Kilovoltage X-Ray Dosimetry for Radiation Therapy

C.-M. Charlie Ma

Dept. of Radiation Oncology, FCCC, Philadelphia, PA

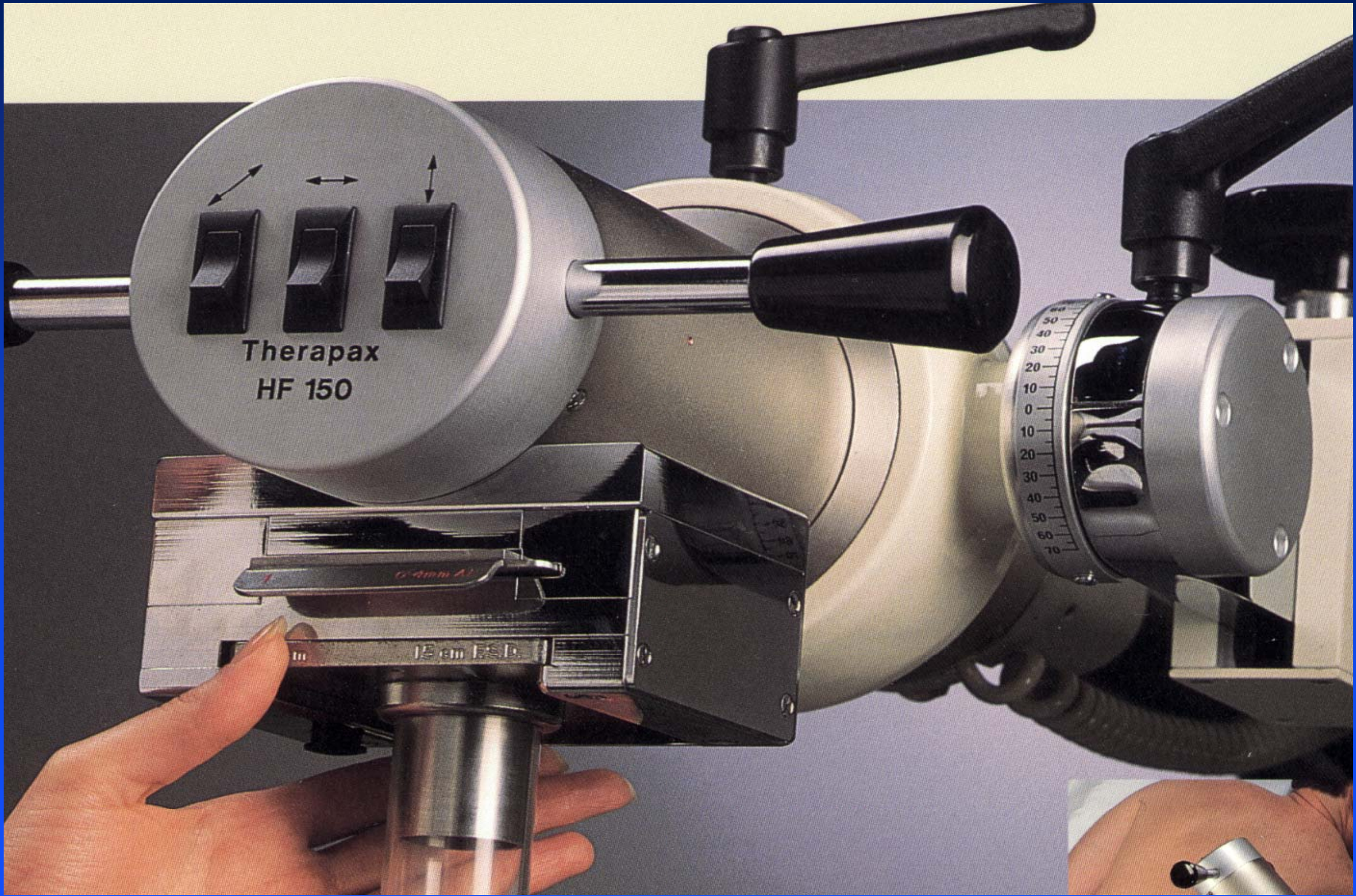
FOX CHASE CANCER CENTER

Clinical Dosimetry Measurements in Radiotherapy
2009 AAPM Summer School
Colorado College, CO
June 21-25, 2009

Outline

- Kilovoltage x-ray dosimetry- a review
- TG-61 formalism for kilovoltage x-ray dosimetry
- Clinical implementation of the TG-61 protocol
- Summary of TG-61 recommendations
- Uncertainty analysis

Therapax HF150 Superficial Unit By Pantak, Inc



A X-ray unit from Gulmay Medical Ltd

The physics of kV x-ray dosimetry

- Very short electron ranges (< 0.5 mm water)
- Large scatter contributions and SSD, field size, beam quality dependent
- Kerma = dose (also K_{col} = K as negl. brem., <0.1%)
- Bragg-Gray cavity conditions very difficult to fulfill - even for air-filled ionization chambers
- Ionization chambers calibrated as “exposure meters” and used as “photon detectors”

Kilovoltage x-ray dosimetry- a review

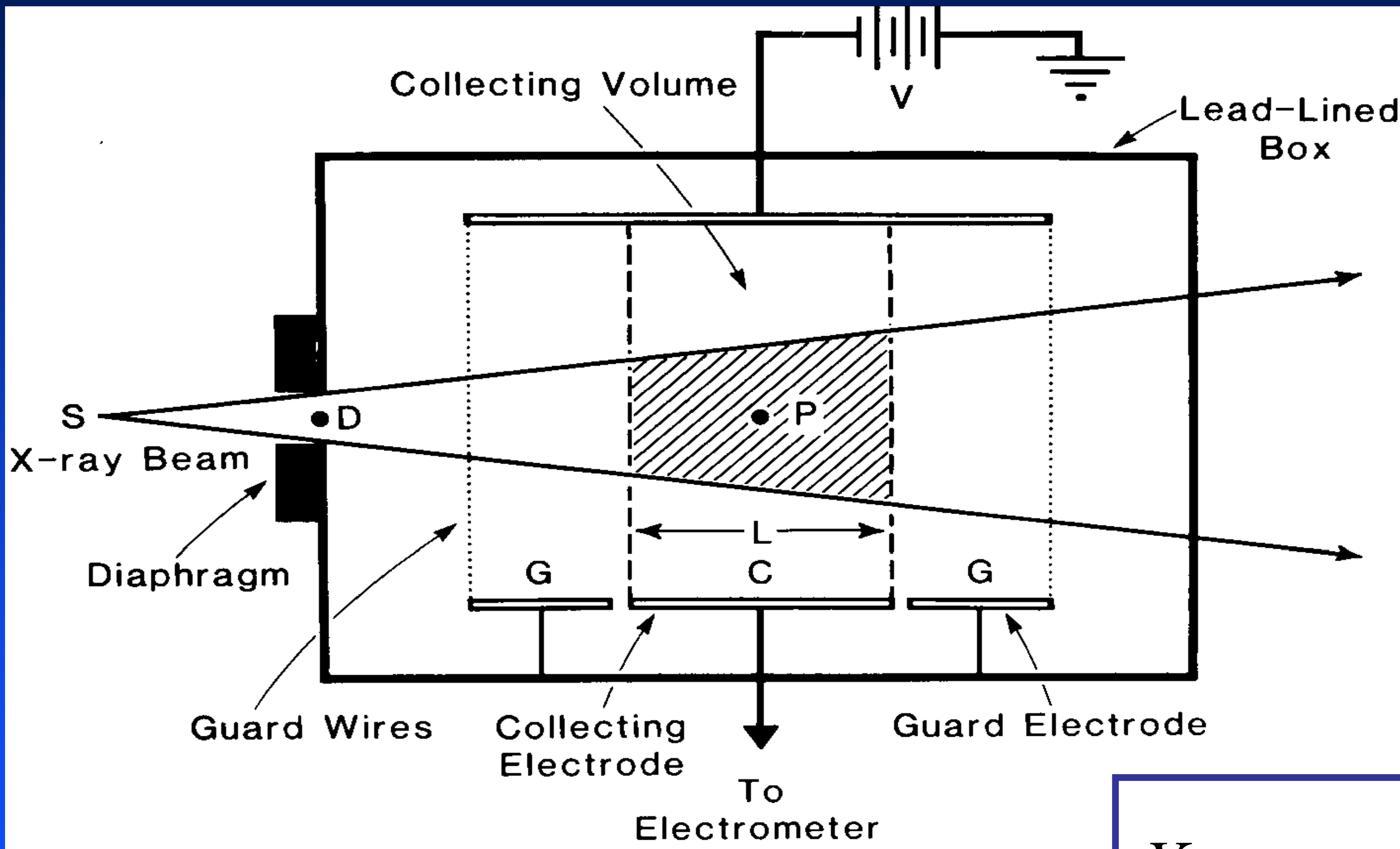
- Kilovoltage x-ray dosimetry is the main theme in the first 70 years following the discovery of x-rays
- The introduction of the roentgen in 1928 at Stockholm Congress of Radiology marked the beginning of precise physical measurement of radiation exposure (dose)
- The universally adopted instrument to measure exposure is the free air chamber ($\pm$1% agreement between national labs in 1932)

Exposure, *X*

$$X = \frac{\mathrm{d}Q}{\mathrm{d}m} (\mathrm{kg/c})$$

where *dQ* is the absolute value of the total charge of the ions of one sign produced in (dry) air when all the electrons liberated by photons in air of mass *dm* are completely stopped in air

Measurement of Exposure



Free Air Chamber

$$X_D = \frac{Q}{\rho A_D L}$$

"Modern" Dosimetry for Kilovoltage X-Ray

- ICRU Report 23 (1973) significant changes made

  40-150 kV in-air method, >150 kV in-phantom

- NCRP Report 69 (1981) only protocol for N. Ame.

