

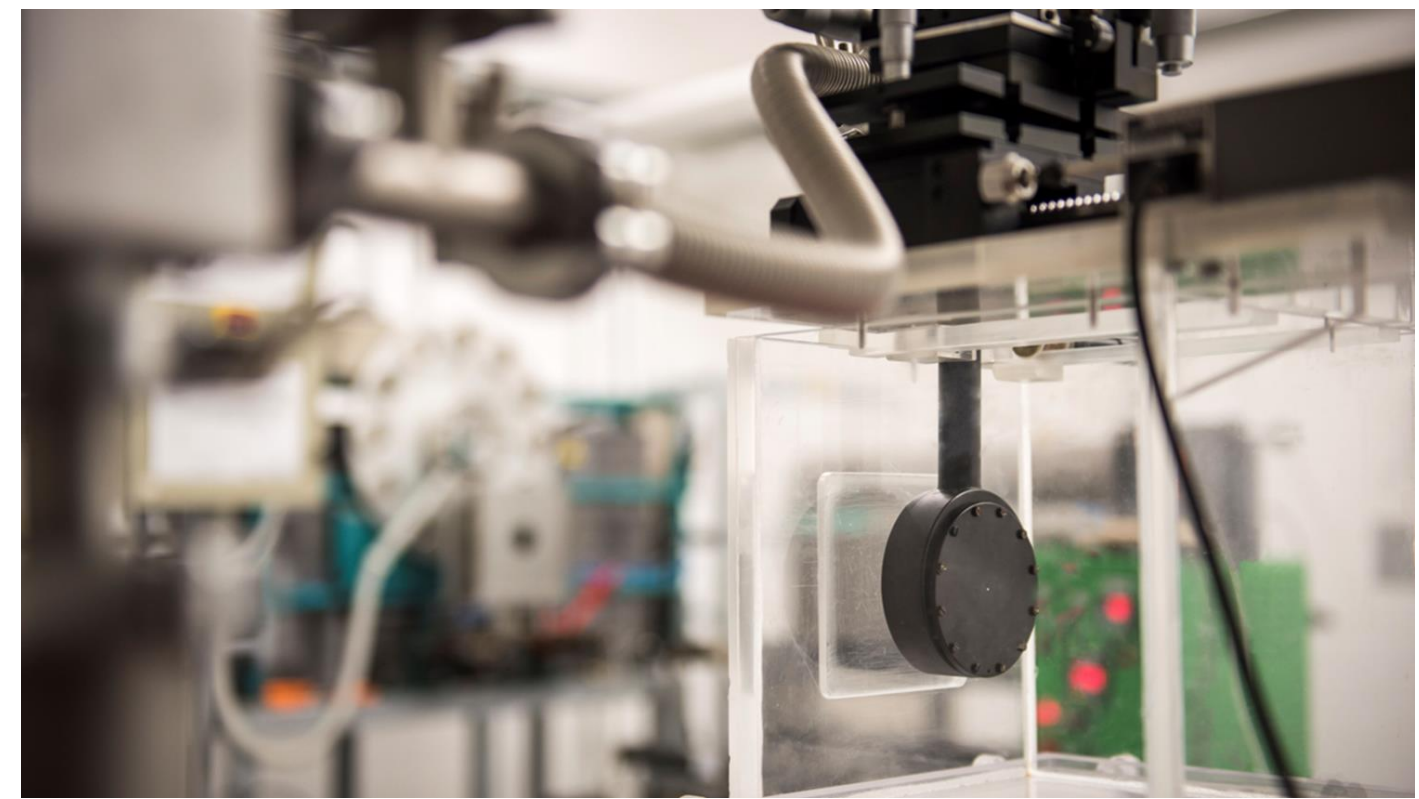
Advancing dosimetry for radiotherapy in medium-energy x-ray beams: the Italian experience at ENEA-INMRI with a graphite calorimeter"

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The aim of this work, carried out at ENEA- INMRI, is to provide data of the calibration factors expressed in terms of D_w (NDwQ) directly determined in water, at 2 g cm⁻² and 98 cm Source to Surface Distance (SSD), for a commercial, Farmer-type IBA FC65-G chamber and a NE2571 chamber, measured through an optimized metrological performance of the Italian Rx calorimeter. The beam qualities are produced at generating potentials between 100 and 250 kV. For high-energy photon, electron, proton, and ion beams, radiotherapy dosimetry can be established using absorbed dose to water (D_w) standards. However, in the domain of medium-energy x-rays dosimetry, there are only few primary standards of D_w available in the world at this time, while calorimetry is comparatively more established at several other radiation modalities employing higher photon energies.

