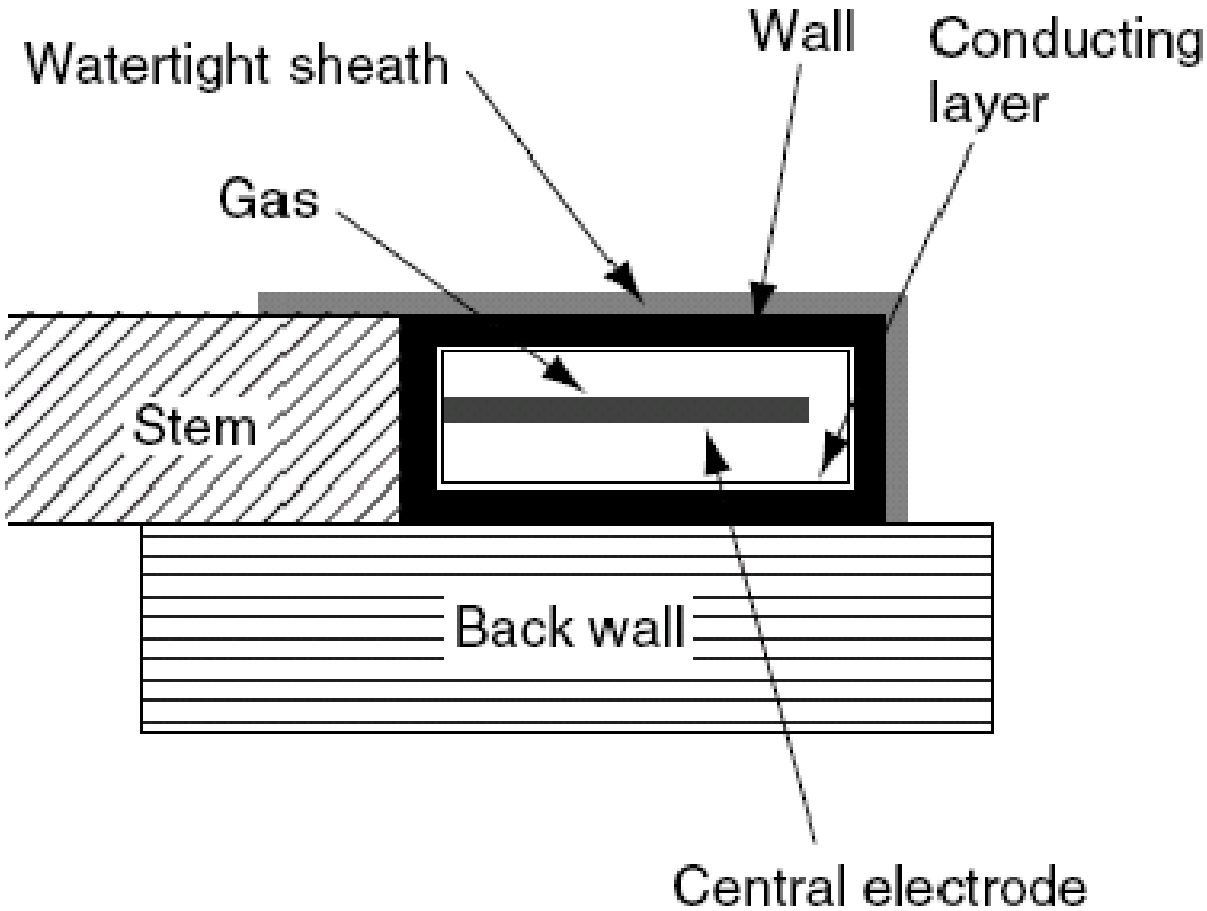
$$f(Q) = \frac{D_{med}(\mathrm{C})}{D_{air}(\mathrm{C})} = \left(\frac{\overline{L_{\Delta}}}{\rho}\right)_{air}^{wall} \left(\frac{\overline{\mu_{en}}}{\rho}\right)_{wall}^{med}$$

Thick-walled cavity chamber free-in-air where the air volume is known precisely (Primary Standards Laboratories):

$$K_{air}(C) = \frac{\overline{D_{air}}}{1 - g_{air}} \left(\frac{\overline{L_{\Delta}}}{\rho}\right)_{air}^{wall} \left(\frac{\overline{\mu_{en}}}{\rho}\right)_{wall}^{air} K'$$

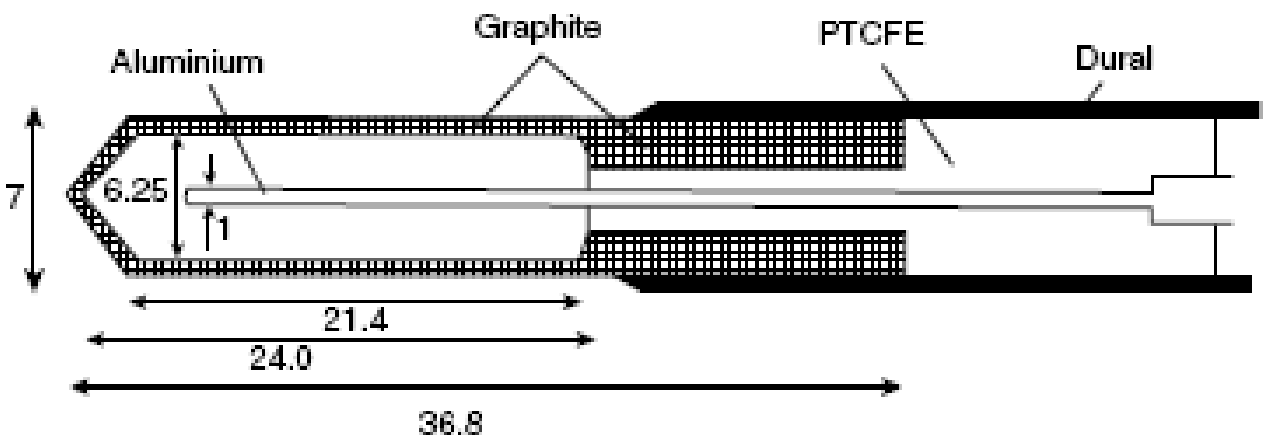
CORRECTION FACTORS FOR ION CHAMBERS (measurements in phantom)

Are real, practical Ion Chambers really Bragg-Gray cavities?