  10 kV and above, in-air method, no BSF given

- IAEA Report 277 (1987) significant changes made

  10-100 kV in-air method, >100 kV in-phantom

“Modern” Dosimetry for Kilovoltage X-Ray

- IPEMB Code of Practice (1996) with three ranges

  Very low- (< 1mmAl) in-phantom, low- (1-8mmAl) in-air, medium-energy (>0.5mmCu) in-phantom

- NCS Code of Practice (1997) two energy ranges

  50 - 100 kV in-air method, 100 - 300 kV in-phantom

- IAEA Code of Practice (2000) - new recommendations

  Absorbed dose based, consistent with other beams

Kilovoltage x-ray dosimetry

- For low-energy (40 - 150 kV, 8mm Al HVL) x-rays - the backscatter method

- For medium-energy (100 - 300 kV, 4mm Cu HVL) x-rays - the in-phantom Method

(except for NCRP Report 69)

AAPM TG-61 Report

(Med. Phys. 28 (6) 2001 868-893)

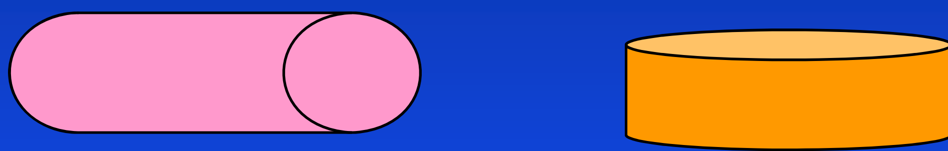
Charles Coffey	Larry DeWerd
Chihray Liu	Charlie Ma (chair)
Ravi Nath	Stephen Seltzer
Jan Seuntjens	

What's New in AAPM TG-61?

- Use both the in-air and in-phantom methods for tube potentials 100 - 300 kV
- More complete data (for water, tissue & bone)
- Recommendations for relative measurements
- Recommendations for QA and consistency check

Detectors for kV x-ray beams

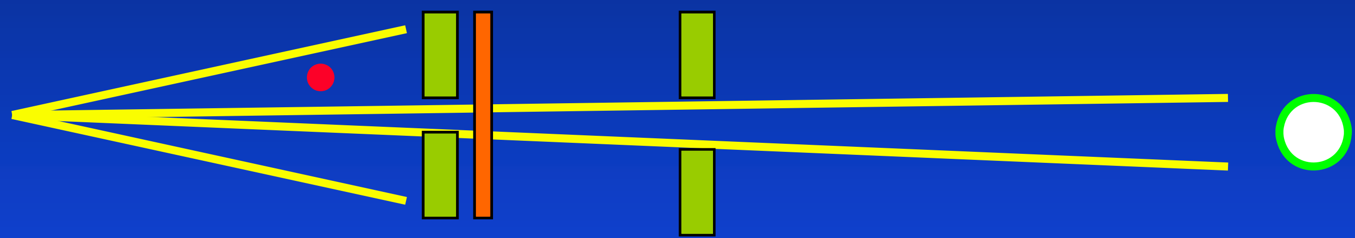
- Air-filled ion chambers are recommended for absolute dose measurements



- Diode, film, diamond detectors for relative measurements

Beam quality specification

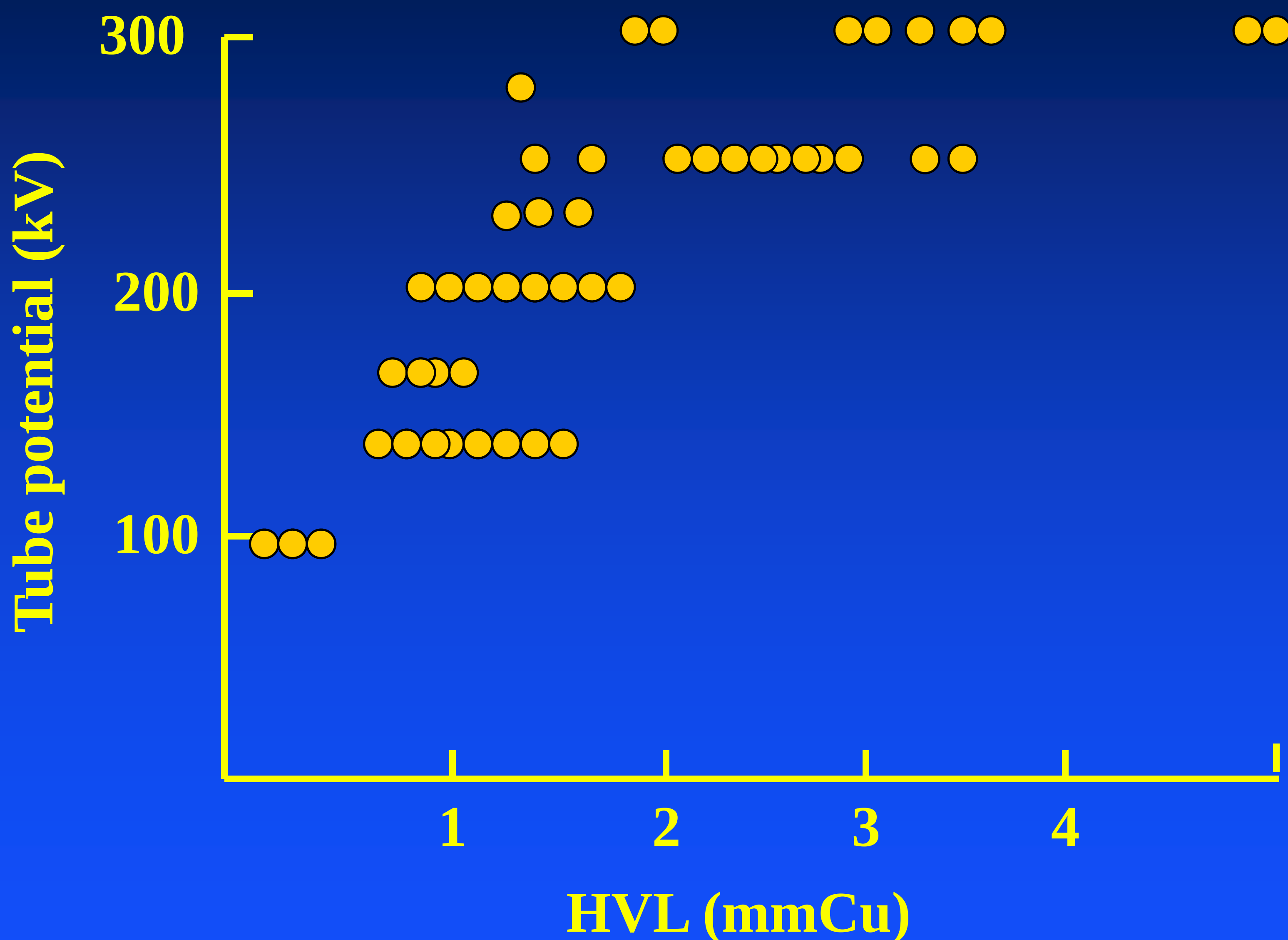
- Use a “narrow beam (good beam) geometry”



- Half-Value Layer expressed in mm Ai or Cu

  for 40-150 kV x-rays: use mmAl

  for 100 - 300 kV x-rays: use mmCu



300
200
100
Tube potential (kV)
1
2
3
4
HVL (mmCu)

Beam quality specification

- Use both tube potential and HVL to specify beam quality for chamber calibration
- Use HVL to specify beam quality for determination of chamber correction and conversion factors

Table 1: UW ADCL and NIST beams compared.

NIST BEAM QUALITIES			UW ADCL BEAM QUALITIES		
BEAM Code	HVL (mm Al)	HC	BEAM Code	HVL (mm Al)	HC
L30	0.22	60	UW30-L	0.22	56
L40	0.49	57	UW40-L	0.49	60
L50	0.75	58	UW50-L	0.75	61
L80	1.83	58	UW80-L	1.83	58
L100[1]	2.8	59	UW100-L	2.80	58
M20	0.152	79	UW20-M	0.153	79
M30	0.36	64	UW30-M	0.354	63
M40	0.73	66	UW40-M	0.73	64
M50	1.02	66	UW50-M	1.02	64
M60	1.68	68	UW60-M	1.68	66
			UW80-M[2]	2.96	68
M100	5.0	72	UW100-M	4.98	72
			UW120-M[2]	6.96	78
M150	10.2	87	UW150-M	10.2	87
M200	14.9	95	UW200-M	14.9	94
M250	18.5	98	UW250-M	18.5	98
S75	1.86	63	UW75-S	1.86	63
S60	2.8	75	UW60-S	2.82	76

All beams are matched as closely as possible to available NIST beam qualities.