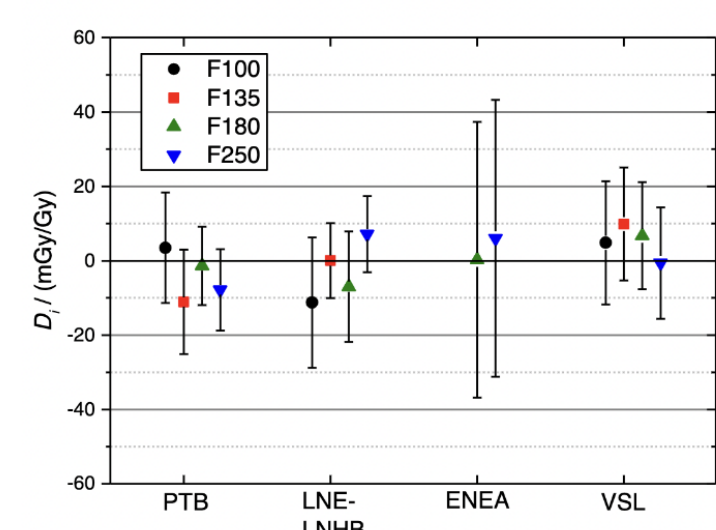
National Standards in medium energy x-ray beams: ENEA RX Graphite Calorimeter

Four primary standards of absorbed dose to water in filtered medium-energy x-ray beams are available at National Metrology Institutes (NMI): three are based on water calorimeters (PTB, Germany; VSL, the Netherlands; LNE-LNHB, France) and one on a graphite calorimeter in a water phantom (ENEA-INMRI, Italy).



The medium energy x-ray beam Rx graphite calorimeter of ENEA-INMRI

The measurement capability of the graphite calorimeter designed and built at ENEA-INMRI was already demonstrated for the CCRI (Consultative Committee for radiation qualities) radiation qualities in the range from 100 kV to 250 kV (CCEMRI 1972) by first participating in a measurement comparison within EURAMET (EURAMET.RI(I)-S13, later linked to BIPM.RI(I)-K9 in 2016 and, in 2018, in a second international comparison that was organised as part of the research project 16NRM03 RTNORM



The BIPM.RI(I)-K9 comparison results for each CCRI quality for ENEA's graphite calorimeter, shown with the results of the German, French and Dutch metrology institutes (PTB, LNE-LNHB and VSL, respectively).

Materials and Methods: X-ray qualities and Ionisation Chambers

Radiation Quality	CCRI-100	CCRI-135	CCRI-180	CCRI-250
Generating Potential / kV	100	135	180	250
Additional Al filtration / mm	3.66	4.08	4.06	4.02
Additional Cu filtration / mm	-	0.20	0.49	1.70
Al or Cu HVL / mm	4.02 (Al)	0.494 (Cu)	0.996 (Cu)	2.498 (Cu)
(μrho) _{air} / cm ² g ⁻¹	0.259	0.183	0.162	0.140
Tube current / mA	20	18	15	13
Mean energy / keV	51.2	69.6	86.8	127.1
Approximate air kerma rate at 10 mA tube current / mGy s ⁻¹	1.0	0.9	1.3	1.6

The medium energy x-ray beam qualities at ENEA-INMRI used in this study.

Air Kerma K and absorbed Dose to water Dw

The calorimeter realizes a measurement of absorbed dose to graphite, D_g , first, which is converted to absorbed dose to water D_w in a second stage. f_c is the measured fractional change of the core thermistor resistance due to irradiation, $\Delta R/R$ and k_{qa} is the quasi-adiabatic energy calibration coefficient, m_c is the mass of its graphite core. Monte Carlo calculations provided the correction factor $C_{w \leftarrow g}$. k_{vol} is a factor correcting for the radial non-uniformity of the beam in the calorimeter core, and k_{sc} corrects for the non-water equivalence of the 4 mm of PMMA phantom entrance window

$$\dot{K} = I_{\text{expanded-collapsed}} \frac{W_{\text{air}}}{e} \frac{\Pi_i k_i}{\rho V \phi(1-g)}$$

