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1 Executive summary

Introduction

Due to both the number of cases of cancer increasing and the ageing of the population, current high levels of demand for diagnostic and interventional radiosurgery, radiology and cardiology procedures will grow. The goal of radiotherapy is to kill tumour cells, while minimising damage to the surrounding healthy tissue; however, small percentage changes in a radiotherapy dose can significantly increase the risk of complications. Uncertainty requirements for radiotherapy and radiosurgery doses are difficult to achieve due to the disparity between calibration and treatment conditions.

This project developed improved calibration practices, better primary dosimeter standards and decreased calibration uncertainties, enabling participating NMIs and DIs to build their own primary dosimeter standards and launch new calibration services. Measurement laboratories accessing these improved calibrations and working with the hundreds of thousands of facilities across Europe, will ultimately bring improved treatment outcomes for patients.

The Problem

There are four million new cases of cancer per year and the number of treatments per year is increasing so there is a need for diagnostic radiotherapy. In addition, the number of interventional radiology/cardiology procedures in developed countries is already very high and will only increase in future due to the ageing of the global population.

The goal of radiotherapy is to kill the tumour cells and simultaneously achieve a high survival rate of the surrounding healthy tissue. A change in the dose of 5 % can result in a normal tissue complication probability of 20 % - 30 %. However the uncertainty requirement for the dose to the tumour (2.5 % ICRU) is not achieved due the gap between the calibration conditions and the conditions used for new treatment modalities based on small and complex radiation fields. This requires the metrological chain to be shortened and hence leading national metrology laboratories have had to launch their own calibration services to answer the needs of the end users.

For diagnostic and interventional radiology/cardiology, the large number of facilities to be calibrated or/and controlled requires the development of a network of primary laboratories that is able to transfer the primary reference to calibration laboratories in their own countries.

In addition to these requirements, there is also the need to evaluate the future end user needs in terms of standards for radiotherapy and for diagnostics.

The Solution

Eight European metrology institutes (NMI/DIs) and two Secondary Standards Dosimetry Laboratories (SSDLs) have developed their skills to build or operate primary standards for water calorimetry for absorbed dose to water, primary standards for an free air ionization chamber and/or primary standards for a cavity ionization chamber.

NMI/DIs relying on secondary standards have been given all of the information needed to be able to design, build and operate primary dosimeters based on water calorimeters, cavity ionization chambers and/or free air ionization chambers. The requirements of ISO/IEC 17025 have been disseminated to facilitate the harmonisation of safer calibration procedures.

The NMI of Bosnia and Hercegovina and the Croatian SSDL have been trained to be able to obtain accreditation in terms of ISO/IEC 17025, and three other NMIs are able to harmonise their self-declared procedures with the one checked by external accreditation bodies.

All partners contributed to harmonised uncertainty budgets to reach 0.5 % and 2.0 % for the reference value in terms of air kerma and absorbed dose to water respectively, calibration procedures and calibration certificates for a better comparison of the capabilities of the laboratories.

Impact

The project created impact on both sides of the metrological chain at the NMI/DI and at the hospital. Within this chain, the work of the NMI/DI or SSDL is to provide national reference values, and to transfer them to the end users.

The participating NMI/DIs and SSDLs got all the information necessary to build and operate primary measurement dosimeters based on a water calorimeter, a cavity ionization chamber and/or free air ionization chambers. After replacing secondary standards by primary standards, the uncertainties associated to the calibration of the transfer dosimeters are significantly reduced.

The project improved and contributed to harmonising the quality assurance procedures for the calibration of transfer dosimeters among the partners following the requirements of ISO/IEC 17025.

By decreasing the uncertainty and harmonising the calibration methods a better knowledge of the doses due to diagnostic irradiation will be achieved, therefore the comparison with the European diagnostic level of reference (DLR) will be possible for radiology services to the benefit of the patients through the optimisation of protection in diagnostic radiology. Decreasing uncertainties and harmonising of the calibration methods for radiotherapy will lead to better treatment outcomes.

Finding companies able to machine with a high level of precision special material such as graphite, an insulator with a high resistance to radiation, is a bottleneck for developing primary dosimeters. Through this project, companies able to do such work got the opportunity to be known through the entire European metrology community for the high quality of their work through dissemination of the project to the EURAMET TC-IR.

2 Need for the project

The very large number of facilities for radiotherapy, interventional radiology/cardiology and radio diagnostic exams requires proximity to calibration services traceable to national primary standards.

There are four million new cases of cancer per year and subsequently the number of treatments per year is increasing so there is a need for diagnostic radiotherapy. In addition, the number of interventional radiology/cardiology procedures in developed countries is already very high and will only increase in future due to the global ageing of the population.

The goal of radiotherapy is to kill the tumour cells and simultaneously achieve a high survival rate of the surrounding healthy tissue. A change in the dose of 5 % can result in a normal tissue complication probability of 20 % - 30 %. However, prior to this project, the standard uncertainty requirement for the dose to the tumour (2.5 %) is very difficult to achieve due the gap between the calibration and treatment conditions. In order to overcome this problem, there was a need for improved traceability of measurement devices, known as dosemeters.

There was a need for leading national metrology laboratories to launch their own calibration services to answer the needs of end users. For diagnostic and interventional radiology/cardiology, the large number of facilities to be calibrated and/or controlled requires the development of a network of primary laboratories that is able to transfer the primary reference to calibration laboratories and end users in their own countries. The primary standards used are either cavity or free air ionisation chambers, used for high and low/medium photon radiation energies respectively, or calorimeters used to measure absorbed dose.

In addition to these requirements, there was also the need to evaluate the future end user needs for standards for radiotherapy and for diagnostics.

3 Objectives

The project addressed the following objectives:

1. To study the design of water calorimeter primary standards so that participating NMIs and DIs seeking to establish a research capability in measuring adsorbed dose to water for high energy beams are able to build and operate the primary standards with a harmonised target uncertainty budget of 2.0 % and harmonised calibration procedures.
2. To study the design of free air chamber primary standards so that participating NMIs and DIs seeking to establish a research capability in measuring the air kerma for low or medium X-ray energies used in radiation protection and diagnostic (i.e. mammography, short pulse) are able to build and operate the primary standards with a harmonised target uncertainty budget of 0.5 % for continuous beam and 1.0 % for pulsed beams and harmonised calibration procedures.
3. To study the design of cavity chamber primary standards so that participating NMIs and DIs seeking to establish a research capability in measuring the air kerma for photon energies such as those of ^{60}Co or/and ^{137}Cs used in radiotherapy are able to build and operate the primary standards with a harmonised target uncertainty budget of 0.5 % and harmonised calibration procedures.
4. To develop for each participant an individual strategy for the long-term development of their research capability in radiation dosimetry including priorities for collaborations with the research and end users community in their country, the establishment of appropriate quality schemes and accreditation (e.g. participation in key comparisons, the entry of CMCs into the BIPM database, accreditation to ISO/IEC 17025). A strategy for offering calibration services from the established facilities to their own country and neighbouring countries will also be established.

4 Results

The main goal of this project was to create research potential for the possible development of primary standards at the partners and eventually at other interested laboratories. The principles of primary measurement methods are well described in the published literature, however the primary standards are not common commercially available products. Based on the information collected in the project, the partners have access to information on existing primary standards, which is not available in the published literature. This is a valuable source of knowledge and experience. A list of potential manufacturers of key components (including contacts and manufacturing cost estimates) was also gathered during the project. This information should help the partners to overcome initial barriers to the development of their own primary standards.