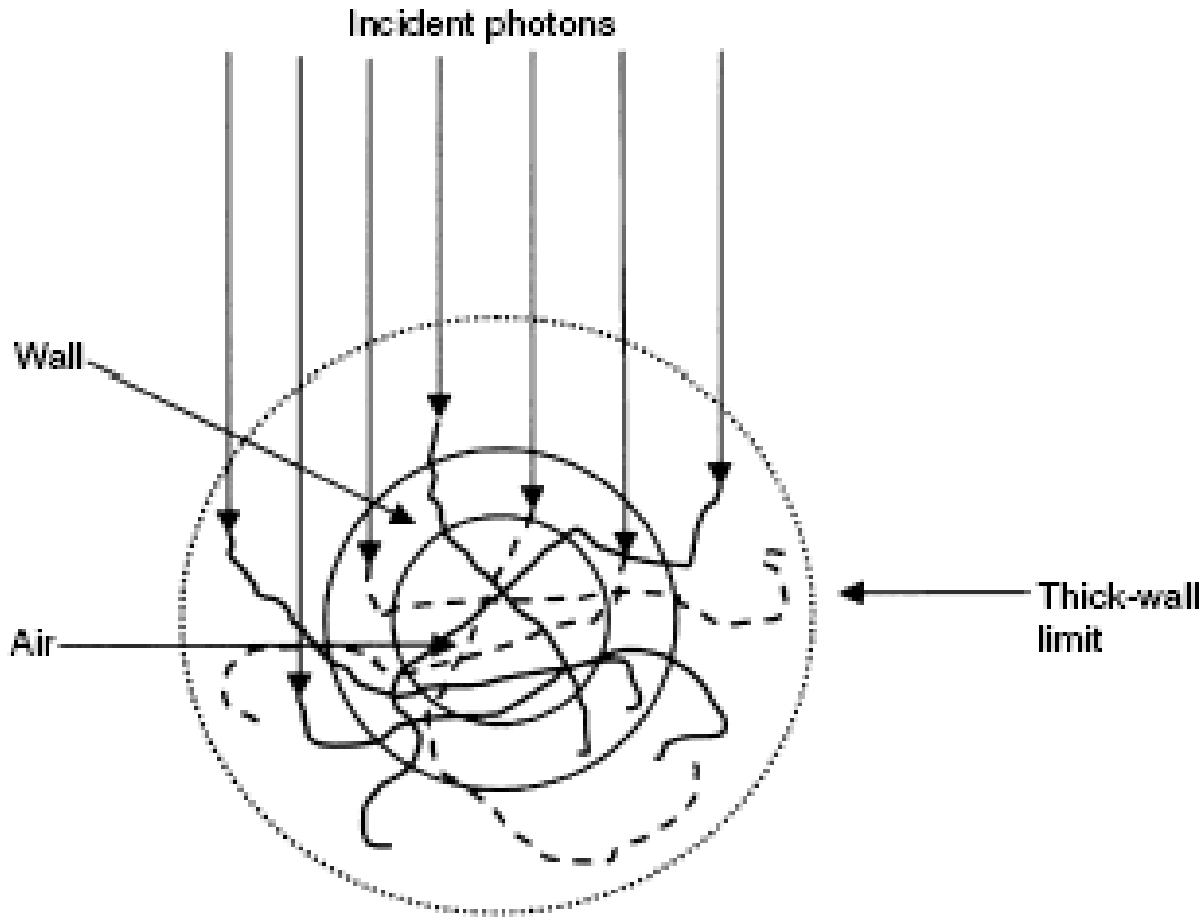
$$D_{med,C}(Q) = \overline{D}_{air}\left(\overline{L_\Delta} / \rho\right)_{air}^{med} \prod_i P_i$$

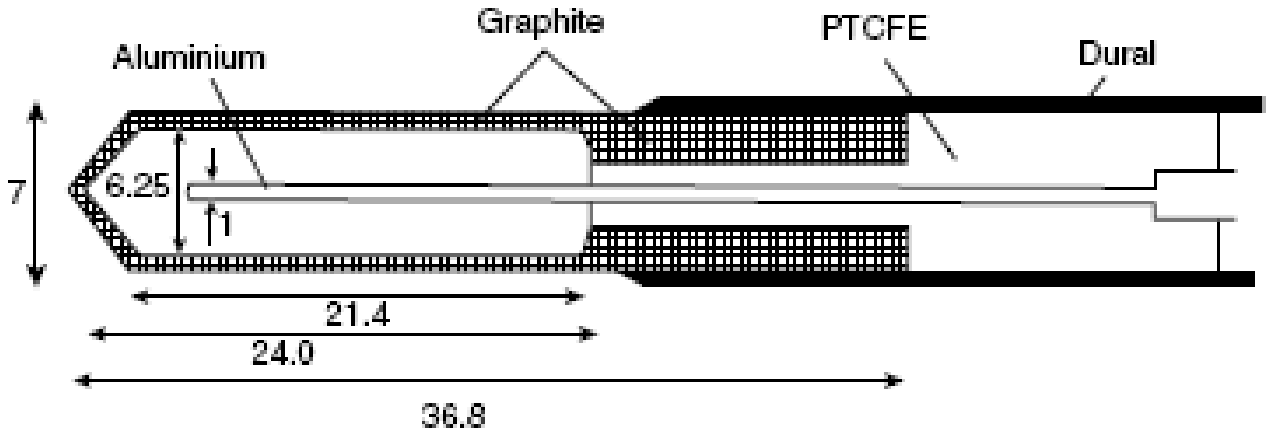
$$D_{med,C}(Q) = \overline{D}_{air}\left(\overline{L_\Delta} / \rho\right)_{air}^{med} P_{repl} P_{wall} P_{cel} P_{stem}$$



FARMER chamber (distances in millimetres)