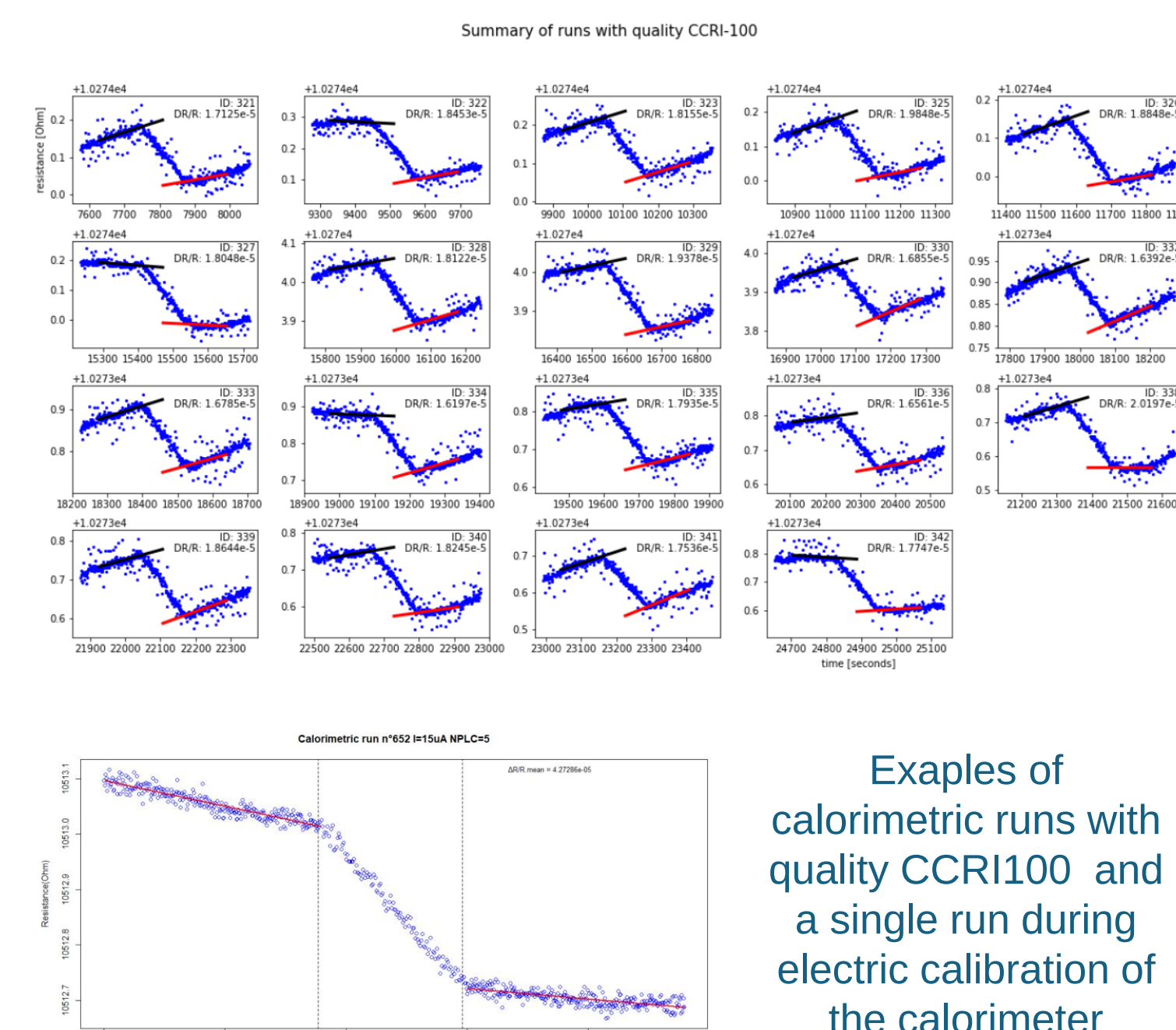
$$\bar{D}_g = \frac{f_c \cdot k_{qa}}{m_c}$$

$$m_c = m_g \cdot k_{mass}$$

$$\bar{D}_w = \bar{D}_g \cdot C_{w \leftarrow g}$$

$$D_w = \bar{D}_w \cdot k_{vol} \cdot k_{sc}$$

Calorimetric Runs and Uncertainties



The IAEA Code of Practice TRS-398 focuses, among other beam qualities, also on medium energy x-rays recommending either an approach based on a direct determination of D_w -when this is achievable- or via a conversion to D_w starting from a measurement of the quantity air kerma whose primary realization is more established at NMIs. The uncertainty budget for the determination of the quantity absorbed dose to water and the uncertainty budget for the estimate of the calibration coefficient NDw, Q for Farmer chambers are shown in the following tables.