4.1 Objective 1: To study the design of water calorimeter primary standards so that participating NMIs and DIs seeking to establish a research capability in measuring adsorbed dose to water for high energy beams are able to build and operate the primary standards with a harmonised target uncertainty budget of 2.0 % and harmonised calibration procedures

The design of water calorimeter primary standards was studied and developed so that participating NMI/DIs and SSDLs seeking to establish a research capability in measuring adsorbed dose to water for high energy beams are able to build and operate the primary standards with a harmonised target uncertainty budget of 2.0 % and harmonised calibration procedures. After an overview of the main features of the CEA-LNE-LNHB water calorimeter design, the following text summarises key issues for the building and operation of a water calorimeter. Detailed information can be found in the proceedings of the project workshop that is available at http://www.lnhb.fr/pdf/Rapport-CEA-R-6467.pdf.

4.1.1 General overview

CEA's latest generation of water calorimeter is designed to operate at 4 °C, the temperature of the maximum density of water, to minimise convective currents inside the water volume that is used for measurements. The inner part of the water calorimeter consists of a 30×30×35 cm^3 radiotherapy water phantom built with 15 mm thick PMMA and filled with demineralised water.

The temperature rise is measured by two thermistor probes, placed inside a cylindrical quartz vessel filled with high-purity water. This quartz vessel can be inserted in the front face of the water phantom (for measurements at a low depth in water) or placed at any depth in the water phantom. In both cases, the calorimeter is suitable for use with horizontal beams only. To insert the quartz vessel in the front face of the water phantom, the vessel is sealed in a PMMA ring with a silicone joint.

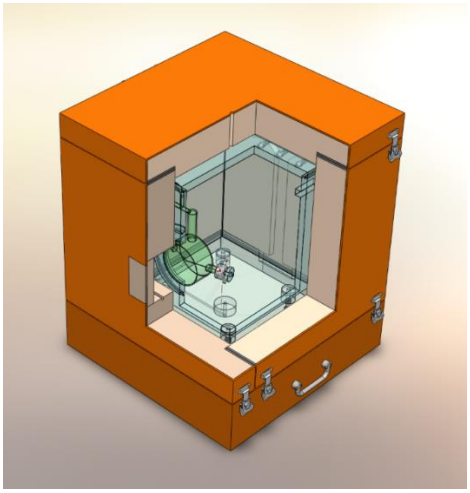

Figure 1: CEA water calorimeter

4.1.3 Key features for building the water calorimeter

- All of the materials are PMMA - extruded polystyrene - PVC box …, except the quartz vessel and capillary that are of standard quality.
- The regulation of the temperature is very important because 4°C will minimise the perturbation due to natural convective thermal transfers inside the water. A water cooling system could be used instead of the cold air circulation that is used in the CEA calorimeter but care must be taken with the entrance window of the calorimeter which has to be as fine as possible in order not to introduce an additional water layer.
- Quartz is chosen for the vessel and the capillary to avoid contamination of the high purity water inside the vessel.
- As the reference depth in water for the definition of absorbed to water depends on the energy of the photons, the calorimeter design must allow the temperature probes to be positioned at different distances. Therefore the front and back faces of the vessel must be as fine as possible, not only to reduce the perturbation of the radiation field and the temperature rise, but also to allow measurement close to the front face.
- The position of the probe inside the vessel is optically measured with a long working-distance microscope objective. This method allows a very small uncertainty such as 50 µm to be reached.
- The heat defect of the water is controlled using high-purity water saturated with nitrogen gas. Argon can be used instead of nitrogen. So special devices must be available in the laboratory to produce this quality of water.
- Air bubbles must be avoided in the capillary which is achieved by using an epoxy resin when putting the probes in the capillary.
- The temperature probe must be calibrated with the best achievable accuracy, namely against the national temperature standard with its own bridge and voltmeter.
- The principle of the electronics is similar for the water and graphite calorimeter, namely DC Wheatstone bridges built with high-precision resistors of 8000 Ω, connected to a precision voltmeter.

- The perturbation factor and the associated uncertainties have to be determined before using the calorimeter:
  - *H,* the water chemical heat defect, is due to chemical reactions in the water and energy deposited in impurities, with a high-purity water such as the one used in the calorimeter this defect is very small but it must be checked for all photon energies. It can reach 0.1 % for medium energy X-rays.
  - k_p is the radiation field perturbation correction factor. It comes first from the thermal enclosure, and particularly from the insulating materials inside the calorimeter window, the quartz vessel and the temperature probes. It is determine using both ionization chamber measurement and Monte Carlo calculation with and without the perturbation.
  - The thermal conduction correction factor (k_c) is studied with a mixed calculation of finite elements and Monte Carlo radiation codes.
  - k_ρ is the density of water correction factor. Since the density of water changes between 4 °C (the temperature of the calorimetric measurements) and 20 °C (the reference temperature for the ionometric measurements), the measured absorbed dose to water must be corrected for this effect. For this the dose gradient at the depth of measurement in water, for the different reference beams, must be known. It is obtained from the central axis depth dose profile in water calculated with a Monte-Carlo code.
- The specific heat capacity of water at 4 °C is taken from the literature to be 4204.8 J kg^{-1} K^{-1}.

4.1.4 Key features for operating the water calorimeter

- As the operating temperature is 4 °C and room temperature is about 20 °C, it is necessary to decrease the temperature inside the calorimeter before measuring the absorbed dose. As the gap between the operating and room temperatures is quite large, a water cooling loop is necessary to speed up the decrease of the temperature inside the calorimeter before the final stabilisation is achieved with the air cooling system. A temperature control loop is necessary to maintain the drift of the temperature to lower than 50 μKmin^{-1}, in order for a negligible temperature rise during irradiation.
- The high-purity water, saturated with nitrogen gas, is pre-irradiated at several hundreds of grays for good control of the heat defect of the water.
- During measurements the Wheatstone bridges are used near equilibrium without re-balancing after each irradiation; instead the bridge equation is applied to calculate the resistance of the thermistors.
- The low thermal diffusivity of water allows the measurement of a local temperature rise over a timescale of a few minutes. The choice of the irradiation time is a compromise between a good signal-to-noise ratio and a minimisation of the thermal transfer effects on the temperature rise measurement. Typically, the irradiation scheme is a sequence of three irradiations of 4 min, followed by a pause of 1.5 h to allow the cone of heat produced by the irradiation in the water to vanish. The temperature rise (ΔT) is determined by an extrapolation to mid-irradiation of the linear fits of the temperature drift before and after irradiation. To account for the temperature probe effect which change the temperature of the water, and which stop the irradiation, the linear fits are calculated with values obtained later than 80 s after the irradiation stops.

4.1.5 Uncertainty budget for the absorbed dose to water measured by water calorimetry

The following tables give examples of the uncertainty budgets achieved for absorbed dose to water measured by water calorimetry in medium energy X-rays (Table 1) and in a Cobalt-60 beam (Table 2).

Table 1: Uncertainty budget for the absorbed dose rate to water D_W measurement in the ISOH300 X-ray beam

Source of uncertainty	Value	Relative uncertainty (%) s_i	Relative uncertainty (%) u_j
Specific heat capacity of water (J kg^{-1} K^{-1})	4204.8	–	0.1
ΔT measurement reproducibility ($N = 102$)	–	0.28	–
Temperature probe positioning	–	–	0.06
Heat defect of water, h	0.0	–	0.3
Thermal conduction correction factor, k_c	[a]	–	0.13
Radiation field perturbation correction factor, k_p	1.0146	–	0.26
Density of water correction factor, k_ρ	1.000 18	–	0.038
Temperature probe depth-in-water correction factor, k_d	1.0007	–	0.15
Temperature probe calibration	–	–	0.1
Irradiation time	–	0.027	–
Quadratic summation		0.28	0.47
Combined relative standard uncertainty (u_c) on $\dot{D}_W$ ($k = 1$)			0.55

[a] Thermal conduction correction factor ($t_{irr.} = 240$ s) applied to each of the three consecutive irradiations of 4 min of one acquisition sequence: $k_c = 1.0081, 1.0064, 1.0059$.