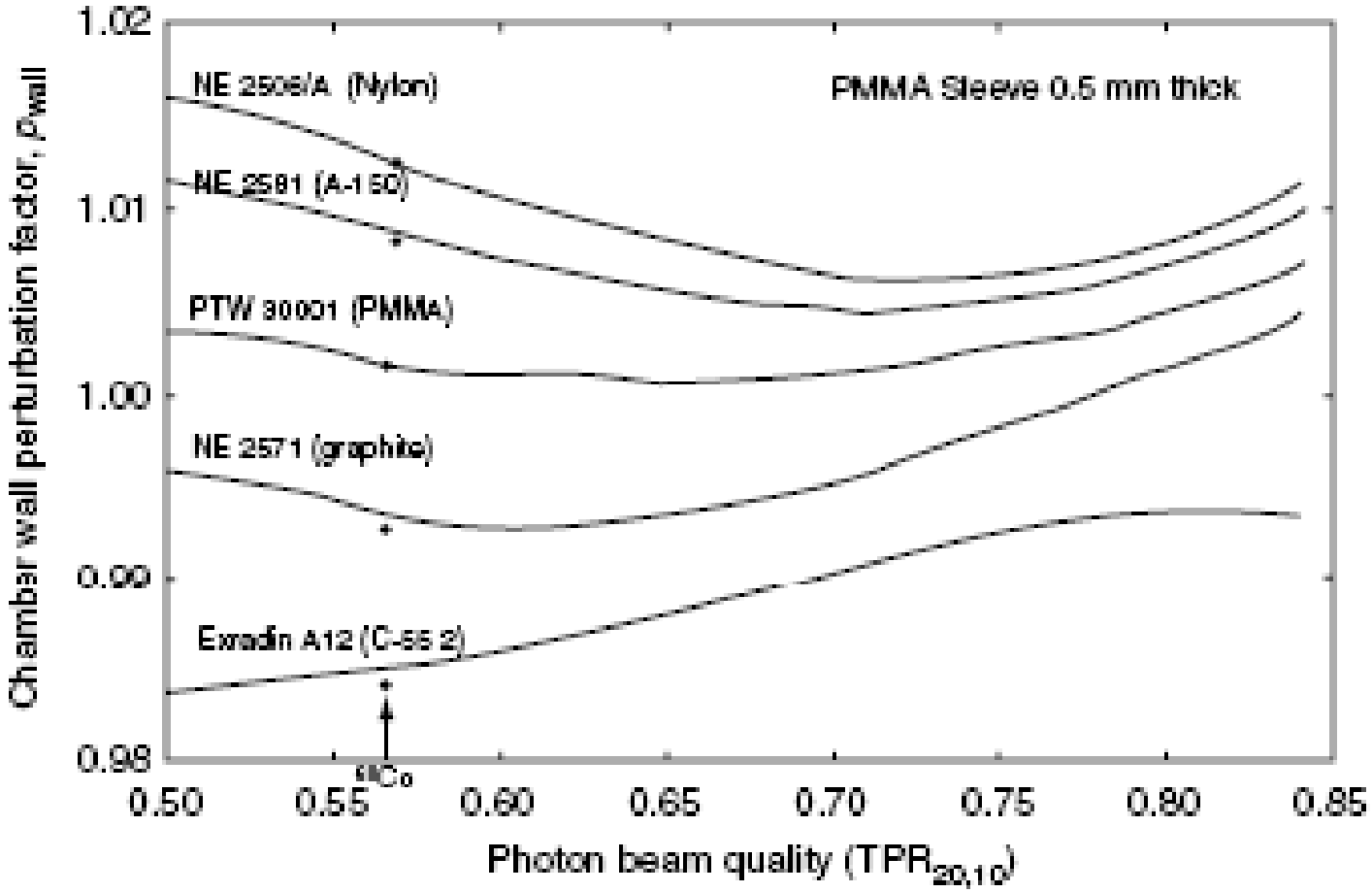
THE EFFECT OF THE CHAMBER WALL

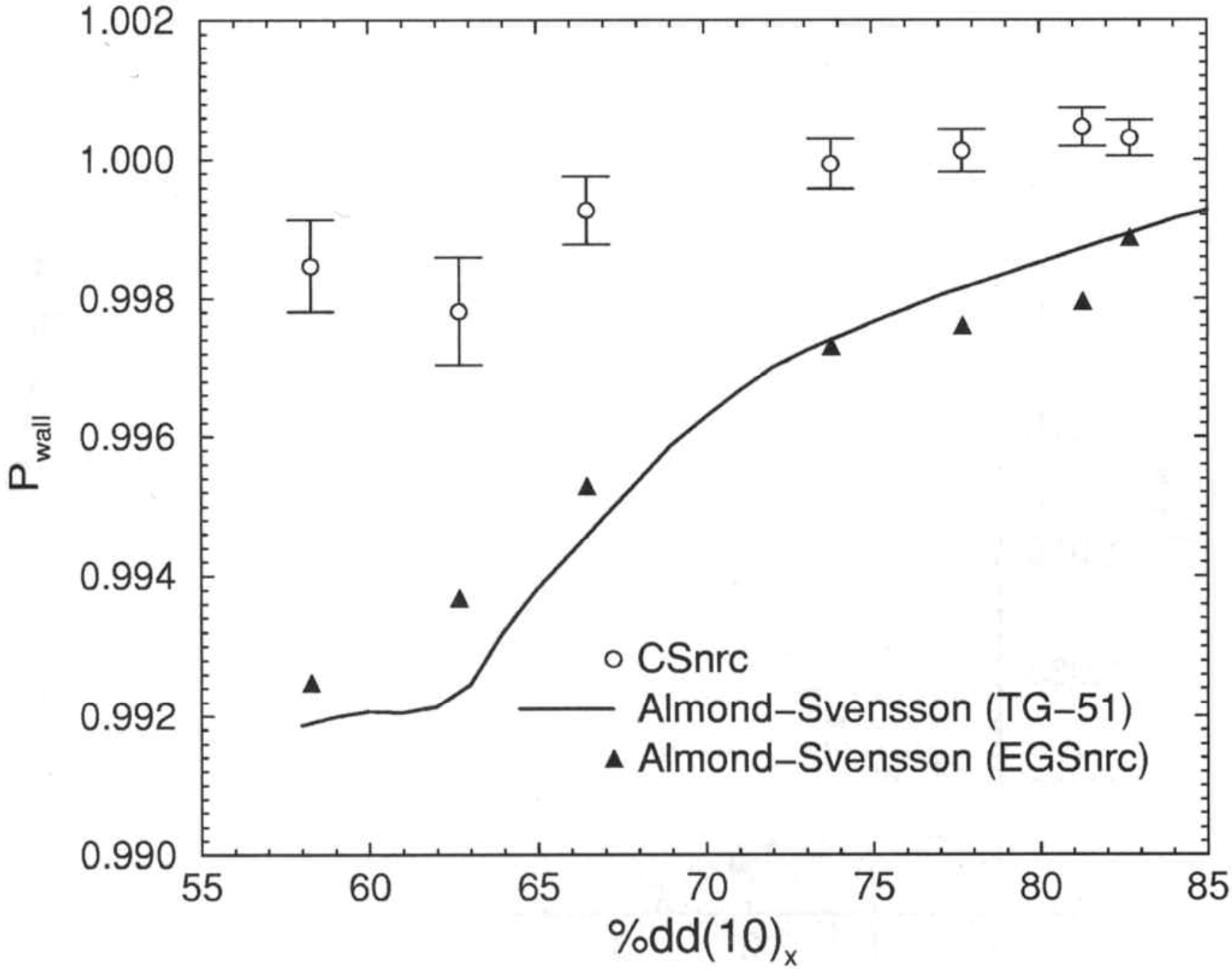