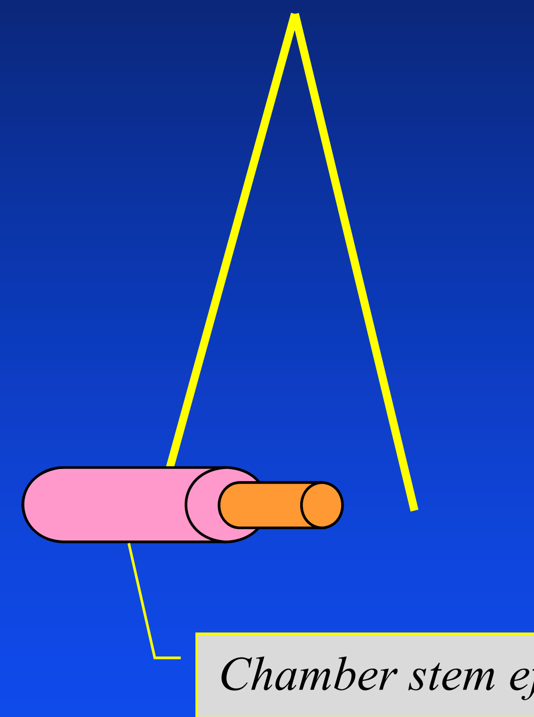
Ionization Chamber Calibration

- Free-in-air K_{air} calibration

$$\boxed{N_K = K_{air} / M}$$

- Free-in-air X calibration

$$\boxed{N_X = X / M}$$



$$\boxed{N_K = N_X (W/e)_{\mathrm{air}} (1-g)^{-1}}$$

$$\boxed{K_{air} = X (W/e)_{\mathrm{air}} (1-g)^{-1}}$$

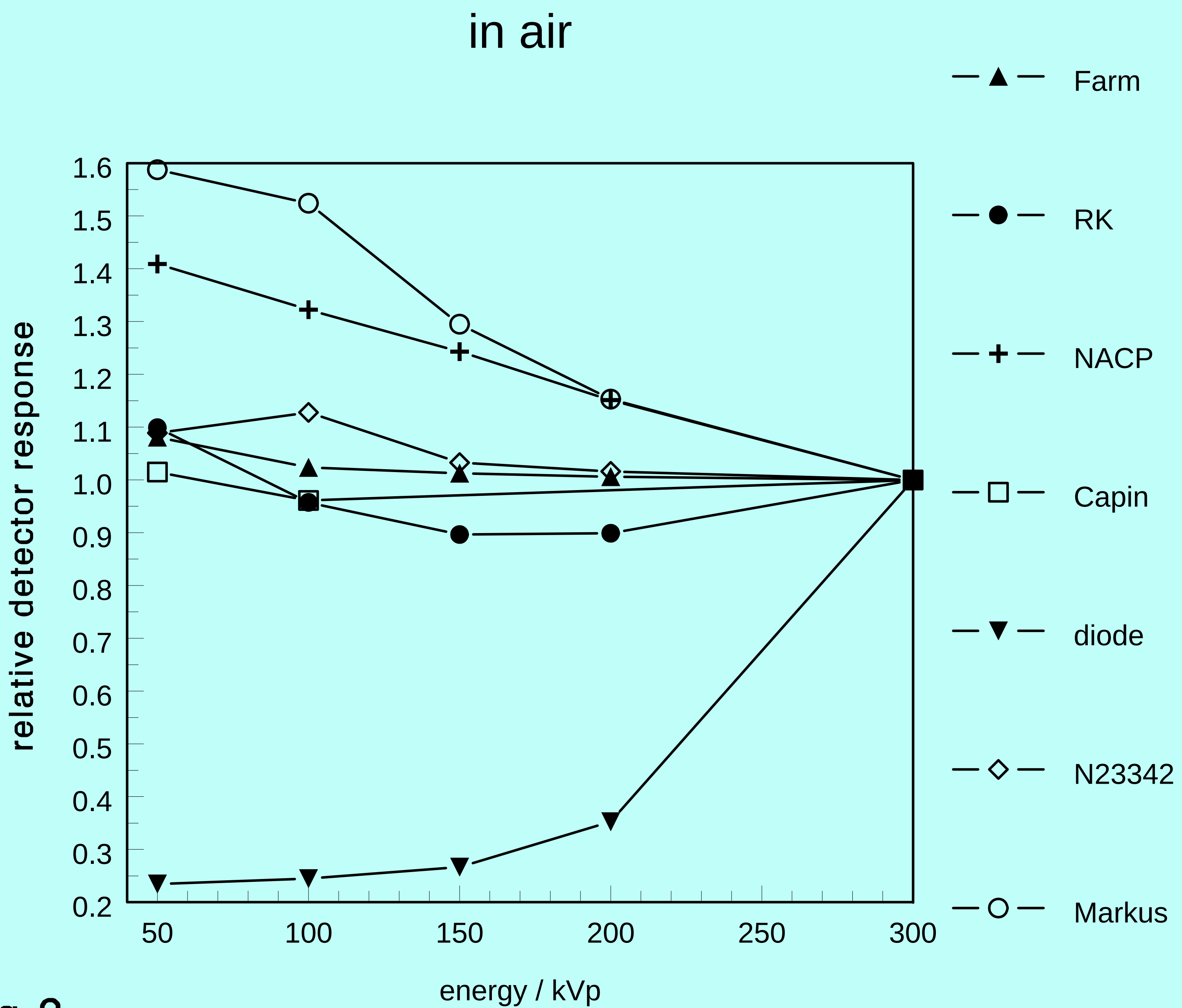
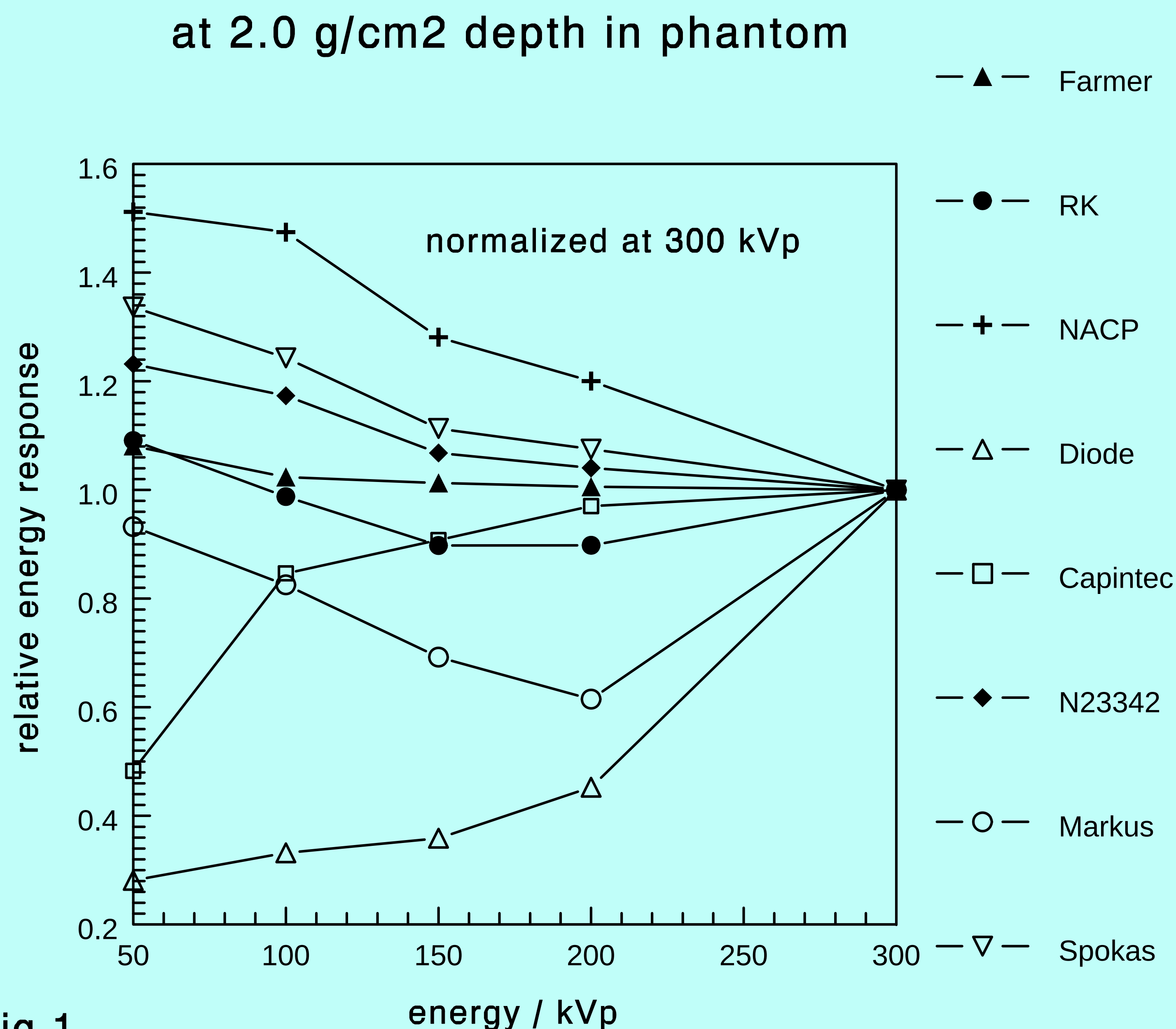

in air
Farm
RK
NACP
Capin
diode
N23342
Markus
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
relative detector response
50
100
150
200
250
300
energy / kVp