Table 2: Uncertainty budget for the absorbed dose rate to water D_W measurement in the CEA ^{60}Co beam

Source of uncertainty	Value	Relative uncertainty 100 si	Relative uncertainty 100 uj
Temperature probe calibration	-	0.10	
Temperature probe positioning	-		0.10
Specific heat of water (J.Kg^{-1}.K^{-1})	4204.8		0.10
Thermal conduction correction factor k_c	*		0.10
Radiation field perturbation correction factor k_p	1.0033	0.10	
Heat defect of water h	0		0.30
Density of water correction factor $k\rho$	1.00032	0.01	
ΔT measurement reproducibility (N=584)	-	0.12	
Quadratic summation		0.19	0.35
Combined relative standard uncertainty on D_w		**0.39**	

** Thermal conduction correction factor ($t_{irr.}$= 240 s) :*
k_c = 1.0043, 1.0012, 1.0004, 0.9997

4.2 Objective 2: To study the design of free air chamber primary standards so that participating NMIs and DIs seeking to establish a research capability in measuring the air kerma for low or medium X-ray energies used in radiation protection and diagnostic (i.e. mammography, short pulse) are able to build and operate the primary standards with a harmonised target uncertainty budget of 0.5 % for continuous beam and 1.0 % for pulsed beams and harmonised calibration procedures.

The design of free air chamber primary standards was studied and developed so that participating NMI/DIs and SSDLs seeking to establish a research capability in measuring the air kerma for low or medium X-ray energies used in radiation protection and diagnostics (i.e. mammography, short pulse) are able to build and

operate the primary standards with a harmonised target uncertainty budget of 0.5 % for continuous beam and 1.0 % for pulsed beams and harmonised calibration procedures. The following text summarises the key issues for the building and operation of a free-air chamber for low-energy and medium-energy X-rays. The information given below was taken from CMI and BEV-PTP's lectures that were given during the project workshop. Detailed information can be found in the proceedings of this workshop that is available at http://www.lnhb.fr/pdf/Rapport-CEA-R-6467.pdf.

4.2.1 General overview

A free-air chamber (FAC) is usually built as a plan-parallel ionization chamber. A beam of X-rays enters the shielded metal box through an opening of an area A, then it travels between two plan-parallel electrodes and leaves the box through an opening on the opposite side without touching the structure of the FAC. An electric field exists between these electrodes, its homogeneity is maintained by a set of guarding bars/rings connected to an equidistantly divided polarising potential.

Main components of FAC:

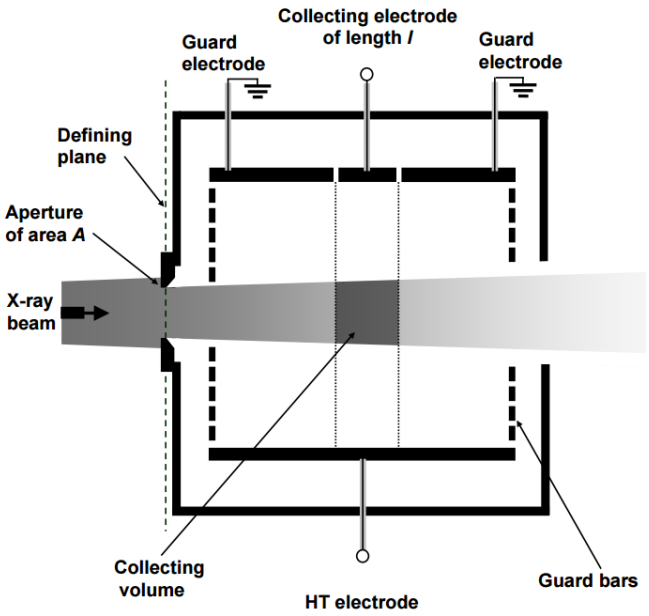

Figure 2: Schematics of a free air ionization chamber

The air kerma is then determined by collecting and measuring the charge created in the measuring/collecting volume:

$$K_{air} = \frac{Q}{m}\frac{W_{air}}{e}\frac{1}{(1-g)}$$

where

Q denotes the collected charge,

m denotes air mass in the collecting volume,

W_{air}/e denotes the energy required to produce an ion pair in dry air (W_{air}/e = 33.97 J/C),

g denotes the fraction of energy loss to bremsstrahlung (for X-rays from 8 kV to 300 kV g is negligible (g = 0)).

Because the collecting volume is a section of air deep inside the FAC and its shape and dimensions are determined by the beam and the effective collector length, it is not possible to measure the actual measuring volume (i.e. the air mass) inside the FAC directly.

However, it can be shown that the charge, Q, collected by a FAC is a measure of the air kerma/exposure at the defining plane of the aperture, corrected for air attenuation between the aperture and collecting electrode. Beam cross-section at the aperture defining plane is equal to the aperture area, A, so the air kerma at the defining plane of the aperture is:

$$K_{A,air} = \frac{Q}{Al.\rho} \frac{W_{air}}{e} \frac{\prod k_i}{(1-g)}$$

where

Q denotes the collected charge,

A denotes aperture area,

l denotes the effective length of the collector (i.e. including half of the air gap),

ρ denotes air density at a pressure of 101.325 kPa, a temperature of 20 ºC and 50 % relative humidity,

Πk_i denotes the product of several correction factors.

4.2.2 Key features for building the free-air chamber

Dimensions:

- *aperture diameter*: ideally this should be as small as possible, but larger then the X-ray tube focus. Some measurable charge/current is needed, so the desired measuring volume should be calculated based on the expected air kerma rates;
- *aperture thickness*: simple solution: calculation of the thickness sufficient to attenuate the primary photons (eg. 1 mm of tungsten for low energies up to 50 keV); more sophisticated approach: MC simulations of the aperture layout and/or shape and optimisation of the aperture influence corrections (useful for medium-energy FAC);
- *aperture-to-collector distance*: has to be larger than the electron range to achieve Charged Particle Equilibrium (CPE);
- *collector length*: ideally this should be as small as possible, because mainly for lower energies the attenuation in air is changing along the collector, but again, some measurable charge/current, is needed so the desired measuring volume based on the expected air kerma rates; for medium energies it can be larger (smaller attenuation change along the collector);
- *internal dimensions* (distance of the internal parts from the beam): has to be larger than the electron range => for low energies: simple calculation based on the electron range, for medium energies: MC simulations and optimisation;
- *outer radiation shielding thickness*: has to ensure sufficient attenuation to minimise the wall transport.

Precise measurements of the following dimensions are necessary using the CMM (Coordinate Measurement Machine): the aperture diameter and length, collector length and air-gap dimensions, aperture-to-collector distance, mutual levelness of the collector and the base electrode. These dimensions are critical for the accuracy of the air kerma determination, so the FAC design should ensure that they would never change after the FAC assembly.

High voltage:

- An electric field strength of approx. 100-200 V/cm is required for sufficient charge collection, i.e. the HV should be approx. 1 kV - 2 kV for low-energy, 4 kV - 6 kV for medium-energy.