source of uncertainty	Type A, %	Type B, %
f_c , fractional change of thermistor resistance during irradiation	0.90	0.14
k_{qa} , quasi adiabatic calibration factor	0.16	0.21
k_r , radial non-uniformity of the calorimeter core	0.14	0.10
$C_{w \leftarrow g}$, graphite to water conversion factor	0.10	0.87
effective core mass	0.10	0.46
monitor chamber normalization	0.05	0.21
calorimeter positioning		0.25
k_{PMMA}	0.10	0.10
quadratic sum	0.94	1.08
combined relative standard uncertainty	1.4	

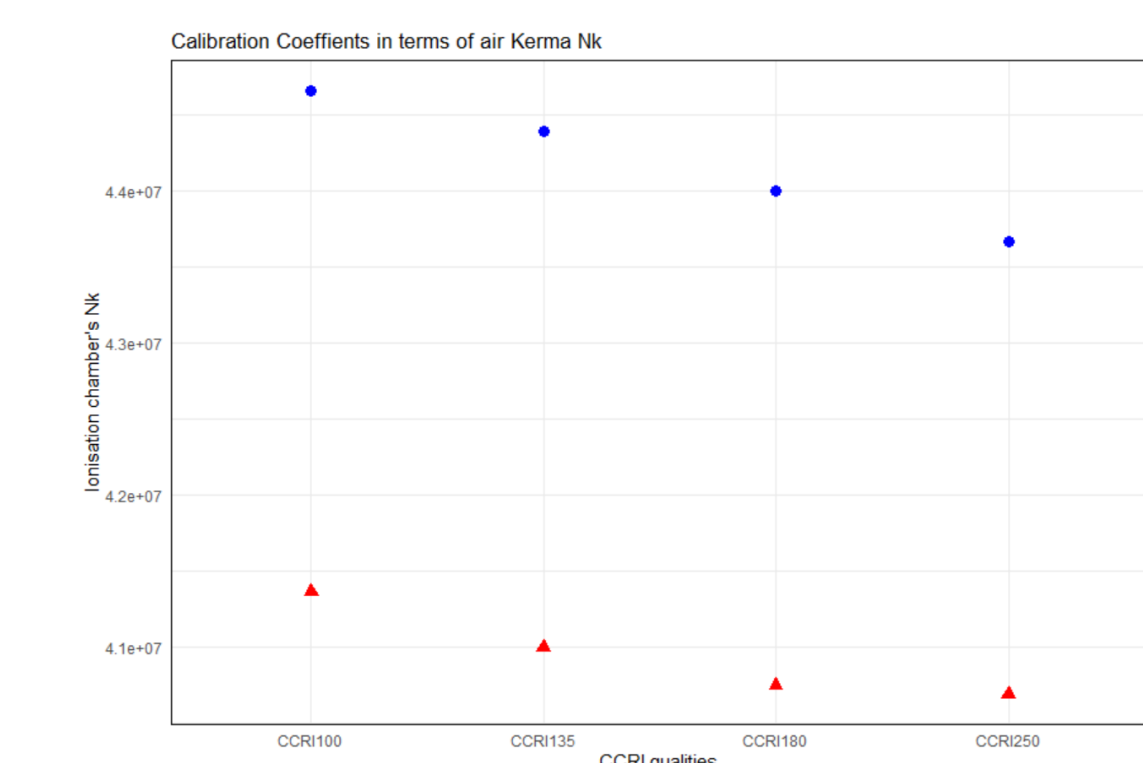
The uncertainty budget for the determination of the quantity D_w in ENEA INMRI

source of uncertainty	Type A, %	Type B, %
D_w standard	0.94	1.08
monitor chamber normalization	0.05	0.16
positioning of the transfer chamber		0.25
chamber signal	0.05	0.13
quadratic sum	0.94	1.13
combined relative standard uncertainty	1.5	