Fig.2



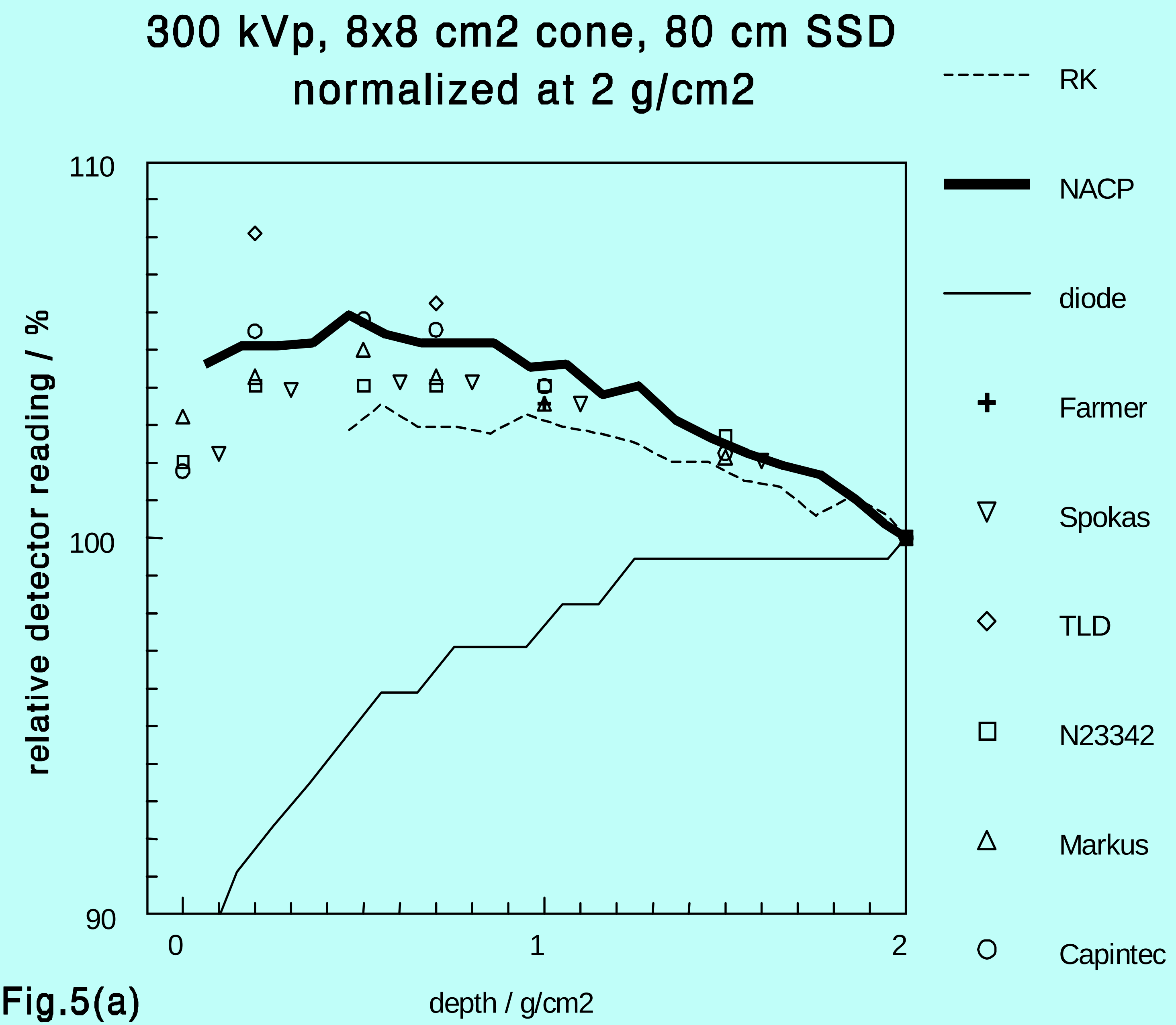
at 2.0 g/cm2 depth in phantom
normalized at 300 kVp
relative energy response
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
50
100
150
200
250
300
energy / kVp
Farmer
RK
NACP
Diode
Capintec
N23342
Markus
Spokas

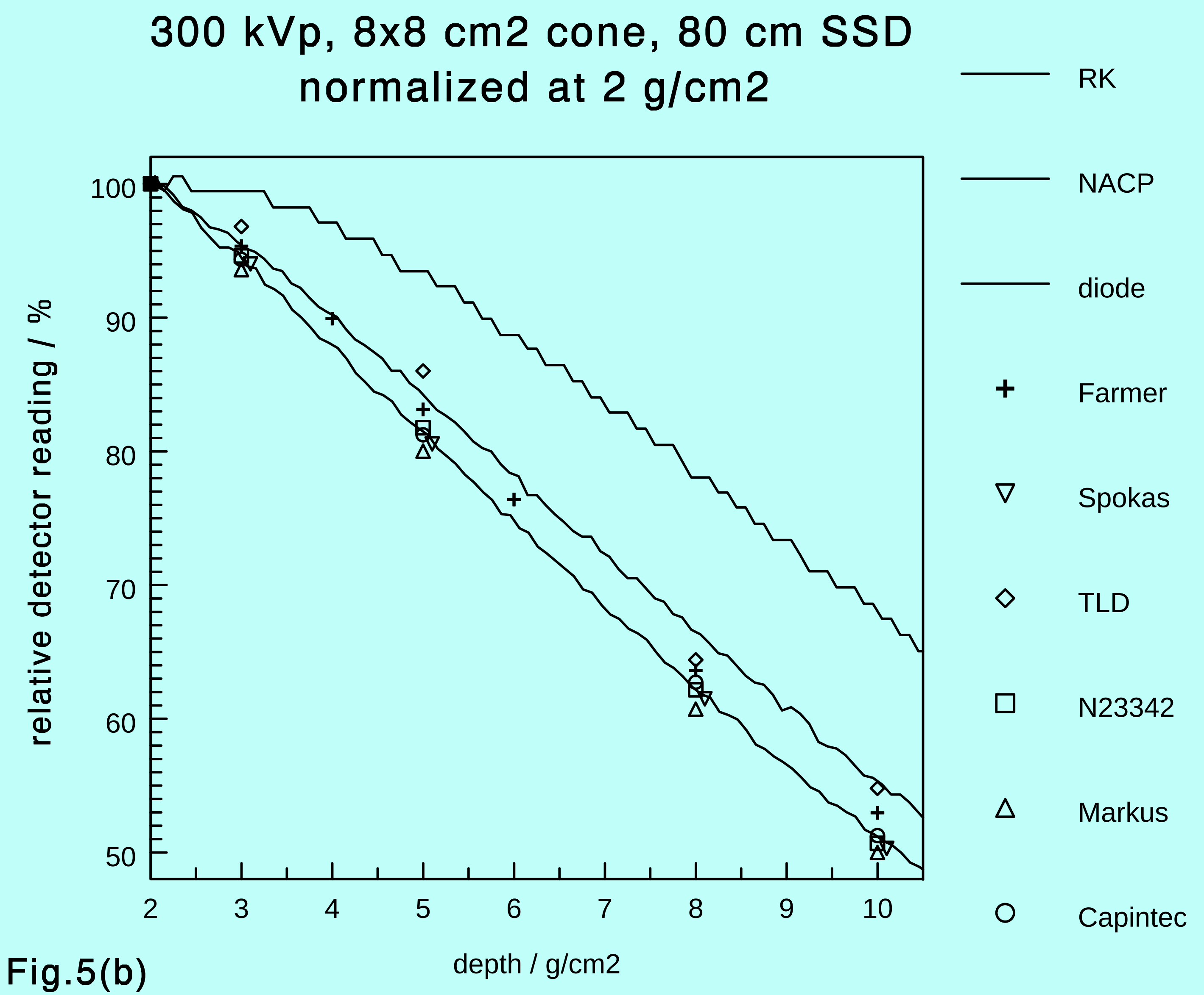
Fig.1

Formalisms for KV X-ray Dosimetry

- For 40-300 kV beams, recommend the back-scatter method if point of interest is on the surface

- For 100-300 kV beams, recommend the in-phantom method if point of interest is at a depth

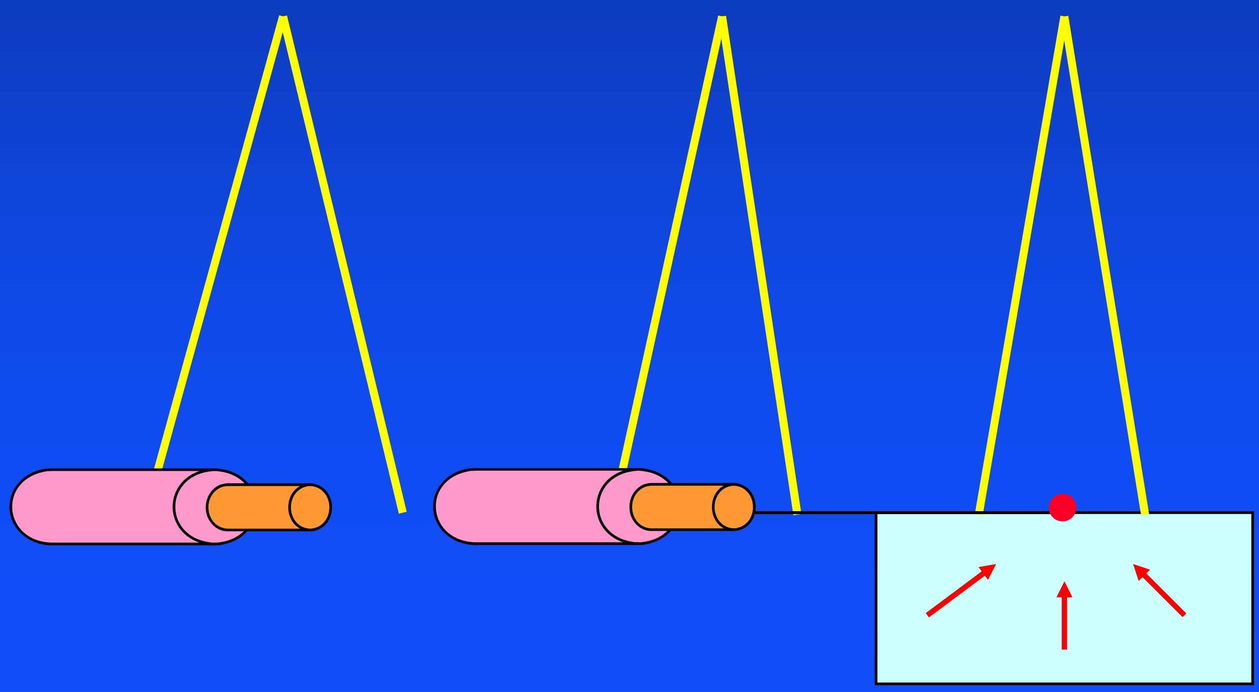

300 kVp, 8x8 cm2 cone, 80 cm SSD
normalized at 2 g/cm2
relative detector reading / %
110
100
90
0
1
2
depth / g/cm2
RK
NACP
diode
Farmer
Spokas
TLD
N23342
Markus
Capintec
Fig.5(a)