Material and make:

- *diaphragm*: tungsten (stable shape, high density, high Z); precise aperture, dimension measurements by CMM (Coordinate Measuring Machine) the necessary with an accuracy of few µm;
- *electrodes*: aluminium alloy; no need for special surface processing, a clean smooth glossy surface is sufficient, however the graphite layer on the base electrode and the collector recommended are by BIPM [3]. *insulators* (i.e. distance pieces between guard electrodes, collector holder): stable shape necessary, carefully cleaned surface to lower the leakage current: sapphire, glass, durable plastic;
- *outer shell*: e.g. stainless steel, lead for the front plate. FAC can be shielded just on the front plate (the impacting beam of X-rays is narrow) or fully shielded on all sides (however this leads to a large total mass of FAC).

Guard electrodes:

- Ideally as many as possible to achieve a homogenous electric field, however a compromise has to be found between the space available and the electric field requirement.
- Preferably thicker electrodes, with a thinner air gap.
- Electric field simulation made using the QuickField™ (finite-element simulation software).

Voltage divider:

- Distributes the HV equidistantly to the guarding electrodes. It is made of resistances of 10 MΩ and placed outside the chamber to reduce heating.

Wires:

- FAC is electro-magnetically shielded, nevertheless it is recommended to use shielded coaxial cables inside the chamber.

Connectors:

- The Measuring chain is similar to that of a secondary chamber, therefore: signal - BNC connector, HV - determined by the HV source (up to 5 kV: SHV Kings1704-1, 5 kV up to 20 kV: Kings1764-1).

Measuring apparatus:

- The same consideration as for a secondary ionization chamber is valid in that the uncertainty of the charge (current) measurement directly influences the resulting air kerma uncertainty, so a precise electrometer (e.g. Keithley 6517A,B) and a stable HV source (eg. Keithley 2290-5 or 2290-10) are necessary.
- An internal temperature sensor is recommended.

Correction factors:

- *"usual"*, i.e. corrections which are the same as for a secondary ionization chamber: correction for humidity, k_h, air pressure and temperature, $k_{T,p}$, correction for HV polarity, k_{pol}, and saturation, k_s;
- *electric field distortion,* k_d*:* it is assumed that the collected charge is evenly distributed between the collector and the base electrode. If the guarding bars are not correctly designed or working or if the collector is not flush with the base electrode, the electric field is not homogenous, the charge is not collected as assumed, thus the collecting volume is not correctly defined. Field homogeneity is usually verified by simulations using a finite element analysis system QuickField™ (Tera Analysis Ltd.). The correction is usually equal to 1, so no correction is applied. Instead an additional uncertainty is introduced to account for this deficit.
- *attenuation,* k_{att}: correction for the attenuation of primary photons between the aperture and the collector; can be determined experimentally (several ways), calculated analytically using μ_{en} values or by MC simulations;
- *scattered photons,* k_{sc}*, and fluorescence photons from Ar,* k_{fl}: correction for secondary photons contributing to the collected charge; can be determined experimentally (tube along the beam inside the chamber) or by MC simulations;

- *charge loss,* k_e: correction for electrons impacting the internal parts of the chamber, thus not contributing to the collected charge; equals 1 for internal dimensions larger than the electron range. Calculated by MC simulations;
- aperture influence: correction for the *transmission* of photons through the aperture, k_{dtr}, and for photons *scattered* on the aperture edge, k_{dsc} - MC simulations;
- *outer wall,* k_p: correction for photon transmission through the outer wall - MC simulations;

4.2.4 Key features for operating the free-air chamber

The measuring method is the same as for the secondary chamber, except that a precise electrometer of a reference class is preferred (eg. Keithley 6517A, B). The main difference is the correct positioning of the FAC, because the chamber axis has to be placed exactly into the beam axis. Therefore a positioning (tilting and shifting) table is necessary as is a method to verify the correct FAC position (e.g. using imaging foils).

4.2.5 Uncertainty budget for the air kerma measured by the free-air chamber

The following tables gives examples of the uncertainty budgets of different free-air chambers extracted from the CCRI(I) key comparison reports published since 2000.

Table 3: Low-energy FACs

Standard	**BIPM**		**LNHB**		**BEV-PTP**		**GUM**	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0007	0.0011	0.0004	0.0016	0.0005	0.0006
Volume	0.0003	0.0005	-	0.0005	-	0.0010	0.0001	0.0005
Positioning	0.0001	0.0001	-	0.0010	-	0.0004	0.0001	0.0001
Correction factors (excl. k_h)	0.0003	0.0012	0.0005	0.0019	0.0005	0.0061* 0.0037	0.0010	0.0009
Humidity k_h	-	0.0003	-	0.0003	-	0.0003	-	0.0003
Physical constant	-	0.0015	-	0.0015	-	0.0015	-	0.0015
Air kerma rate	0.0005	0.0019	0.0009	0.0029	0.0006	0.0066* 0.0045	0.0011	0.0019
	0.0020		**0.0030**		**0.0066*** **0.0045**		**0.0022**	

*for the 10 kV quality

Table 4: Medium-energy FACs

Standard	BIPM		LNHB		BEV-PTP		GUM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0007	0.0011	0.0004	0.0008	0.0005	0.0006
Volume	0.0001	0.0005	-	0.0005	-	0.0010	0.0001	0.0005
Positioning	0.0001	0.0001	-	0.0010	-	0.0004	0.0001	0.0001
Correction factors (excl. k_h)	0.0003	0.0010	0.0005	0.0019	0.0004	0.0023	0.0011	0.0008
Humidity k_h	-	0.0003	-	0.0003	-	0.0005	-	0.0006
Physical constant	-	0.0015	-	0.0015	-	0.0015	-	0.0015
Air kerma rate	0.0004	0.0019	0.0009	0.0029	0.0006	0.0031	0.0012	0.0020
	0.0019		**0.0030**		**0.0032**		**0.0023**	

4.3 Objective 3: To study the design of cavity chamber primary standards so that participating NMIs and DIs seeking to establish a research capability in measuring the air kerma for photon energies such as those of ^{60}Co or/and ^{137}Cs used in radiotherapy are able to build and operate the primary standards with a harmonised target uncertainty budget of 0.5 % and harmonised calibration procedures.

The design of cavity chamber primary standards was studied and developed so that participating NMI/DIs and SSDLs seeking to establish a research capability in measuring the air kerma for photon energies such as those of ^{60}Co or/and ^{137}Cs used in radiotherapy are able to build and operate the primary standards with a harmonised target uncertainty budget of 0.5 % using harmonised calibration procedures. Information collected in the project should create research potential in the area of possible development of partners' and other interested laboratories own primary standards. The following text summarises the key issues for the building and operation of a cavity chamber. The information given below is taken from the CMI, IST, IFIN-HH, and BEV-PTP's lectures that were given during the project workshop. Detailed information can be found in the proceedings of this workshop that is available at http://www.lnhb.fr/pdf/Rapport-CEA-R-6467.pdf.

4.3.1 General overview

A cavity chamber is an air cavity surrounded by an "air-equivalent" wall, with atomic number, Z, similar to the effective atomic number of air, Z_{air}, with a larger density, and with a thickness that allows CPE to exist. The wall material is usually graphite.

In order to make charge measurements, a high voltage is applied to the outer electrode of the cavity chamber (the graphite wall) and a central electrode is placed inside the chamber so that it collects the charge created in the air cavity. This central electrode is preferentially made of the same material as the wall, in order to have a homogeneous cavity. Insulators are placed between the two electrodes and a guard ring is placed in order to prevent leakage (Figure 3). Cavity chambers are usually vented. The venting hole allows the air inside the cavity to be related to the air outside it.