Incident photons
Wall
Air
Thick-wall
limit



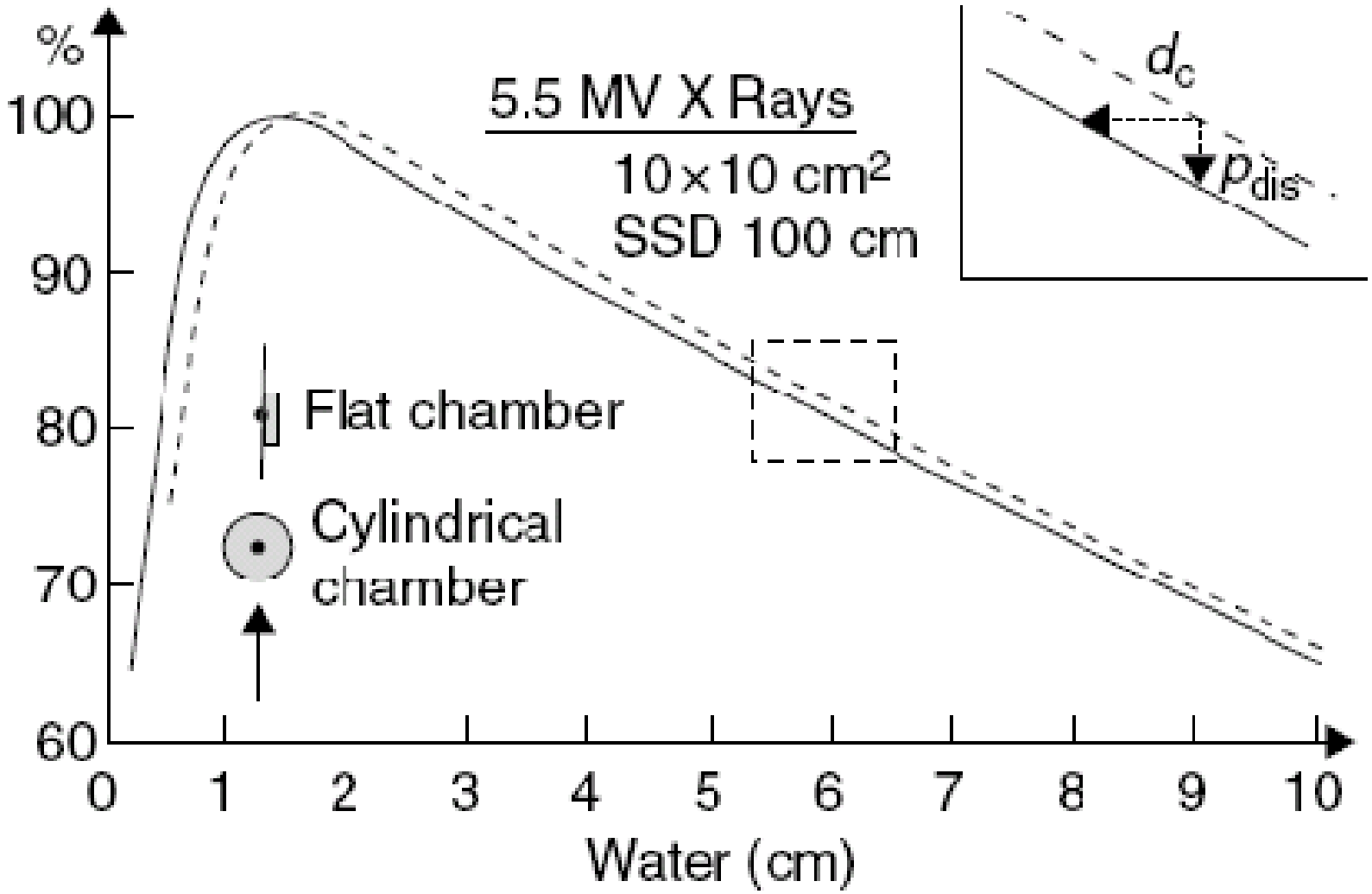
The Almond-Svensson (1977) expression:

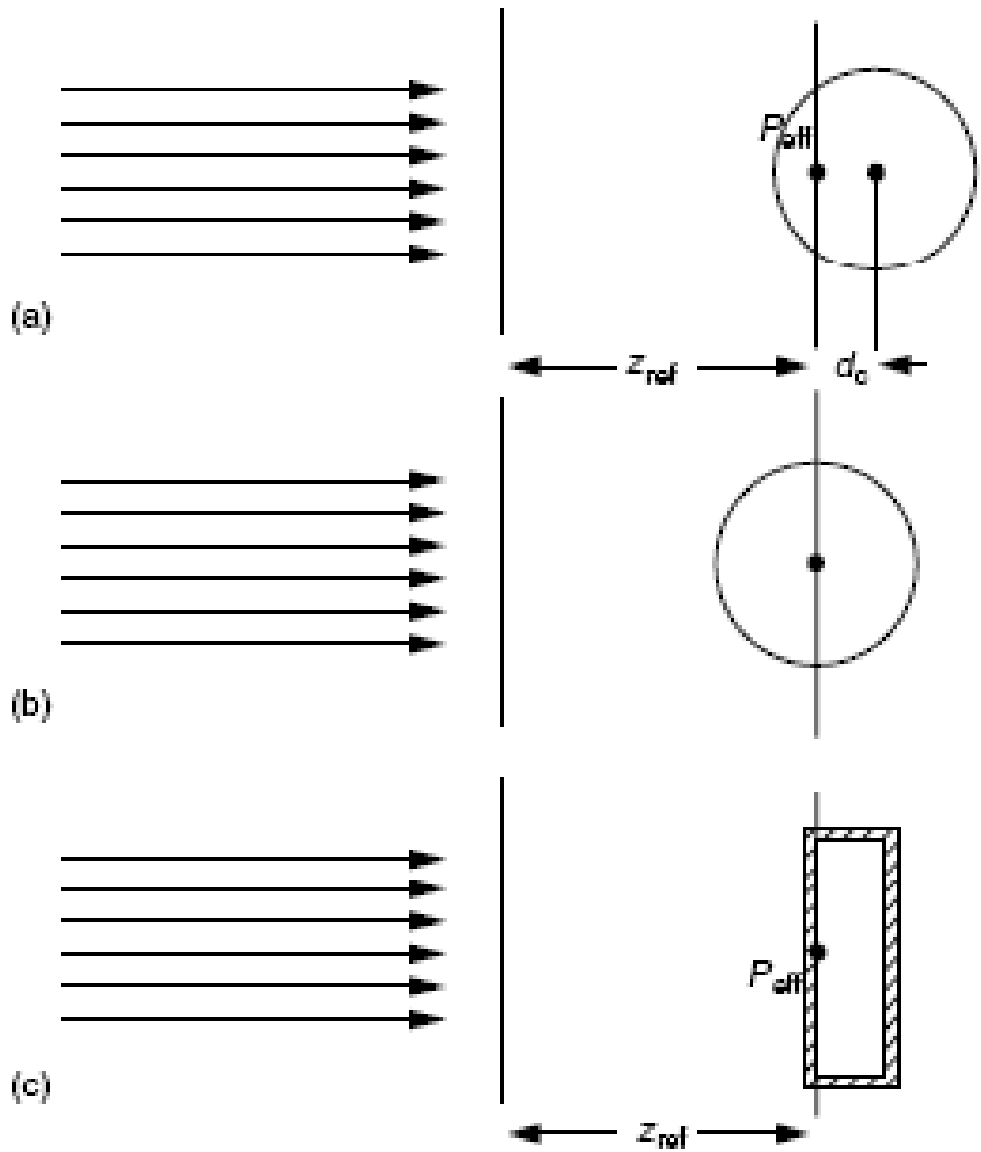
$$P_{\text{wall}} = \frac{\alpha\left[\left(\overline{\frac{\mu_{en}}{\rho}}\right)_{\text{wall}}^{\text{med}}\left(\overline{\frac{L_{\Delta}}{\rho}}\right)_{\text{air}}^{\text{wall}}\right] + (1-\alpha)\left(\overline{\frac{L_{\Delta}}{\rho}}\right)_{\text{air}}^{\text{med}}}{\left(\overline{\frac{L_{\Delta}}{\rho}}\right)_{\text{air}}^{\text{med}}}$$


PMMA Sleeve 0.5 mm thick
NE 2561 (A-150)
PTW 30001 (PMMA)
NE 2571 (graphite)
Exradin A12 (C-552)
60Co
Chamber wall perturbation factor, p_{wall}
Photon beam quality ($TPR_{20,10}$)
1.02
1.01
1.00
0.99
0.98
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85


1.002
1.000
0.998
0.996
0.994
0.992
0.990
P_{wall}
55
60
65
70
75
80
85
%dd(10)$_x$
CSnrc
Almond–Svensson (TG–51)
Almond–Svensson (EGSnrc)

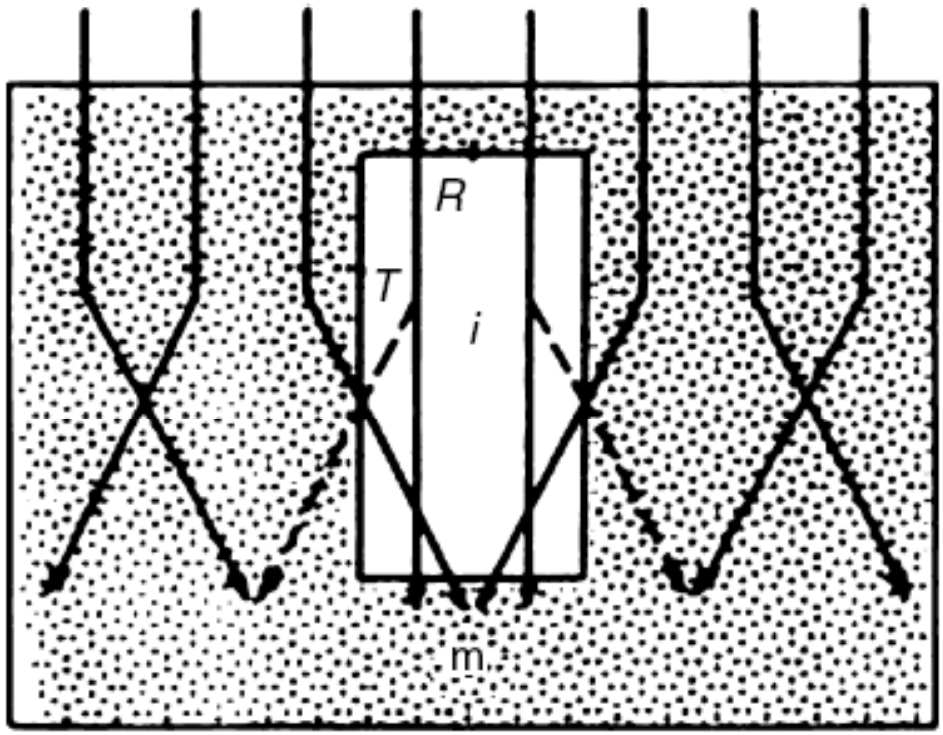
THE EFFECT OF THE FINITE VOLUME OF THE GAS CAVITY