300 kVp, 8x8 cm2 cone, 80 cm SSD
normalized at 2 g/cm2
relative detector reading / %
100
90
80
70
60
50
2
3
4
5
6
7
8
9
10
depth / g/cm2
RK
NACP
diode
Farmer
Spokas
TLD
N23342
Markus
Capintec
Fig.5(b)

The Backscatter (in-air) Method

- For surface dose determination

$$D_w = M N_K (\mu_{en}/\rho)^{\mathrm{w}}_{\mathrm{air}} P_{stem,air} B_w$$



Derivation for the Backscatter (In-air) Method

- Determine the air kerma at a point in air in absence of the chamber

$$K_{\text{air}}^{\text{in–air}} = M N_K P_{\text{stem,air}}$$

- Convert air kerma to water kerma by

$$K_{\text{w}}^{\text{in–air}} = K_{\text{air}}^{\text{in-air}} (\mu_{\text{en}} / \rho)_{\text{air}}^{\text{w}}$$

- Derive water kerma on the surface using a backscatter factor

$$K_{\text{w}} = K_{\text{w}}^{\text{in–air}} B_{\text{w}}$$

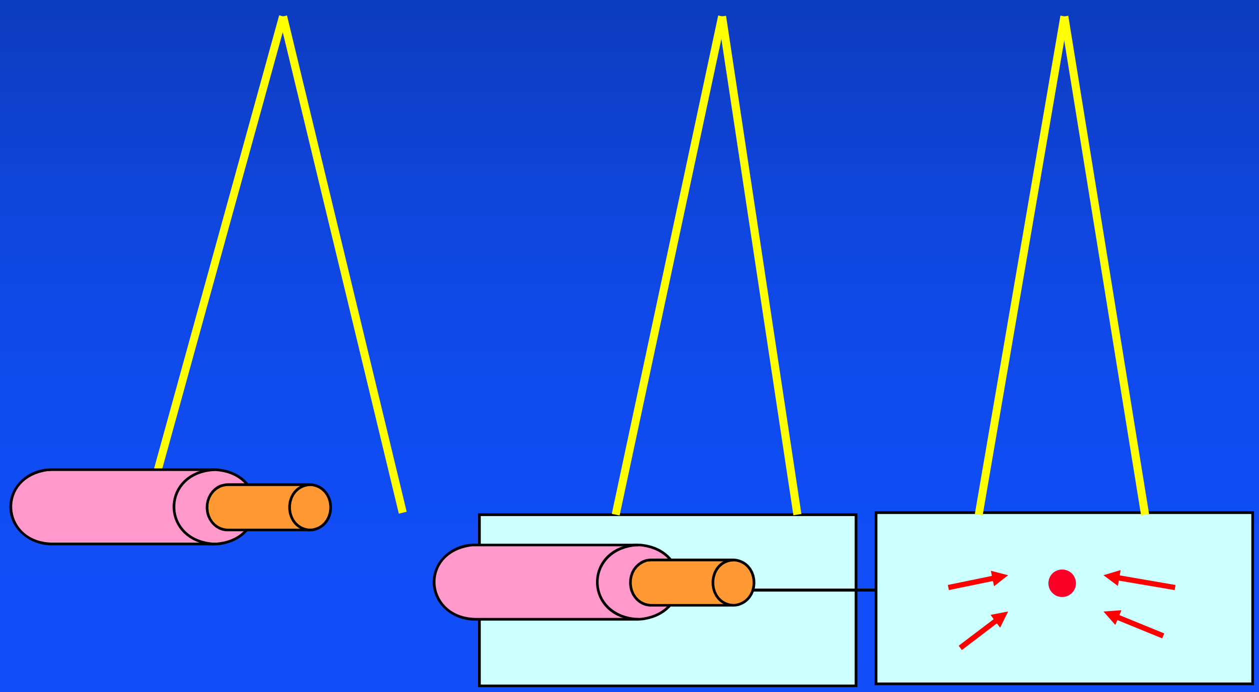
- Derive absorbed dose to water from water kerma assuming charged particle equilibrium

$$D_{\text{w}} = K_{\text{w}} \text{ CPE exists}$$

The In-Phantom Method

- For dose determination at a depth

$$D_w = M N_K (\mu_{en}/\rho)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{sheath}} P_{\mathrm{Q,cham}}$$



Derivation for the In-Phantom Method

- Determine the air kerma at a point in water in absence of the chamber

$$K_{\text{air}}^{\text{in-water}} = M N_K P_{\text{Q,cham}} P_{\text{sheath}}$$

- Convert air kerma to water kerma by

$$K_{\text{w}} = K_{\text{air}}^{\text{in-water}} (\mu_{\text{en}} / \rho)_{\text{air}}^{\text{w}}$$

- Derive absorbed dose to water from water kerma assuming charged particle equilibrium

$$D_{\text{w}} = K_{\text{w}} \quad \text{CPE exists}$$

In-air mass energy-absorption coefficient ratio

Table 2 Ratios of mass energy-absorption coefficients averaged over the primary photon spectrum for the beams described in Table 1.

HVL (mm Al)	HVL (mm Cu)	w/air	tissue/w	muscle/w	lung/w	skin/w	bone/w
0.300	0.010	1.037	0.917	1.016	1.031	0.890	4.20
0.381	0.012	1.033	0.918	1.020	1.035	0.893	4.28
0.875	0.027	1.023	0.922	1.030	1.045	0.902	4.51
1.35	0.422	1.022	0.926	1.032	1.047	0.909	4.45
2.65	0.090	1.025	0.933	1.032	1.046	0.920	4.25
4.76	0.195	1.034	0.942	1.029	1.040	0.934	3.82
9.17	0.574	1.057	0.960	1.018	1.026	0.956	2.885
14.5	1.71	1.088	0.979	1.003	1.005	0.979	1.741
17.6	3.01	1.102	0.986	0.996	0.997	0.985	1.276
19.8	4.32	1.108	0.989	0.993	0.993	0.988	1.080
20.8	4.92	1.109	0.990	0.992	0.992	0.989	1.032

In-water mass energy-absorption coefficient ratio

Table 3 Ratios of mass energy-absorption coefficients averaged over the photon spectrum at 2 cm depth in water irradiated by the beams described in Table 1. The field size is 100 cm^2 defined at 50 cm SSD.

HVL (mm Al)	HVL (mm Cu)	w/air	tissue/w	muscle/w	lung/w	bone/w
0.300	0.010	1.022	0.921	1.030	1.046	4.54
0.381	0.012	1.019	0.922	1.033	1.049	4.61
0.875	0.027	1.018	0.924	1.035	1.050	4.63
1.35	0.422	1.020	0.929	1.035	1.049	4.46
2.65	0.090	1.025	0.935	1.033	1.047	4.23
4.76	0.195	1.032	0.941	1.030	1.042	3.91
9.17	0.574	1.049	0.954	1.022	1.031	3.23
14.5	1.71	1.077	0.972	1.008	1.013	2.145
17.6	3.01	1.094	0.981	1.000	1.002	1.560
19.8	4.32	1.103	0.986	0.996	0.996	1.255
20.8	4.92	1.105	0.988	0.994	0.994	1.150

Water kerma based backscatter factor

Table IVb (continued). Water kerma based backscatter factors for a water phantom as a function of field diameter (d), source surface distance (SSD), and radiation quality (HVL).