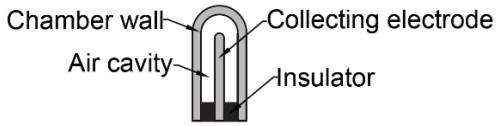

Figure 3: A schematic of a cavity chamber, including a collecting electrode and the insulator between it and the outer electrode (the wall)

Cavity theories can be applied when Bragg-Gray conditions exist. These conditions state that the cavity should be small (compared to the electrons range), so that it does not disturb the fluence of the electrons crossing it (CPE or TCPE) and that the thickness of the wall should be at least equal to the maximum range of secondary electrons released by photons, so that only the electrons crossing the cavity contribute to the absorbed dose.

Under these conditions, the air kerma is written as:

$$K_{air} = \left(\frac{Q}{m_{air}}\right)\left(\frac{\overline{W}}{e}\right)_{air}\left(\frac{\overline{\mu}_{en}}{\rho}\right)_{air,wall}\overline{S}_{wall,air}\left(\frac{1}{1-\overline{g}_{air}}\right)$$

where

Q denotes the collected charge,

m_{air} denotes air mass in the collecting volume,

W_{air}/e denotes the energy required to produce an ion pair in dry air (W_{air}/e = 33,97 J/C),

$(\mu_{en}/\rho)_{air,wall}$ denotes mean air-to-graphite mass energy absorption coefficient ratio,

$S_{wall,air}$ denotes the mean graphite-to-air mass stopping power ratio

g_{air} denotes the mean fraction of the energy of the electrons liberated by the photons lost in the radiative processes in air.

The charge Q is measured under experimental conditions. This equation gives the air-kerma under ideal conditions. To determine the quantity under real conditions, correction factors must be taken into account.

4.3.2 Key features for building the cavity chamber

Choice of wall material:

Graphite is the most used wall material for cavity chambers, due not only to its atomic number (*Z*=6), similar to that of air, but also because it is readily available with high purity and known composition, it is dimensionally stable, its machining can be made with high precision and it is also an electrical conductor. For graphite cavity walls, a thickness of 3 mm is sufficient to attend the Bragg-Gray conditions.

Choice of insulators:

Usual insulating materials for use in ionization chambers are polystyrene (PS), polyethylene (PE), polytetrafluoroethylene (PTFE, commercial name: Teflon), polymethylmethacrylate (PMMA) or polycarbonate (PC, commercial name: MAKROLON), all with very good electrical insulating characteristics. Even though Teflon is very highly resistant to humidity in air, it is very easily damaged by radiation, for doses from approximately 10^4 Gy, so this is an insulator that should be avoided when constructing ionization chambers.

A good solution is provided by cross-linked polystyrene (X-linked PS), as its volume resistivity is almost as good as that for Teflon, and even though its resistance to humidity is not as good, it is very radiation resistant.

Cleaning:

Electrical leakage is a surface effect that can be reduced if all the surfaces of the insulator are properly cleaned and polished. In particular, humidity, oil or skin transferred to the insulator, or any kind of dirt (like graphite dust, for example) may be responsible for leakage and affect the measurements.

These problems can be avoided if the insulators are handled with gloves and if the insulators are wiped with pure ethyl or methyl alcohol using a cotton swab and polished. The dusts that can contaminate the surface of the insulators can be blown away with a rubber syringe, for example.

Cavity chamber design:

The cavity chambers used as national standards may have several shapes, for example PTB has cylindrical models, whereas BIPM holds parallel plate chambers. NIST has spherical models, which are the same as at CEA/LNE-LNHB, which also holds cylindro-spherical ones.

In cylindrical chambers, the effective collecting volume of the cavity is smaller than its geometrical volume, because the conducting surfaces of the chamber (the walls) meet at right angles and in the close vicinity of those corners, in the top and bottom of the chamber, the electric field is approximately null (see figure 1.b). Charged particles generated in those regions will therefore not contribute to the collected ionization current. For cavity chambers with spherical geometry there are no corners between the conducting surfaces (see figure 1.a) and in that case the dead volume is drastically reduced. The electric field inside the cavity chamber can be simulated with finite element calculations. The chamber is built in two parts that are joined preferably with a push fit, without any glue or screws.

Verification of the machining quality of the graphite walls:

After the chamber is constructed, its interior has to be inspected through the observation of radiographs in order to evaluate the machining of their interior in different angles, to evaluate the adjustment of the two parts of the chamber, namely if there are any air gaps between them, which could influence the inner volume of the chamber, and the uniformity of the wall's thickness.

Assembling the chamber:

Figure 3 gives an example of a central electrode and graphite wall connection. It is recommended to verify the assembly of the chamber by radiographs.

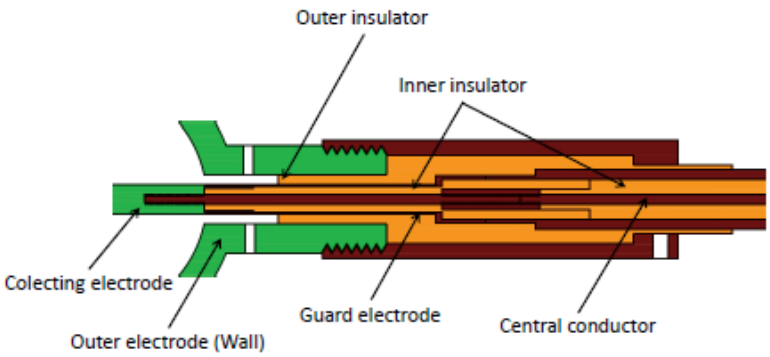

Figure 4: Representation of the assembly of the two groups of insulators and the guard ring

Collecting volume of the cavity chamber:

Determining the collecting volume is one of the most important aspects related to the construction of air kerma cavity standards, since the collected charge depends directly on it. Once the geometrical volume is identified

as being identical to the effective volume, the next step is to establish a method to calculate the geometrical volume.

The effective collecting volume is defined as the volume inside the cavity where charged particles are generated and collected by the inner electrode, and then measured. The methodology consists of determining the inner volume of the cavity, V_{int}, to which the volumes of the central electrode, $V_{central}$, and of the chamber's neck, V_{neck}, as well as a small volume below the central electrode, V_0, are subtracted.

The effective collecting volume is hence given by the expression:

$$V_{eff} = V_{int} - V_{central} - V_{neck} - V_0$$

The inner volume of the graphite chamber can be measured using the gravimetric method - by weighing the contents of a suitable liquid of known temperature and density, usually pure water. The volumes $V_{central}$, V_{neck} and V_0 can be obtained by length measurements e.g. using a length scale interferometer.

Correction factors:

- corrections which are the same as for a secondary ionization chamber: correction for humidity, k_h, air pressure and temperature, $k_{T,p}$, correction for HV polarity, k_{pol}, and saturation, k_s;
- *wall correction,* $k_{wall} = k_{at} \cdot k_{sc}$ is a central subject in the current state of the art of the air-kerma cavity standards. It is introduced to take into account the attenuation and scatter in the cavity wall. Before 2000, k_{wall} was determined experimentally, by linearly extrapolating the measured results to zero wall thickness. After the limitations of the extrapolation methods were demonstrated and the results for the wall correction factors using different MC codes were validated, most of the primary standards laboratories re-evaluated the k_{wall} for their standards;
- *correction for axial non-uniformity,* k_{an}: The radiation intensity varies according to the inverse square law. Given that a cavity chamber has a finite volume and is centred at the reference point where the air-kerma rate is to be determined, its response will depend on this distance variation. k_{an} may be obtained using MC simulations;
- *correction for radial non-uniformity,* k_{rn}: correction for beam radial non-uniformity in the finite volume of the ionization chamber;
- *stem correction,* k_{stem}: correction for the presence of the chamber stem, can be determined by MC simulations or experimentally;

4.3.3 Key features for operating the cavity chamber

The measuring method is the same as for the secondary chamber, except that a precise electrometer (reference class) is preferred (eg. Keithley 6517A,B).