%
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
Water (cm)
5.5 MV X Rays
10×10 cm²
SSD 100 cm
Flat chamber
Cylindrical chamber
d_c
p_{dis}


(a)
P_{eff}
z_{ref}
d_c
(b)
(c)
P_{eff}
z_{ref}

FLUENCE PERTURBATION?

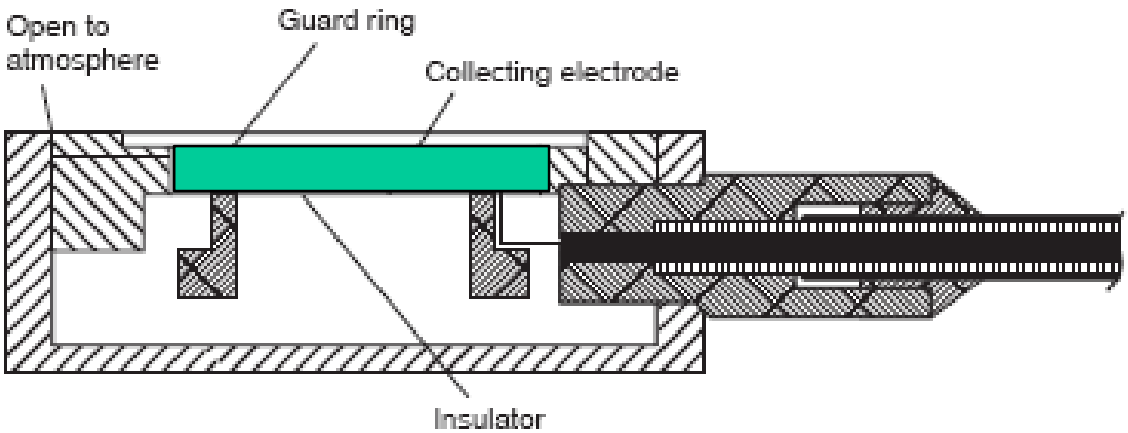
Electrons

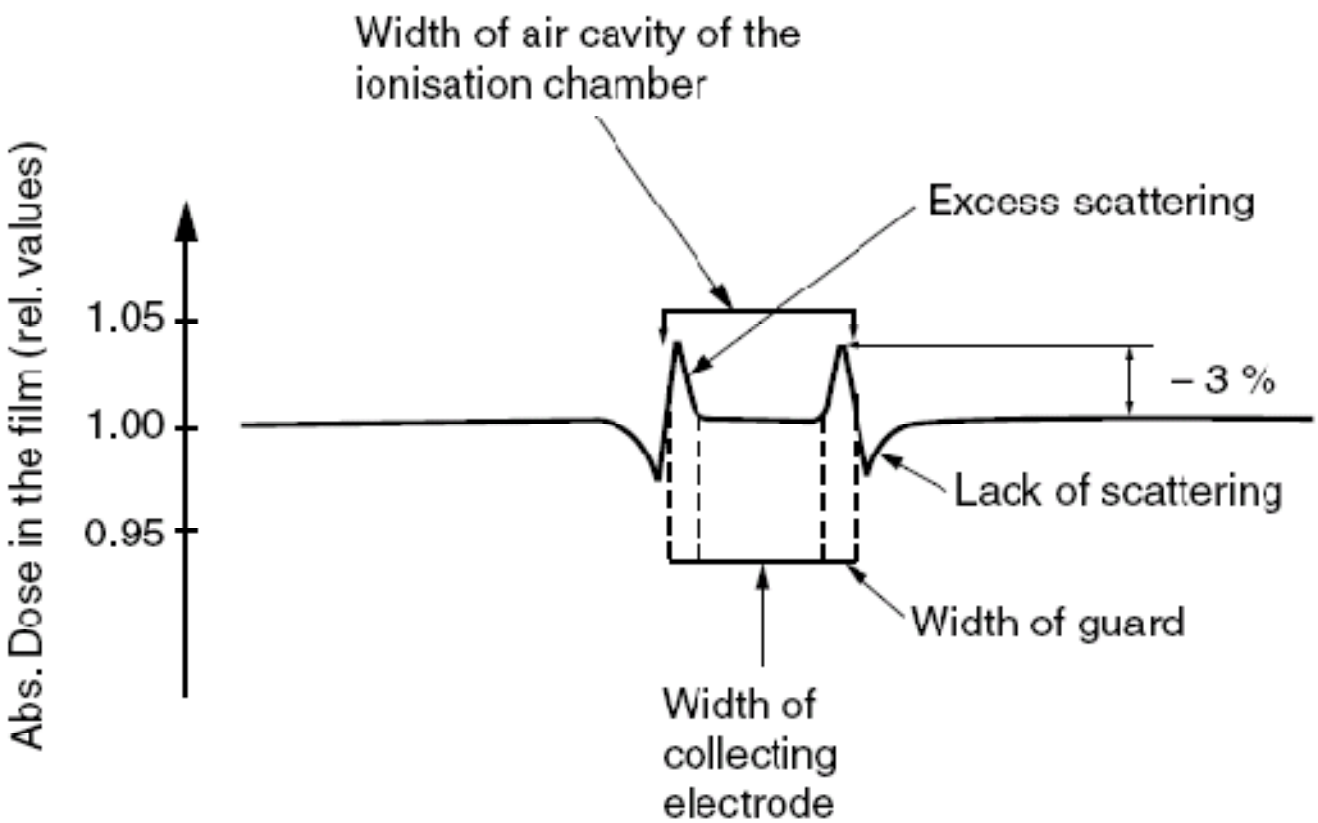


$$\Phi_{med}\left(\mathrm{P}_{\mathrm{eff}}\right) = \Phi_{cav} P_{fl}$$

Johansson *et al* used chambers of 3, 5 and 7-mm radius and found an approximately *linear* relation between (1- P_{fl}) and cavity radius (at a given energy).

