Actual metrological conditions for ionizing chamber calibration in radiotherapy

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ABSTRACT

BACKGROUND: *Since 1976 it has been recognized that an accuracy of ±5% in the delivery of an absorbed dose to a target volume is necessary for successful therapy treatment. Recent studies have concluded that combined standard uncertainty in dose delivery should be smaller than ±3.5 %. The basic radiotherapy requirements initiated some changes in calibration approach. New approach included beam as vital part of calibration chain and also insisted on realization of measurement quality assurance through legal metrology, international key and supplementary intercomparisons, national comparisons, and routine calibration.*

METHODS: *In past twenty years there were three various protocols for absorbed dose determination in radiotherapy that had been based on various principles and various calibration concepts. As there were three conversions in air kerma concept the basic national protocol was changed. We gave up air kerma concept and developed absorbed dose primary standard by ionometric approach and assured appropriate transfer of calibration through four various laboratory levels. The primary standard was realized with combined uncertainty better than 0.3%, 1σ. Transfer of calibration was realized through calibration coefficient determination.*

RESULTS: *Before Code of Practice IAEA 398 was adopted some steps were made in verification of absorbed dose to water primary standard. This standard was established after bilateral intercomparison with Hungarian National Office of Measure (OMH) in 1999 and also after international supplementary comparison organized by International Bureau of Weights and Measures (BIPM) in Sevres, in 2001. Results of the BIPM intercomparison were presented in this paper and they are recognized as national input true value of absorbed dose. Verification of national absorbed dose true value gave us the opportunity to establish new calibration protocol in our radiotherapy centers. We also introduced the new regulatory paper for determination of ionization chamber calibration coefficient. New metrological conditions and calibration manual for radiotherapy chamber were presented in this paper.*

CONCLUSION: *As the method for in-water calibration for gamma and high-energy photons generated in accelerators has been established in our country it gives us possibility to join regional EUROMET program for high-energy photon beam calibration. The first step of calibration in gamma beam quality included also users of high-energy beam in order to fulfill the main metrology goal: calibration in conditions similar to those of users as much as it is possible.*

KEY WORDS: *Radiometry; Calibration; Reference Standards; Radiotherapy, High Energy; Technology Assessment, Biomedical*

INTRODUCTION

Since 1976 it has been recognized that an accuracy of ±5% in the delivery of an absorbed dose to a target volume is needed for successful therapy treatment (1). Some clinicians have requested even closer limits such as ±2%, which has recently become quite possible in standard laboratories but it is not easy to achieve such limits in hospital routine conditions (1-5). These statements have been made in a context where uncertainties are estimated at the 95% confidence level, and have been interpreted as if they correspond to approximately two standard deviations. Recent studies have concluded that for certain types of tumors combined standard uncertainty in dose delivery should be smaller than ±3.5 %. Modern radiotherapy has confirmed the need for high accuracy in dose delivery if new techniques, including dose escalation in 3-D conformal radiotherapy, are to be applied (6,7). The basic radiotherapy requirements initiated some changes in calibration approach. New approach included beam as vital part of calibration chain and also insisted on the realization of measurement quality assurance.

Measurement quality assurance

The main part in radiotherapy quality assurance is metrological assurance. From the standpoint of legal metrology it is necessary to assure: development of standard instruments and methods, appropriate education, calibration laboratories, metrology regulatory papers, and measuring and calibration methods unification (8). Metrological assurance is the basic part of measurement quality assurance, which is performed through legal metrology, international key and supplementary intercomparisons, national comparisons, and routine calibration (8). Legal metrology defines calibration methods, standard instruments and legislation to assure public warranty in the country.

International intercomparisons are performed between national primary standards only for the purpose to assure that particular primary standard defined internationally is in agreement with measuring unit in satisfactory way. International Bureau of Weights and Measures (Bureau International Des Poids et Mesures - BIPM) is the organizer of such intercomparisons, but recently some regional metrology organizations have been recognized as intercomparison coordinators (EUROMET). National intercomparisons are performed for the purpose to check measurement practice in radiotherapy centers but also to recognize and set up magnitude of errors, which become upper limits for corrective measures. Calibration represents pure transfer of measuring unit from primary standard through lower level standards to field instruments.