4.3.4 Uncertainty budget for the air kerma measured by cavity chamber

The following table gives an example of the uncertainty budget of a primary cavity chamber at BEV-PTP (Austria).

Table 5: Uncertainty of Calibration Coefficients BEV-PTP Primary Standards for Co-60 for Air Kerma

symbol	$u_{i,A}$	$u_{i,B}$	$u^2_{i,A}$	$u^2_{i,B}$
ρ_a	-	0,01 %	-	0,000 1 %^{2}
V	-	0,12 %	-	0,014 4 %^{2}
W/e	-	0,15 %	-	0,022 5 %^{2}

symbol	$u_{i,A}$	$u_{i,B}$	$u_{i,A}^2$	$u_{i,B}^2$
g_a	-	0,02 %	-	0,000 4 %^{2}
$(\mu_{en}/\rho)_{a,c}$	-	0,05 %	-	0,002 5 %^{2}
$S_{c,a}$	-	0,30 %	-	0,090 0 %^{2}
k_{pol}	0,02 %	-	0,000 4 %^{2}	-
k_s	0,02 %	0,02 %	0,000 4 %^{2}	0,000 4 %^{2}
k_h	-	0,03 %	-	0,000 9 %^{2}
k_{stem}	0,02 %	0,02 %	0,000 4 %^{2}	0,000 4 %^{2}
$(k_{at} \cdot k_{sc})$	0,02 %	0,10 %	0,000 4 %^{2}	0,010 0 %^{2}
k_{an}	-	0,10 %	-	0,010 0 %^{2}
k_m	-	0,02 %	-	0,000 4 %^{2}
			$\sum_i u_{i,A}^2$	$\sum_i u_{i,B}^2$
			0,001 6 %^{2}	0,152 0 %^{2}
			$U_{N_K} = \sqrt{\sum_i u_{i,A}^2 + u_{i,B}^2} \quad (k=1)$	
			0,39 %	

4.4 Objective 4: To develop for each participant an individual strategy for the long-term development of their research capability in radiation dosimetry including priorities for collaborations with the research and end users community in their country, the establishment of appropriate quality schemes and accreditation (e.g. participation in key comparisons, the entry of CMCs into the BIPM database, accreditation to ISO/IEC 17025). A strategy for offering calibration services from the established facilities to their own country and neighbouring countries will also be established.

The individual strategy was prepared for the long-term development of partners' research capability in radiation dosimetry. Depending on the situation, it includes priorities for collaborations with the research and end users communities in their country, the establishment of appropriate quality schemes and accreditation to ISO 17025 (e.g. participation in key comparisons, the entry of CMCs into the BIPM database) with the final goal to launch calibration services for the benefit of end users.

As written above, before launching new services it is necessary to get an ISO 17025 accreditation. Two conditions must be fulfilled to get it: (i) the quality system must fulfil the requirements of ISO 17025 in terms of management and measurements and (ii) the laboratory must attend comparisons. After getting the accreditation, it is possible to propose CMC lines and finally to launch calibration services.

The analysis of the partners' calibration methods showed that the existing procedures follow the requirements of ISO 17025, and a few improvements were made following the analysis of the calibration certificate templates. Thus, these analyses allowed the partner's protocols to be harmonised. Two peer review audits (IMBiH and VINS) were organised as this audit is needed to get the accreditation, whatever the chosen accreditation scheme (external or self-accreditation). IRB got its ISO 17025 accreditation in Nov. 2016.

Some partners already started building primary standard during the project, i.e. IST, CMI and IFIN-HH for cavity chambers, GUM, SCK-CEN for water calorimeters. Midterm strategies were established to develop free air chambers at IST, CMI and SCK-CEN. Once these standards are fully operational those NMI/DIs will be able to participate in international comparisons with an improved uncertainty level.

CEA did not add new CMC lines during the project as the existing ones already cover radiotherapy, radio diagnostic and radiation protection calibrations. CEA will continue to study the stakeholder feedback to develop new references, namely for radiotherapy to follow the evolution of the techniques toward small stereotactic radiation beams. It plans to attend the 2018 BIPM on going key comparison for low and medium energy X-rays. CEA will continue to run its external ISO 17025 accreditation. CEA will continue its effort to share its knowledge about primary standards with NMI/DIs.

IRB plans to get new accreditations in 2018 for: (i) Calibration in the field of radiation protection (chamber and detector) in the field of Cs-137 and N beam X-ray qualities, and (ii) Calibration in the field of diagnostic radiology - mammography, tomography and RQR qualities. IRB published two new CMC lines in 2017 for absorbed dose and air kerma calibration in Co-60 beams. IRB attended bilateral comparisons with IAEA (i) using chambers for diagnostic radiation qualities RQR5, RQT9, RQR-M2, RQA-M2, and (ii) using chambers for radiation protection with Cs-137

The BEV-PTP CMCs will be kept up to date as well as the calibration services. In 2019, they plan to attend the key comparison for absorbed dose to water for Co-60 and air kerma for Cs-137 and Co-60.

IMBiH started establishing calibration services for radiation protection. It has not submitted a CMC claim yet because of the lack of international comparison. The protection level bilateral comparison in terms of air kerma with IAEA is planned for February/March 2018, and it is planned to use it as supporting evidence to publish relevant CMCs in the KCDB of CIPM MRA for air kerma and dose equivalent quantities. If other comparisons for protection level with Cs-137 are made available at the EURAMET TC-IR meeting in February 2018, IMBIH will ask to participate. The timeline for submitting the CMC claim is not fixed, however, it is hoped to have the claim submitted before the end of summer 2018. To avoid delaying the services, radiation protection calibrations will be available (with or without CMCs – depending on how quick the procedure is) in 2018. The next phase will be to meet other stakeholder needs to provide calibrations in the area of diagnostic radiology and X-ray calibration (protection and diagnostic level). This new phase is planned in a new IAEA TC 2018-2019 project. This project starts in January 2018. After the end of this project, other projects, such as IMBIH cooperation with PTB (2018-2021) and CMI (2018-2020) will be used for knowledge transfer and bilateral comparisons.

SCK-CEN does not plan to extend their CMC list in the short term future. Only the declaration of BIPM should be updated when new official comparisons are completed. The existing CMC will need to be moved to the new building and the installations will need a complete re-characterisation. Based on the present planning of the project, the radiotherapy calibrations (in terms of Dw and Ka) represent the first priority and it was requested that the installation is commissioned first. Participation in official comparisons to support the existing CMC will be of high importance. In January 2018, SCK-CEN plans to attend the IAEA/SSDL comparison of therapy level ionization chamber calibration coefficients" for the beginning of 2018.

The long-term strategy of IFIN-HH, based on the results of this project, consists of the development of new calibration services, dedicated to medical dosimetry. This strategy, which is now in progress is considering the development in IFIN-HH of a new calibration facility for radiotherapy; it will include a new irradiator with a Co-60 radioactive source (activity of 5000 Ci). The funding of this facility was approved by the ministry in December 2017. Using this new calibration facility, new calibration procedures will be implemented, and the results of this project will be used. When the new calibration facility is in operation, IFIN-HH will be in the position to participate in international comparisons in these fields and will be able to ask for new CMC lines.