Summarising the experimental work by the Wittkämper, Johansson and colleagues, for the NE2571 cylindrical chamber P_{fl} increases steadily from ≈ 0.955 at $\overline{E}_z$ = 2 MeV, to ≈ 0.980 at $\overline{E}_z$ = 10 MeV, and to ≈ 0.997 at $\overline{E}_z$ = 20 MeV.


Open to atmosphere
Guard ring
Collecting electrode
Insulator


Width of air cavity of the ionisation chamber
Excess scattering
Abs. Dose in the film (rel. values)
1.05
1.00
0.95
– 3 %
Lack of scattering
Width of guard
Width of collecting electrode

GENERAL CAVITY THEORY

We have so far looked at two *extreme* cases:

i) detectors which are large compared to the electron ranges in which CPE is established (photon radiation only)

ii) detectors which are small compared to the electron ranges and which do not disturb the electron fluence (Bragg-Gray cavities)

Many situations involve measuring the dose from photon (or neutron) radiation using detectors which fall into neither of the above categories. In such cases there is no exact theory. However, so-called *General Cavity Theory* has been developed as an approximation.

In essence these theories yield a factor which is a weighted mean of the stopping-power ratio and the mass-energy absorption coefficient ratio:

$$\frac{\overline{D_{\mathrm{det}}}}{D_{\mathrm{med}}} = d\left(\frac{\overline{L_{\Delta}}}{\rho}\right)_{\mathrm{med}}^{\mathrm{det}} + \left(1-d\right)\left(\frac{\overline{\mu_{en}}}{\rho}\right)_{\mathrm{med}}^{\mathrm{det}}$$

where *d* is the fraction of the dose in the cavity due to electrons from the medium (Bragg-Gray part),

and (1 - *d*) is the fraction of the dose from photon interactions in the cavity ("large cavity"/photon detector part)

Paul Mobit

EGS4

$CaSO_4$ TLD discs, 0.9 mm thick

Photon beams

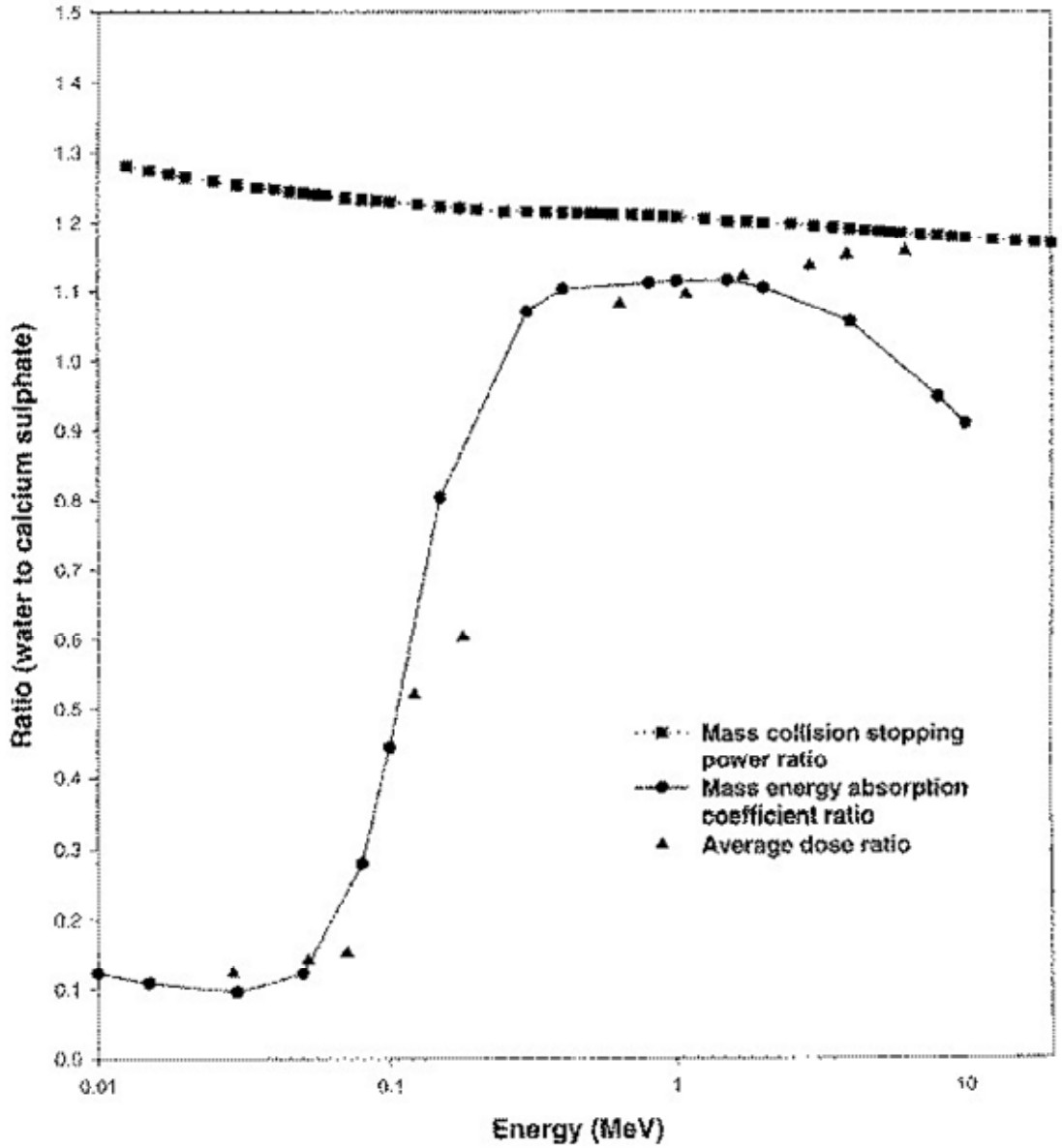


Figure 2. Calcium sulphate TLD discs, 0.9 mm thick, in MV and kV x-ray beams: comparison of the Monte Carlo derived average dose ratio, water to $CaSO_4$, with the mass collision stopping-power and mass energy-absorption coefficient ratios, as a function of the mean photon energy.