Beam quality

SSD

SSD (cm)	d (cm)	HVL (mm Cu) 0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.5	2.0	3.0	4.0	5.0
10	1	1.062	1.057	1.056	1.054	1.052	1.050	1.046	1.043	1.037	1.033	1.026	1.021	1.017
	2	1.120	1.118	1.119	1.113	1.108	1.106	1.103	1.097	1.081	1.071	1.057	1.046	1.038
	3	1.159	1.161	1.161	1.155	1.150	1.147	1.143	1.135	1.116	1.102	1.081	1.067	1.054
	5	1.210	1.224	1.226	1.221	1.217	1.214	1.209	1.199	1.170	1.151	1.122	1.101	1.082
	10	1.269	1.306	1.316	1.313	1.311	1.310	1.307	1.294	1.254	1.227	1.186	1.154	1.126
	15	1.287	1.335	1.348	1.348	1.348	1.348	1.347	1.332	1.289	1.260	1.213	1.178	1.146
	20	1.292	1.344	1.361	1.362	1.362	1.363	1.364	1.349	1.303	1.273	1.225	1.188	1.155
20	1	1.061	1.058	1.055	1.054	1.053	1.051	1.048	1.045	1.038	1.033	1.024	1.020	1.018
	2	1.116	1.118	1.119	1.114	1.110	1.107	1.102	1.097	1.084	1.074	1.056	1.046	1.039
	3	1.158	1.164	1.168	1.161	1.155	1.152	1.147	1.140	1.122	1.107	1.082	1.067	1.057
	5	1.214	1.232	1.242	1.238	1.233	1.229	1.219	1.209	1.184	1.164	1.127	1.104	1.088
	10	1.290	1.331	1.352	1.353	1.353	1.349	1.339	1.326	1.291	1.260	1.204	1.168	1.141
	15	1.320	1.377	1.407	1.412	1.415	1.411	1.403	1.389	1.350	1.316	1.251	1.207	1.174
	20	1.333	1.397	1.434	1.441	1.447	1.443	1.436	1.421	1.381	1.345	1.278	1.230	1.194
30	1	1.063	1.060	1.056	1.054	1.052	1.050	1.047	1.044	1.038	1.033	1.024	1.020	1.018
	2	1.120	1.122	1.119	1.113	1.108	1.105	1.101	1.096	1.084	1.073	1.056	1.046	1.038
	3	1.164	1.168	1.169	1.161	1.155	1.152	1.146	1.139	1.121	1.107	1.084	1.068	1.055
	5	1.220	1.242	1.242	1.239	1.235	1.231	1.221	1.211	1.184	1.164	1.130	1.106	1.087
	10	1.297	1.348	1.363	1.366	1.367	1.360	1.347	1.332	1.292	1.263	1.214	1.177	1.147
	15	1.330	1.401	1.417	1.429	1.438	1.433	1.422	1.405	1.360	1.327	1.270	1.226	1.189
	20	1.348	1.426	1.446	1.464	1.478	1.473	1.464	1.446	1.399	1.364	1.302	1.254	1.213
50	1	1.065	1.059	1.054	1.053	1.052	1.050	1.047	1.045	1.038	1.034	1.025	1.020	1.018
	2	1.121	1.121	1.118	1.114	1.111	1.108	1.103	1.097	1.084	1.073	1.056	1.047	1.040
	3	1.163	1.169	1.170	1.163	1.157	1.154	1.148	1.140	1.121	1.106	1.084	1.069	1.057
	5	1.225	1.240	1.247	1.244	1.240	1.235	1.226	1.214	1.184	1.163	1.131	1.108	1.089
	10	1.308	1.350	1.367	1.372	1.376	1.371	1.360	1.344	1.304	1.274	1.222	1.184	1.152
	15	1.345	1.408	1.433	1.443	1.452	1.450	1.446	1.428	1.379	1.346	1.285	1.237	1.195
	20	1.361	1.439	1.471	1.486	1.499	1.498	1.495	1.478	1.428	1.391	1.325	1.272	1.226
100	1	1.062	1.059	1.055	1.053	1.052	1.050	1.047	1.045	1.038	1.034	1.025	1.020	1.018
	2	1.121	1.121	1.117	1.114	1.111	1.108	1.104	1.098	1.085	1.074	1.057	1.047	1.040
	3	1.163	1.169	1.170	1.165	1.160	1.156	1.150	1.142	1.122	1.107	1.085	1.070	1.057
	5	1.224	1.239	1.245	1.243	1.241	1.237	1.227	1.217	1.188	1.167	1.132	1.109	1.090
	10	1.310	1.349	1.370	1.378	1.383	1.378	1.369	1.353	1.311	1.278	1.226	1.188	1.155
	15	1.353	1.413	1.447	1.456	1.463	1.461	1.458	1.441	1.393	1.356	1.291	1.244	1.204
	20	1.373	1.446	1.490	1.502	1.513	1.514	1.516	1.499	1.447	1.406	1.334	1.282	1.237

Applicator size

Ratio of backscatter factors, bone to water

Table 4. Ratios of backscatter factors, bone to water, for photon beams 50 - 300 kV (0.875 - 20.8 mm Al HVL) with different field sizes defined at different SSD.

SSD (cm)	HVL (mm Al)	$\frac{B_{bone}}{B_w}$ (1 x 1 cm^2)	(2 x 2 cm^2)	(4 x 4 cm^2)	(10 x 10 cm^2)	(20 x 20 cm^2)
50	0.875	0.943	0.916	0.890	0.865	0.858
	2.65	0.972	0.938	0.892	0.829	0.798
	9.17	1.022	1.015	0.984	0.885	0.827
	14.5	1.039	1.065	1.079	1.028	0.958
	17.6	1.036	1.069	1.100	1.095	1.049
	20.8	1.022	1.048	1.073	1.094	1.079
30	0.875	0.943	0.916	0.890	0.867	0.861
	2.65	0.973	0.935	0.888	0.834	0.807
	9.17	1.023	1.017	0.988	0.891	0.835
	14.5	1.039	1.067	1.076	1.025	0.967
	17.6	1.037	1.067	1.101	1.090	1.047
	20.8	1.023	1.046	1.078	1.091	1.078
10	0.875	0.943	0.916	0.893	0.874	0.873
	2.65	0.973	0.941	0.901	0.849	0.836
	9.17	1.023	1.017	0.980	0.915	0.878
	14.5	1.039	1.064	1.071	1.032	1.005
	17.6	1.037	1.066	1.092	1.086	1.070
	20.8	1.022	1.044	1.075	1.087	1.078

Overall chamber correction factor

Table VII. Overall chamber correction factors $P_{Q,cham}$ for common cylindrical chambers in medium-energy x-ray beams. The data applies to 2 cm depth in the phantom, and 100 cm^2 field size.

Chamber Type / HVL (mmCu)	NE2571	Capintec PR06C	PTW N30001	Exradin A12	NE2581	NE2611 or NE2561
0.10	1.008	0.992	1.004	1.002	0.991	0.995
0.15	1.015	1.000	1.013	1.009	1.007	1.007
0.20	1.019	1.004	1.017	1.013	1.017	1.012
0.30	1.023	1.008	1.021	1.016	1.028	1.017
0.40	1.025	1.009	1.023	1.017	1.033	1.019
0.50	1.025	1.010	1.023	1.017	1.036	1.019
0.60	1.025	1.010	1.023	1.017	1.037	1.019
0.80	1.024	1.010	1.022	1.017	1.037	1.018
1.0	1.023	1.010	1.021	1.016	1.035	1.017
1.5	1.019	1.008	1.018	1.013	1.028	1.014
2.0	1.016	1.007	1.015	1.011	1.022	1.011
2.5	1.012	1.006	1.012	1.010	1.017	1.009
3.0	1.009	1.005	1.010	1.008	1.012	1.006
4.0	1.004	1.003	1.006	1.005	1.004	1.003

Chamber Sheath Correction Factor

Table IV: The Monte Carlo calculated correction factors p_s for polystyrene (ρ = 1.06 gcm^3) sleeves of thickness *t*. Other conditions are the same as Table II. The 1-σ statistical uncertainties are smaller than 0.001.

Beam quality (mm A1)	p_s for Polystyrene			
	t = 0.5 mm	t = 1 mm	t = 2 mm	t = 3 mm
1.04	0.990	0.981	0.962	0.943
2.94	0.995	0.990	0.981	0.972
4.28	0.996	0.993	0.986	0.979
9.20	0.999	0.997	0.994	0.992
13.0	1.000	0.999	0.998	0.997
16.6	1.000	0.999	0.999	0.999
21.5	1.000	1.000	1.000	1.000

Consistency between the in-air and in-phantom methods

- Select a method based on point of interest
- Check consistency only if PDD can be measured accurately
- Experimental studies indicated consistent results (about 1%) using both methods at 100 and 300 kV

Ma, Li and Seuntjens (1998) Med Phys 25: 2376-84

Table II Dose ratios calculated based on Eq. 12 for a 100 kV (2.43 mm Al) beam with a 100 cm^2 field defined at 80 cm SSD. The chamber readings were corrected for temperature, pressure, polarity and ion recombination. The PDD curves were measured using the NACP chamber and corrected using the Monte Carlo calculated C_z factors. The ratios of mass energy-absorption coefficients for water to air, the backscatter factors and the chamber correction factors were taken from the ICRU[3] (reference depth = 5 cm), IPEMB[25] (reference depth = 2 cm) and the NCS[26] (reference depth = 2 cm) dosimetry protocols. The IAEA chamber correction factors were taken from[14] while mass-energy absorption coefficient ratios were from [2].For this work, the correction factors were taken from ref[8].

	ICRU (1973)	IAEA (1987, 1996)	IPEMB (1996)	NCS (1997)	This work
M_{air}	27.99	27.99	27.99	27.99	27.99
B_w	1.252	1.260	1.277	1.281	1.280
$M_{z=ref}$	13.69	13.69	25.84	25.84	25.84
$P_{Q,cham}$	1.000	1.030	1.023	1.005	0.990
$\dfrac{\left[\left(\frac{\mu en}{\rho}\right)_{w,air}\right]_{air}}{\left[\left(\frac{\mu en}{\rho}\right)_{w,air}\right]_{z=ref}}$	1.000	1.000	1.000	0.996	1.000
$PDD_{z=ref}$	0.375	0.375	0.707	0.707	0.707
R	0.960	0.938	0.956	0.976	0.990