GUM does not foresee the launch of new services regarding this project. The goal of GUM is to build a primary standard or update existing ones, so cavity chambers and water calorimeter are under study. After finishing

testing chambers, GUM will attend comparisons with BIPM to update its CMC lines for Cs-137 and Co-60 (air kerma), the goal is to reduce uncertainty to 0.5 %. After finishing work on their water calorimeter, GUM will add lines for absorbed dose to water. They will participate in the following comparison: (i) in 2018 - BIPM.RI(I)- K1 Measurement of air kerma for Cobalt 60 and BIPM.RI(I)- K5 Measurement of air kerma for Caesium 137, and (ii) in 2019 - BIPM.RI(I)- K4 Measurement of absorbed dose to water for Cobalt 60.

All the VINS services are traceable to IAEA through a secondary standard. During the timeline of the project, new equipment was obtained which allowed additional radiation qualities to be established, including W+Al 28, RQR 2 and T8-T11. This resulted in new calibration services being offered to the end users and the expanded scope of accreditation. A bilateral comparison was completed with BEV and 18 CMC lines were drafted. After the project completed, VINS will continue to participate in all available comparisons. A bilateral diagnostic comparison with IAEA is currently ongoing and new CMC lines will be drafted based on this comparison. VINS will try to join additional comparisons in order to be able to submit CMC lines for all calibration services included in the accreditation scope. Considering the available equipment, VINS will try to establish new radiation qualities and provide additional calibration services to end users. Three more mammography qualities (W+Al 25, W+Al 30, W+Al 35) will be established in 2018 and the W+Mo radiation quality will be established until 2020. Calibration of KAP-meters in terms of PKA and CT-chambers in terms of PKL will be offered to the end users (outside of accreditation scope). Accreditation of these services will be considered in three years, when the demand for calibrations of these instruments is analysed.

The long-term strategy of CMI is a) to implement primary measurements methods for the national standard of air kerma and to use BIPM key comparisons as supporting evidence for relevant CMC lines, and b) to extend the reference to low-energy X-rays in order to be able to cover mammography. Information gathered in the frame of this project was and will be used for the development of primary standards. In parallel, new Mo/Mo, W/Ag and W/Al mammography qualities were installed and characterised. The formal procedure to extend the Czech national standard of air kerma is ongoing at present and in 2017 revised CMC lines were sent to EURAMET for review. However, this procedure has been temporarily suspended in July 2017 because of current discussion and expected changes in the CMC structure and also in order to implement the values recommended by ICRU 90 to primary standards.

4.5 RMGs results

Three RMGs were organised during the course of this project, two at CEA/LNE-LNHB and one at SCK-CEN.

4.5.1 Characterisation, determination and development of a conversion protocol for converting DAP to D_w in small beam radiotherapy, researcher Vedrana Makaric from IMBiH, home organisation CEA/LNE-LNHB.

For radiotherapy beams smaller than about two centimetres, the concept of absorbed dose to water at a point suffers from the lack of lateral electronic equilibrium. Two approaches are possible to overcome this difficulty, (i) introduce correction factors to account for the dosemeter, the collimator and the size of the beam, this is the IAEA TRS 483 approach, or (ii) use a new quantity, namely the Dose Area Product (DAP), which intrinsically corrects the lack of electronic equilibrium, associated with a conversion protocol from DAP to D_w. This approach was taken in this RMG. Its objective was to develop and validate a conversion protocol from DAP to D_w in small beam radiotherapy. The first part of the work consisted of measuring the dose distribution with small dosimeters and films in order to select the most accurate and feasible techniques to determine the conversion factor necessary to determine D_w from DAP. The second part corresponds to interpretation and analysis of the data (in terms of the uncertainty budget) in order to develop and validate the conversion protocol. In addition, the CEA/LNE-LNHB provided two training courses to the RMG researcher in the fields of radiation protection and radiation safety and one practical training course on the use of the linear accelerator.

The beam profile measurements with an ionization chamber PTW 31014 and with a diamond detector PTW 60019 have been performed for five different beams, 6 MV, 12 MV and 20 MV in 10 cm x 10 cm fields and 6 MV, in 4 cm x 4 cm and 2 cm diameter fields. The diamond detector showed the best behaviour particularly at the edge of the beam where a steep variation of the dose is encountered. This allows the DAP to be calculated and the conversion factor to D_w to be established.

$$\frac{N_{Dw}}{k_{prof}(S)} = \frac{N_{DAPw}(S)}{S}$$

Where N_{Dw} is the calibration factor in terms of absorb dose to water at a point

N_{DAPw} is the calibration factor in terms of dose area product in water over an area S

S is the area of the beam

k_{prof} is the profile correction factor over the area S derived from the diamond profile measurements

The results will be confirmed with gafchromic EBT3 film 2D measurements.

4.5.2 Traceability of absorbed dose for radiation protection. Researcher Stelia Catalin Tuta from IFIN-HH, home organisation CEA/LNE-LNHB

Electronic Spin Resonance (ESR) is a method for studying materials with unpaired electrons. The basic concepts of ESR are analogous to those of nuclear magnetic resonance (NMR), but it is electron spins that are excited instead of the spins of atomic nuclei. By applying the microwave (MW) radiation and varying the magnetic field, the unpaired electron transitions occur when the energy difference between spin states equals the microwave quantum energy. Measurements of the absorbed mW energy yield the ESR spectrum.

The absorbed dose is proportional to the peak-to-peak (P2P) height of the central resonance of the alanine spectrum. This approach greatly simplifies the measurement process.

The aim of this RMG was to implement the Alanine/ESR technic at IFIN HH and to evaluate its applicability to radiotherapy end-to-end quality control. This objective implies the control of spectrometer parameters of interest for alanine absorbed dose measurements. In this case, the parameters of the ESR Spectrometer were studied: microwave power, the modulation amplitude, the conversion time and the sweeps of the spectrum.

Two sets of Alanine dosimeters were irradiated. One set was irradiated in a water phantom with an Elekta Linac Accelerator of the DOSEO platform at CEA in the dose range of 1–10 Gy and the other set, in air kerma with a Co-60 source irradiator in the dose range of 11–1000Gy.

Alanine pellets were provided by Gamma-Service GmbH. The pellet sizes are 4.8 mm in diameter and 3 mm in height, and their weight is 67.5 ± 0.1 mg. The dosimeters are made up of 4 alanine pellets included in a Delrin cylindrical container.

An optimisation of the operational parameters of the ESR spectrometer was performed in order to determine the range of doses used in radiotherapy/radiosurgery using the alanine dosimeters system. A value of 1.2% of the uncertainty budged was achieved using the CEA/LNE-LNHB measurement protocol. A new protocol was proposed in order to improve the dose threshold. The results present a slightly improvement, but the principal disadvantage was the long acquisition time.

Table 6: Example of an uncertainty budget

Type of uncertainty		Uncertainty
EPR measurement relative uncertainties (Sk)	Readout for 4 pellets	1.0%
	Mass	0.01%
	Gain	0.1%
	Drift of the Spectrometer	0.4%
	Irradiation correction	0.1%
	Position of the pellets in the Cavity	0.30%
Calibration curve D = aS + b uncertainty	Slope uncertainty (u_a) in grays/a.u.	0.0034
	Ordinate uncertainty (u_b) in grays	0.049
Relative uncertainty on absorbed dose D		1.2%

4.5.3 A feasibility study for developing a secondary standard $H_p(3)$ ionization chamber for eye lens dosimetry. Researcher Sandra Ceklic, VINS, home organisation SCK-CEN

Cataract is an eye lens disease characterised by eye lens opacity. In recent years, monitoring the eye lens has become more important due to epidemiological studies which implied that the dose for cataract induction could be lower than that assumed. ICRP lowered the annual limit from 150 mSv to 20 mSv. However, the dose to the eye (as an organ) is not directly measurable, therefore, the personal dose equivalent, $H_p(3)$, at a position on the head near to the eye, is usually measured.