SUMMARY OF KEY POINTS

- The aim of "Cavity Theory" is to determine $f(\mathrm{Q}) = \left(\dfrac{D_{med}}{\overline{D}_{\mathrm{det}}} \right)_{\mathrm{Q}}$.

- Expressions for $f(\mathrm{Q})$ are required whenever one wishes to determine the absorbed dose using a detector calibrated at one radiation quality, $\mathrm{Q}_{\mathrm{ref}}$, in a radiation field with a *different* photon and/or electron fluence spectrum.

- The starting point for deriving "exact" cavity theories for the two limiting cases are $D_{med} \overset{CPE}{=} \mathrm{h}\nu\, \Phi_{med} \left(\dfrac{\mu_{en}}{\rho} \right)_{med}$ for photons and

$$D_{med} \overset{\delta\text{-eqm.}}{=} \Phi_{med} \left(\frac{S_{col}}{\rho} \right)_{med} \text{ for charged particles.}$$

- In the case of a *large photon detector* in a photon field where there is ≈CPE both in the undisturbed medium and in the detector's sensitive material, we have $f(\mathrm{Q}) = \frac{D_{med,z}}{\overline{D}_{det}} = \frac{\left(\overline{\mu}_{en} / \rho\right)_{med}}{\left(\overline{\mu}_{en} / \rho\right)_{det}}$, usually written as $\left(\frac{\overline{\mu}_{en}}{\rho}\right)_{det}^{med}$.
- The *large photon detector* conditions are generally fulfilled for practical, non-gaseous detectors in **kilo**voltage photon fields, but almost never for **mega**voltage photons.
- The μ_{en}/ρ ratio must be evaluated over the photon energy fluence spectrum $(\Psi_E)_{med,z}$ in the medium at the depth of the detector.

- In a photon-irradiated medium where the ranges of the (secondary) electrons greatly **exceed** the dimensions of the sensitive detector material, the detector acts as an "electron senser" or *Bragg-Gray* cavity and f(Q) is given by the ratio of the mass collision stopping powers averaged over the electron-fluence spectrum:

$$\frac{\left(\overline{S}_{col} / \rho\right)_{med,z}}{\left(\overline{S}_{col} / \rho\right)_{gas}} \quad \text{or} \quad \left(\frac{\overline{S_{col}}}{\rho}\right)_{gas}^{med}.$$

- Charged-particle equilibrium in the medium is **not** required for a detector to behave as a Bragg-Gray cavity in a megavoltage photon field; however, the numerical values in tables of stopping-power ratios often only apply to depths where there is ≈CPE.

- The gas-filled ionization chamber is the only practical example of a Bragg-Gray detector in a megavoltage photon field; ion chambers do not behave in a Bragg-Gray fashion in kilovoltage x-ray fields due to the drastic reduction in electron ranges.

- In (megavoltage) electron fields essentially all practical detectors behave in a Bragg-Gray manner, due to the long ranges of the (primary) electrons. The unrestricted stopping-power ratio, $\left(\overline{S_{col}} / \rho\right)_{gas}^{med}$ or $(s^{\mathrm{BG}})_{med,det}$, is strictly valid only for δ-ray equilibrium in the detector (and in the medium), but is an acceptable approximation either when gas and medium are closely matched (similar I-values) and/or for detectors where the value of the Spencer-Attix cutoff Δ is large (in practice, all non-gaseous detectors).

- To account for the influence of the finite range of δ-rays on ion-chamber response, Spencer and Attix (1955) developed a special form of cavity integral, and stopping-power ratio, $\left(\overline{L_{\Delta}} / \rho\right)_{gas}^{med}$, involving a cutoff Δ related to cavity size, and the use of the collision stopping power *restricted to losses below* Δ *in magnitude*.

- The water/air stopping-power ratio is a rapidly varying function of electron energy (due to the much greater influence of the relativistic *density* or *polarization* effect in condensed materials than in gases), necessitating accurate characterization of (megavoltage photon and electron) beam quality via Monte Carlo simulation, especially as a function of depth in electron beams.

- For virtually all other medium/detector combinations of practical interest the stopping-power ratio varies either negligibly or very slowly with electron energy (e.g., Si/water, C/water, LiF/water) and the unrestricted ratio $\left(\overline{S_{col}} / \rho\right)_{gas}^{med}$ evaluated at the mean (primary) electron energy is an adequate approximation.

- The use of practical ion chamber designs involves several important departures from perfect Bragg-Gray behavior; correction or *perturbation* factors are required, which multiply the product of D_{air} and the stopping-power ratio. The principal corrections are P_{wall}, P_{repl}, and P_{cel}, which correct for the non-medium equivalence of the wall material, the finite size of the air cavity, and presence of the central electrode (for cylindrical or thimble chambers), respectively.

- The fluence-perturbation component of P_{repl} in cylindrical (or thimble) chambers is negligible in photon beams at $z \geq d_{max}$ but not in electron beams, and can be several percent below unity at low energies; for this reason, well-guarded parallel-plate chambers are preferred for beams with $\overline{E}_o \leq 10$ MeV.

- Recent Monte-Carlo work has demonstrated that the approximate two-component Almond-Svensson expression for P_{wall} used in all the Codes of Practice seriously overestimates the departure of P_{wall} from unity for Farmer-type chambers. Also P_{wall} for parallel-plate chambers in electron beams is not always close to unity despite the assumption of unity in the Codes of Practice.

- None of the non-gaseous practical detectors (e.g., thermoluminescent detector, semiconductors, film, diamond) behaves as a Bragg-Gray cavity in a megavoltage photon field; nor can $\left(\overline{\mu_{en}} / \rho\right)_{det}^{med}$ be applied as their dimensions are insufficient for CPE in the detector material; strictly, these are *Burlin* cavities.

Thank you for your attention