Guidelines for dosimetry in other phantom materials

- Determine the surface dose for other phantom materials from

$$D_{\mathrm{med},z=0} = C_{\mathrm{w}}^{\mathrm{med}} D_{\mathrm{w},z=0}$$

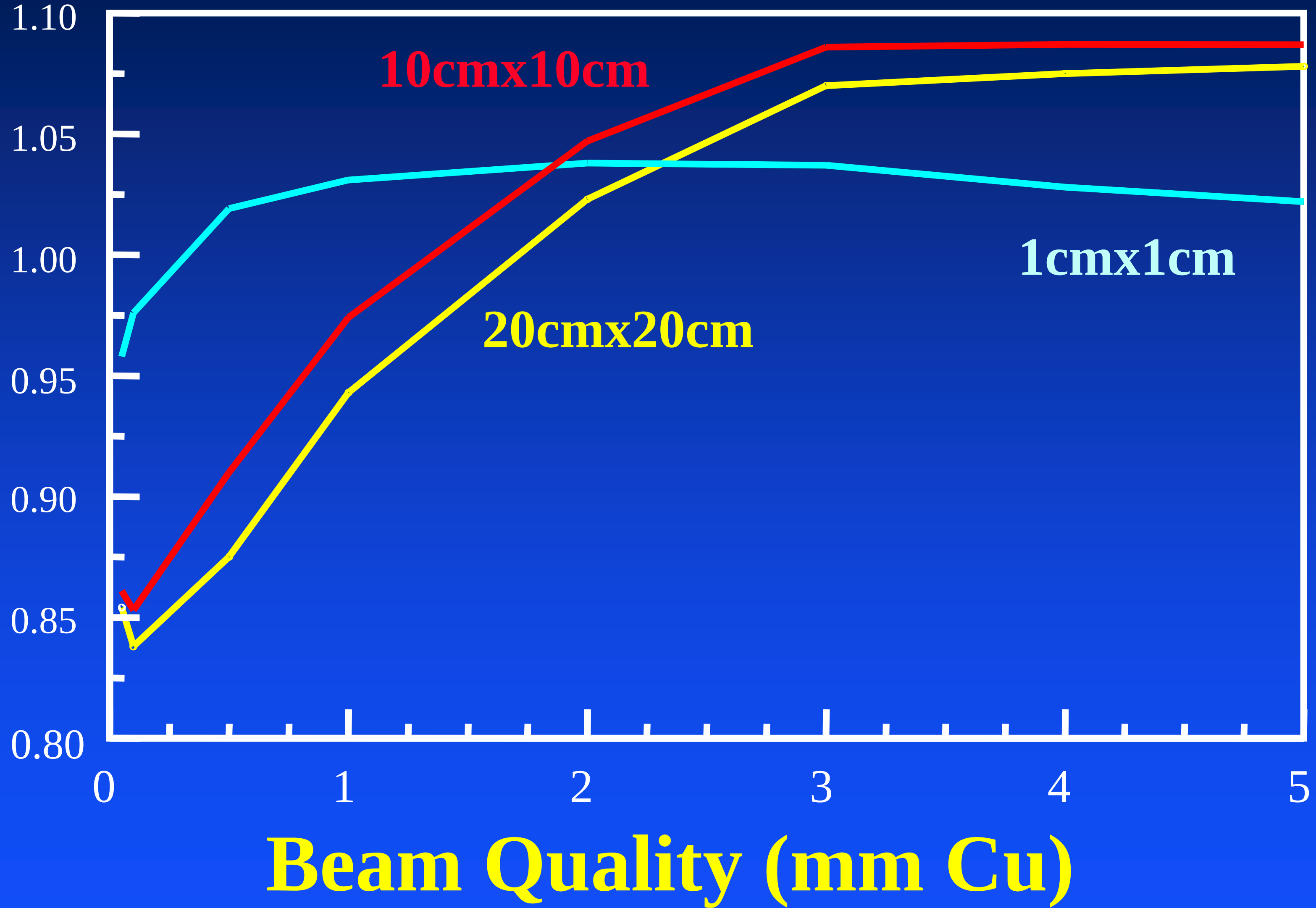
- where

$$C_{\mathrm{w}}^{\mathrm{med}} = \frac{B_{\mathrm{med}}}{B_{\mathrm{w}}} \left[(\mu_{\mathrm{en}} / \rho)_{\mathrm{w}}^{\mathrm{med}} \right]_{\mathrm{air}}$$

Vary significantly

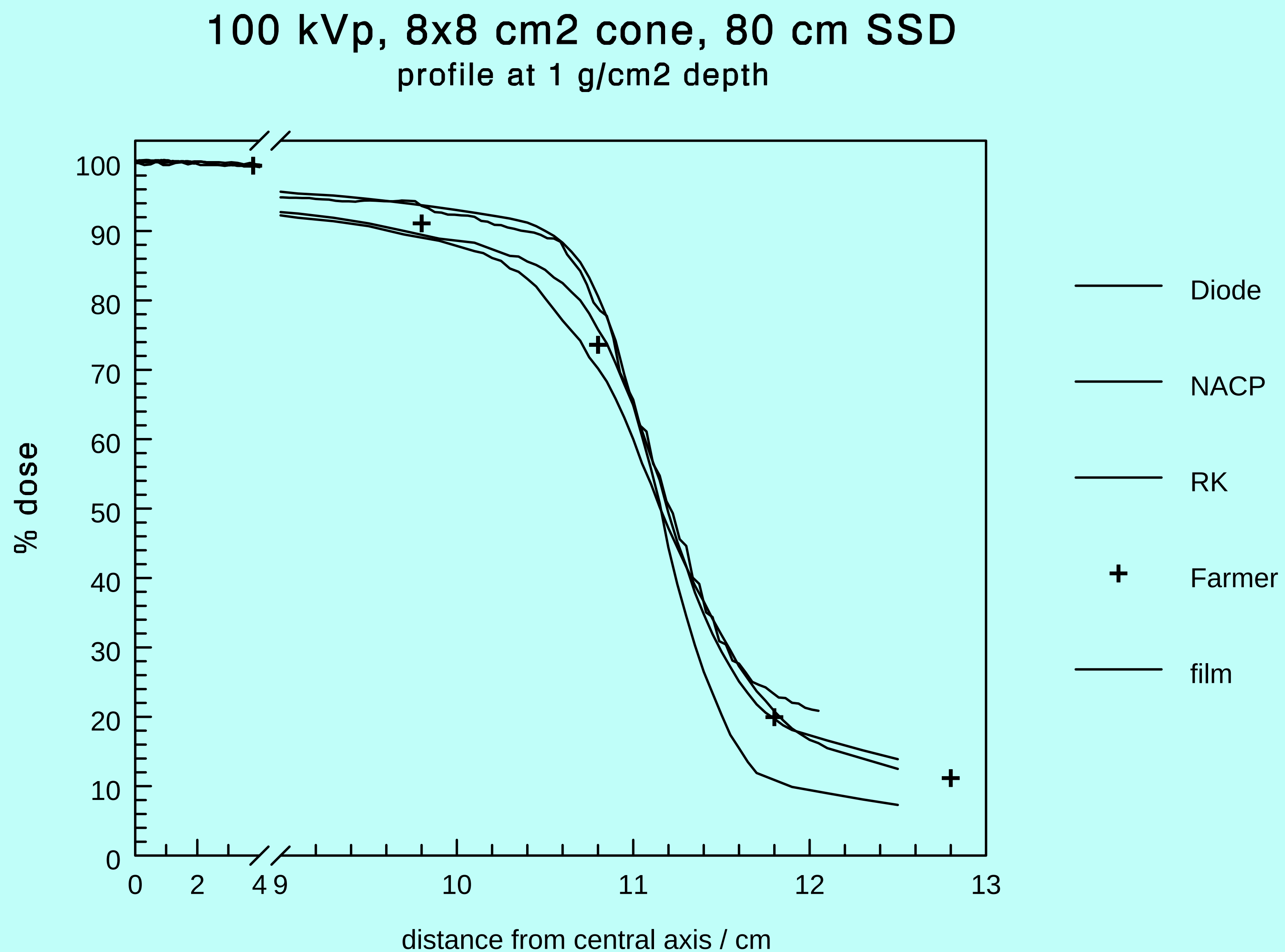
- The backscatter factor ratios are significant for bone to water but close to 1.0 for soft tissues.