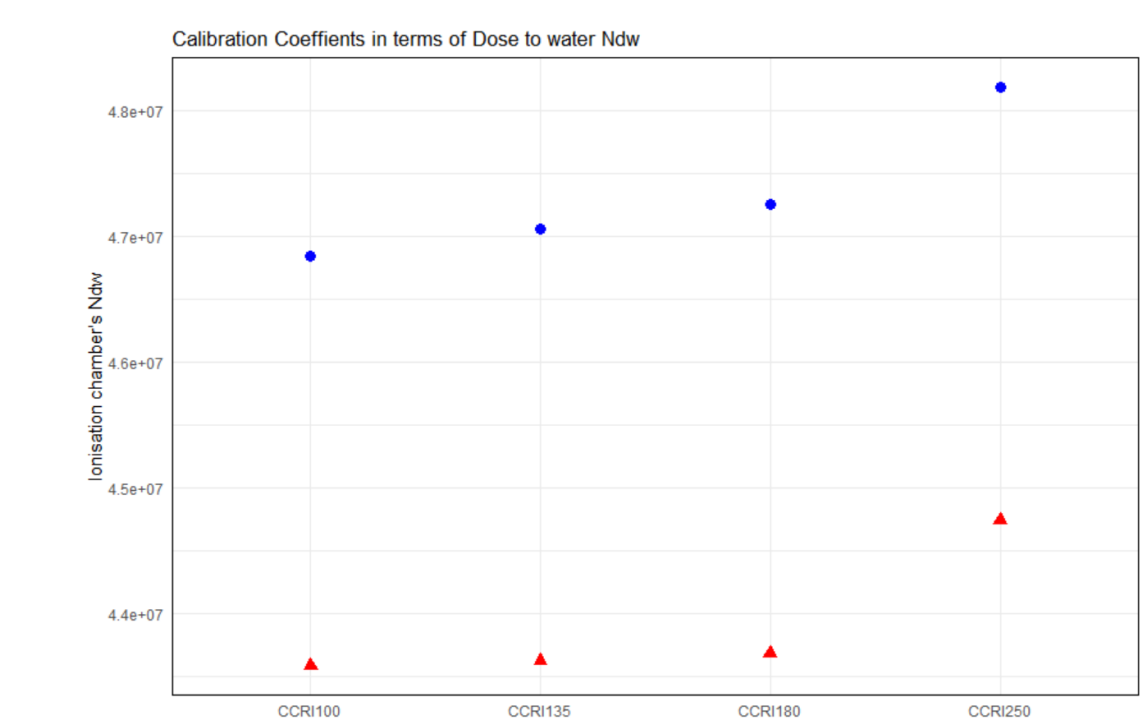
The uncertainty budget for the estimate of the calibration coefficient NDw, Q for Farmer chambers

Analisis and Results

At the kV x-ray beam qualities used, the calibration factors of the ionization chambers were determined in terms of air-kerma with traceability to the Italian national primary standard at ENEA-INMRI, a free-air- chamber, and put in comparison with the set of calibration coefficients expressed in terms of absorbed dose to water, the results can be seen in the following graphs.



Ionisation chambers Calibration coefficients Nk



Ionisation chambers Calibration coefficients NDw



The Farmer chambers IBA FC65-G and NE2571 used for measurements in air and in water.

Conclusions

In this study, in the effort to improve the accuracy of the determination of the quantity absorbed dose to water D_w in medium energy x-ray beams through a refinement of the calorimeter that constitutes the Italian national standard of absorbed dose to water in medium energy x-rays, the calibration coefficients of two types of Farmer Chambers has been determined in terms of air kerma K and in terms of absorbed dose to water D_w , using respectively the free-air-chamber Attix-type chamber Victoreen model no. 451, and the water-graphite calorimeter, in 4 different kV x-ray beam qualities in the range between 100 kV-250 kV.

Physical quantity or procedure	Relative standard uncertainty (%)	
	Ndw based	Nk based
Step 1: standards laboratory		
Calibration of secondary standard (ND or NK) at ENEA-INMRI	1.6	0.42
Long term stability of secondary standard	0.1	0.1
Calibration of the user dosimeter at the standards laboratory	0.5	0.5
Combined uncertainty in step 1	1.6	0.66
Step 2: User X ray beam		
Procedure to obtain the calibration coefficient in the user beam	0.5	0.5
Chamber perturbation correction		1.0
Field size dependence of the chamber perturbation factor		0.5
Ratio of the mean mass energy absorption coefficient water to air		0.5
Geometry correction factor	0.2	
Long term stability of the user dosimeter	0.3	0.3
Dosimeter reading MQ relative to timer or beam monitor	0.1	0.1
Procedure to obtain the calibration coefficient in the user beam	0.5	0.5
Establishment of reference conditions	1.0	1.0
Correction for influence quantities k	0.8	0.8
Combined uncertainty in step 2	1.4	1.9
Combined standard uncertainty of the Q (steps 1 and 2)	1.70	1.61

Table of Uncertainties of the two methods

Using the IAEA TRS-398 formalism the results shown that the calibration of the reference ionization chambers in terms of D_w reached a total uncertainty budget of 1,70% and of 1.61% in terms of air kerma free in air. The uncertainties involved are comparable between the two approaches, and very similar in our case, the direct approach with NDw still remains the most worthy, as per the premise of TRS 398, as well as one of the few still available in the world.