At present, there is no device available that directly measures $H_p(3)$. Therefore, the goal of this research was to design a secondary standard ionization chamber for performing direct eye lens dosimetry measurements of $H_p(3)$, in workplace fields like hospitals and in calibration laboratories. Using this chamber the standard reference values for a certain dosemeter quantity will be provided in calibration laboratories and transferred to end users at medical institutions. Direct measurement of $H_p(3)$ will decrease the uncertainties due to energy and angle dependence of the response of the chamber.

The Monte Carlo method was used to investigate the possible design of the new $H_p(3)$ ionization chamber and to study the energy and angle responses. To validate this method, Monte Carlo simulation was initially performed for the $H_p(10)$ ionization chamber and results were compared with experimental results. For a wide range of energies (N-25 to N-200) the deviation from the experimental results was 5 %, while for N-200 to N-300 it was 7 %. For S-Cs and S-Co radiation qualities larger deviations were found, 10 % and 20 % depending on the set of experimental results that were compared. Considering that the goal of this research was to obtain an energy response within ±10 % these results clearly validate the applied simulation method and therefore it was used for the design of a new $H_p(3)$ ionization chamber.

The concept was to use a commercially available spherical ionization chamber to be embedded in a PMMA phantom. Considering the shape of an eye the spherical ionization chamber was chosen as the most adequate. The TK-30 ionization chamber, manufactured by PTW, has the characteristics that mostly fitted our requirements: the volume that allows measurements of low dose rates, the inner radius that is close to the average radius of the human eye, the wall thickness of 3 mm of polyoxymethylene and a good energy response. Taking into account physical consideration of the scattering properties compared with the head, the spherical shape of the phantom was also selected.

For the design of the new $H_p(3)$ ionization chamber, described in the previous paragraph, Monte Carlo simulations were performed. The goal was to obtain the most constant energy and angular response in terms

of operational quantity, $H_p(3)$, and the dose equivalent to the eye lens, H_{lens}. To achieve the optimal geometry for $H_p(3)$, chamber simulations were performed for different size phantoms and different wall thickness of the chamber. The results showed that the most constant energy response of the ionization chamber in terms of H_{lens} was for a 20 cm diameter of the PMMA phantom and a 3.24 mm wall thickness. The energy response for this design of the chamber was within ±7 %. The energy response of the chamber in terms of $H_p(3)$ was more constant for 15 cm diameter PMMA and it was within ±10 %, with exception, for N-10 and N-15 where larger deviations were spotted. For this design the energy response in terms of H_{lens} was within ±10 %. The response of the chamber with 15 cm diameter PMMA in terms of $H_p(3)$ and H_{lens} was investigated for monoenergetic photon beams and it was also within ±10 % for a wide range of energies from 20 keV to 1000 keV. Therefore, the optimum geometry for the new chamber for eye lens dosimetry was achieved with the TK-30 ionization chamber and the 20 cm diameter PMMA phantom around it. The uncertainty budget for the calibration and Monte Carlo method for the new ionization chamber had an expanded uncertainty (k=2) with a conventionally true value H_{lens} of 4.8 %. The next step of the study is to build this new $H_p(3)$ chamber.

5 Impact

Dissemination

Papers were published in the proceedings for the project Absorb workshop and in the Metrologia journal.

Research results were presented at national and international conferences including the Czech Association of Medical Physicists, American Association of Physicists in Medicine and Radiological Protection in Health.

A training course on primary standards for absorbed dose in water and air was run for external delegates from the scientific community. Partners were trained on primary standards building for absorbed dose in water and air, and performed ISO 17025 audits.

The following Good Practice Guides about how to build primary standards were published on the project website:

- Guide on how to build a free air ionisation chamber
- Guide on how to build a cavity chamber
- Guide on how to build a calorimeter

Impact on industrial and other user communities

Over twenty stakeholders mainly from hospitals joined the project and were informed about the results concerning uncertainty reduction and calibration methods harmonisation, with the aim of establishing a direct calibration service.

National reference values are being transferred to clinics through the calibration of dosemeters, leading to better diagnosis and treatment in radiotherapy.

Companies able to machine special materials such as graphite, an insulator, with a high level of precision, were checked and/or identified and cooperation started in some partnering countries.

Impact on metrology and scientific communities

Metrology institutes participating in the project were trained in building primary standards and they were provided with the software for automatic measurement, correction factors and the associated uncertainty calculations for standards based on water calorimetry, the cavity ionisation chamber and the free air ionisation chamber.

IST built and tested their cavity chamber, now the national primary standard, after a key comparison registered in the BIPM database.

IFIN-HH has started building their primary standard based on a cavity ionisation chamber.

CEA are working with the Spanish metrology institute CIEMAT in order to establish a new primary standard for air kerma based on a cavity ionisation chamber.

The partners were provided with the information needed to build primary standards. BEV-PTP, SCK-CEN and GUM have plans to build their own primary standard in the future.

Impact on relevant standards

Presentations of the project's results were made to the following standards committees:

- ISO TC85 SC2 WG2, responsible for standard ISO 4037 dealing with reference radiation quality
- EURAMET TC-IR, the technical committee for ionising radiation, where project workshop proceedings were presented with the link to CEA's official website, and also partners' plans to update or set new CMC lines
- BIPM CCRI(I) consultative committee, with the emphasis on planned participation of the partners in key comparisons organised by BIPM
- IEC WG45 working group, and will be taken into account in the preparation of new or updated standards.

Future potential impact

Collaborations will continue between many of the partners, in particular aimed at measurements using water calorimeters, free air ionisation chambers and cavity ionisation chambers. Results will be presented at future conferences, and partners will participate in international comparisons organised by IAEA, EURAMET and BIPM.

The longer term impact will be to share the knowledge on primary standards and harmonise the calibration procedure according to ISO 17025. This will allow shorter traceability chains, thus improving the traceability and accuracy of the ionising radiation doses delivered to the patients.

6 List of publications

[1] Proceedings of the Absorb workshop, ISSN 0429-3460, www.lnhb.fr:

1) V. Sochor: Free air chamber – principle of operation, basic design.

2) A. Steurer: Free air chamber at BEV.

3) MI. Camacho Caldeira: Cavity chamber, From collected charges to air kerma.

4) MI. Camacho Caldeira: Cavity chamber manufacturing.

5) S. Bercea: Development of a cavity ionization chamber at IFIN-HH – primary standard for air kerma.

6) A. Steurer: Measuring system (current measurement) and evaluation software.

7) MI. Camacho Caldeira: Electronic associated to IC.

8) S. Bercea: Electronic associated to IC and IC characteristics.

9) MI. Camacho Caldeira: Cavity chamber, correction factors measurement.

10) MI. Camacho Caldeira: Cavity chamber, correction factors calculation.

11) A. Steurer: Cavity chamber at BEV.

12) A. Steurer: Measurement calibration method at BE

13) B. Rapp: Calorimetry – water and graphite calorimeter pro and con.

14) A. Steurer: Graphite calorimeter at BEV.

15) J.-M. Bordy: Introduction to uncertainty budget GUM method.

[16] C. Kessler, L.C. Mihailescu et al.: Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the SCL.CEN, Belgium at the BIPM in Co-60 gamma radiation, Metrologia 54(2017) Tech. Suppl. 06004.

[17] J.-M. Bordy et al.: Comparison on the uncertainty budget, www.lnhb.fr.

7 Website address and contact details

A project public website has been created and can be found under http://absorb-empir.eu.

The contact person for general questions about the project is Jean-Marc Bordy, CEA/LNE-LNHB,

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The contact person for the project website and the exploitation and dissemination of the project's results is Vladimir Sochor, CMI, vsochor@cmi.cz).