Ratio of Backscatter Factors, Bone to Water



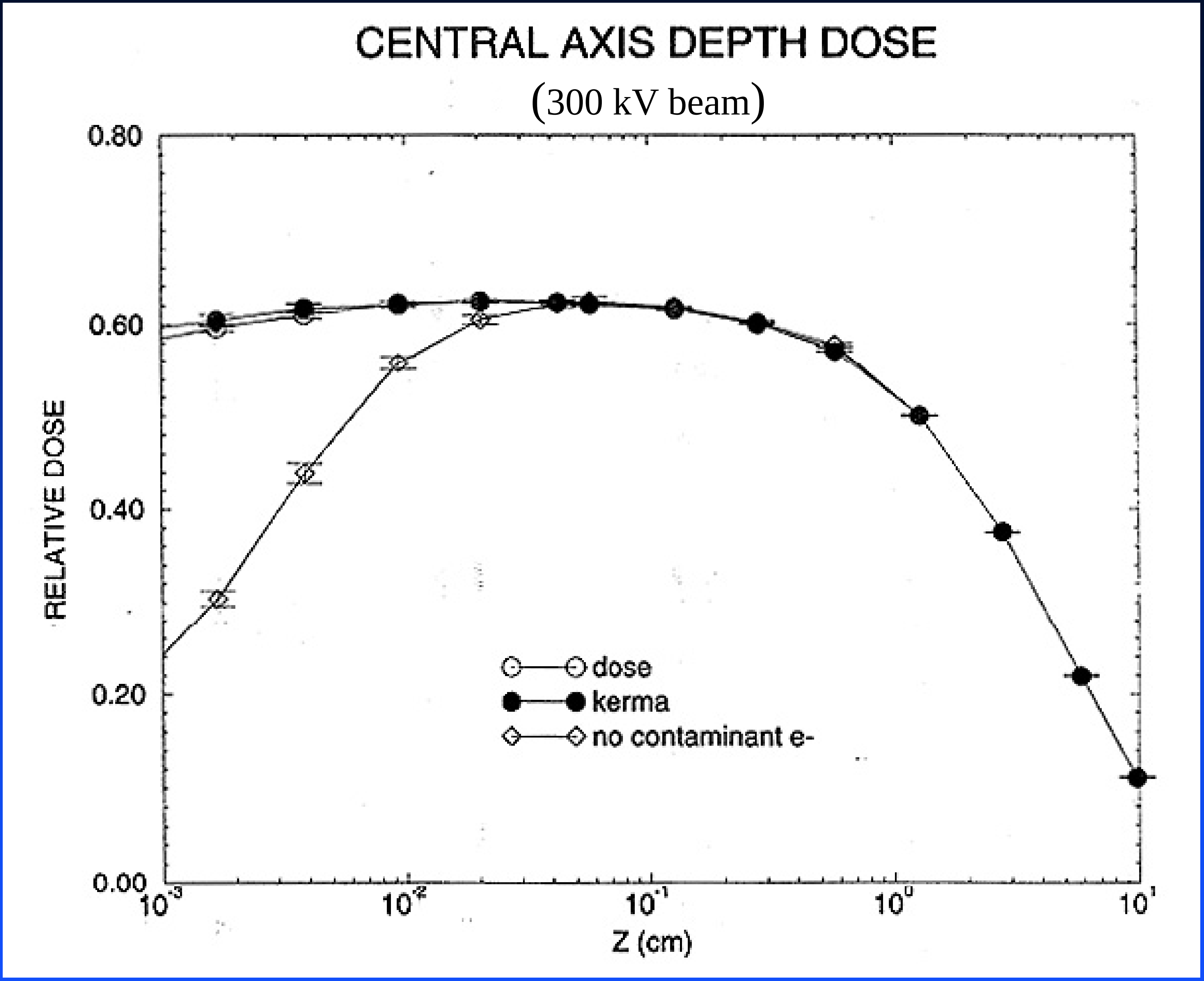
Relative dosimetry measurement

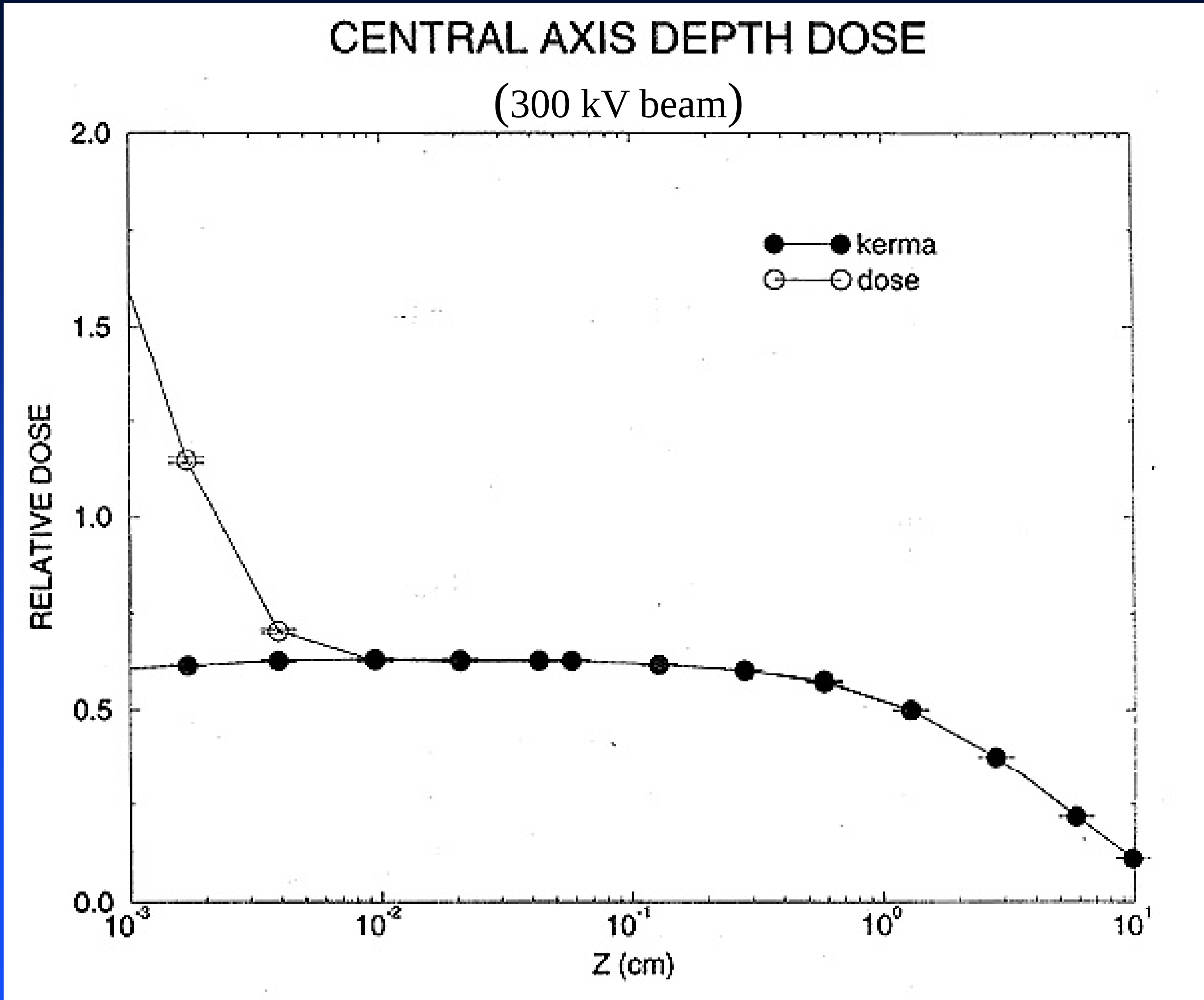
- Large uncertainty in PDD measurements
- Large uncertainty in profile measurements
- Effect of electron contamination
- Choice of detectors
- Choice of phantom materials



100 kVp, 8x8 cm2 cone, 80 cm SSD
profile at 1 g/cm2 depth
% dose
100
90
80
70
60
50
40
30
20
10
0
0
2
4
9
10
11
12
13
distance from central axis / cm
Diode
NACP
RK
Farmer
film

Fig.6


CENTRAL AXIS DEPTH DOSE
(300 kV beam)
0.80
0.60
0.40
0.20
0.00
RELATIVE DOSE
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Z (cm)
dose
kerma
no contaminant e-


CENTRAL AXIS DEPTH DOSE
(300 kV beam)
kerma
dose
RELATIVE DOSE
2.0
1.5
1.0
0.5
0.0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Z (cm)

Summary of TG-61 Recommendations

- Water phantom for absolute dose determination, 2 cm depth for > 100 kV, plastic phantoms for routine checks
- Effective point of measurement: center of air cavity

  40-70 kV: parallel plate chamber
  70-300 kV: cylindrical chamber

- Use both tube potential and HVL for chamber calibration
- Appropriate build-up for parallel plate chambers

Summary of TG-61 Recommendations

- Narrow beam geometry for HVL determination
- What method to use depending on beam quality and point of interest (POI)

  40-100 kV : only the in-air method should be used

  100-300 kV : the in-air method if POI on surface

  100-300 kV : the in-phantom method if POI at a depth

- Inter-compare chamber for correction/conversion factors
- Use HVL as beam quality specifier for conversion and correction factor (tabular data preferred)
- Quality assurance (daily, monthly, annually)

Estimated combined standard uncertainty

TABLE III. Estimated combined standard uncertainty (1 σ) in D_w at the reference depth in kilovoltage x ray beams using a chamber calibrated in-air in terms of air kerma.

	Type of quantity or procedure	Uncertainty (%)	
	In-air method (for low and medium energies)		
1	N_K from standards laboratory or ADCL	0.7	
2	Effect of beam-quality difference between calibration and measurement	2.0	
3	Backscatter factor B_w	1.5	
4	$P_{stem,air}$	1.0	
5	$[(\bar{\mu}_{en}/\rho)^{water}_{air}]_{air}$	1.5	
6	In-air measurement in the user's beam	1.5	
	Combined standard uncertainty for $D_{w,z=0}$		3.5
7	Conversion to dose to tissue at the phantom surface	1.0	
	Combined standard uncertainty for $D_{tissue,z=0}$		3.6
8	Determination of dose at other points in water	3.0	
	Combined standard uncertainty for $D_{w,z}$		4.7
	In-phantom method (for medium energies only)		
1	N_K from standards laboratory or ADCL	0.7	
2	Effect of beam-quality difference between calibration and measurement	2.0	
3	Chamber correction factor $P_{Q,cham}$	1.5	
4	Chamber waterproofing sheath correction factor P_{sheath}	0.5	
5	$[(\bar{\mu}_{en}/\rho)^{water}_{air}]_{water}$	1.5	
6	In-water measurement in the user's beam	2.0	
	Combined standard uncertainty on $D_{w,z=2\text{ cm}}$		3.6
7	Determination of dose at other points in water	3.0	
	Combined standard uncertainty on $D_{w,z}$		4.7

3.5% a
surfac

4.7%
a dept

Conclusions

- Exposure/kerma based dosimetry procedures
- Backscatter method for both low- and medium-energy x-ray beams
- Complete data set available for μ_{en}/ρ, B, $P_{Q,cham}$ and P_{sheath}
- Consistent results using both formalisms

Questions for kV x-ray dosimetry

1. Does a Farmer chamber have enough buildup for kV x-ray beams?
2. Does the Bragg-Gray cavity theory apply to a Farmer chamber for kV x-ray beams?
3. Is the difference between K_{col} and K significant for kV x-ray beams?
4. Are air-filled ionization chambers used as “photon detectors” or “electron detectors” for kV beams?

Answers:

1. Yes, electron ranges < 0.5mm of water
2. No, significant energy deposition from electrons generated in the air cavity
3. No, $g < 0.1\%$
4. “Photon detectors”