MATERIALS AND METHODS

Absorbed dose determination

Absorbed dose to tissue is physical quantity relevant in radiotherapy ionizing radiation application. At national level, absorbed dose primary standard could be realized, by water calorimeter, chemical dosimeter, and by ionometric approach with ionization chamber and appropriate tissue equivalent phantom. The last one has been chosen in our country (9). In past twenty years there were three various protocols for absorbed dose determination in radiotherapy based at various principles and various calibration concepts (6-10). Conversion factor method is based on mathematical transfer of exposure as measured value to absorbed dose. Physical sense of this factor is relative energy absorption in the conditions of electron equilibrium. Generally, this concept overestimates absorbed dose true value. It also does not put into account bremsstrahlung and also various responses depending of chamber construction.

Air kerma method is based on air kerma as conventional quantity that takes into account two-staged process of energy transfer from indirectly ionized particle to medium. Formalism is based on air kerma measurement and absorbed dose evaluation by using several interaction coefficients. Generally, this method, underestimates true value of absorbed dose. Air kerma is widely accepted and many national metrology organizations, including ours, developed air kerma primary standards; BIPM organized ongoing key comparison of this quantity. From the strictly metrological standpoint air kerma is the first quantity in dose metrology - so-called quantity of good choice.

Direct absorbed dose measurement in water has more advantages. Among them is the answer to a simple question: Why did we give up kerma concept?

Ionometric concept of in-air measurements includes three conversions such as: conversion from one physical quantity to another (air kerma to absorbed dose to water); conversion from one energy spectra (1.25 MeV continuous gamma radiation of ^{60}Co) to another different energy spectra (medium X-ray energies, high-energy X rays, and electron radiation and protons) and conversion from one medium to another (from in-air to in-water measurements) (11).

Each of these conversions introduces uncertainty, which increases total uncertainty of absorbed dose determination. From those reasons it was necessary to change calibration protocols and methods. Energy from accelerator X-ray beam has been specified only in terms of mean photon energy even though it does not depend just on incident electron energy but also on target parameters and beam homogenizer. These data are usually unknown for users so it has been impossible to realize proper calibration transfer traceable to primary standard. Additional problem in various chamber recombination factors is recognized in beam nature if we transfer calibration from continuous ^{60}Co gamma beam to real high energy pulsed accelerator beam as their specters are different. From that stand point it was necessary to realize metrological assurance, which we started from 1989.

Realization of metrology assurance

Transfer of calibration starts from international intercomparison level which allows standard laboratory to introduce true value in its own country. Ionometric approach is based on relative measurements. They are suitable for international intercomparisons (12). Transfer calibration should pass through four various levels of laboratories. In our country we established transfer presented in Table 1 (6,11). The main advantage of this transfer is that the same quantity is measured at every stage of calibration.

Table 1. Calibration levels

Standard instrument level	Reference beam quality	Physical quantity	Calibration coefficient	Object of transfer
Primary	gamma ^{60}Co	D_w, D_w'(1)	N_{Dwq0}(2)	National intercomparison, Secondary standard
Secondary	gamma ^{60}Co	D_w, D_w'(1)	N_{Dwq0}(2)	Working standards, Reference standards, Field instruments
Reference	gamma ^{60}Co, electron and X (LINAC), proton beam from cyclotron	D_w, D_w'(1)	N_{Dwq0}(3)	Field instruments

(1) meaning of absorbed dose rate
(2) calibration coefficient in reference beam
(3) calibration coefficient in users beam

Absorbed dose to water national primary standard

Absorbed dose primary standard in our country is developed by ionization chamber type ND 1006, produced in National Bureau of Measures of Hungary, and appropriate water phantom. Wall material of the chamber is air equivalent plastic (r=1.8 g/cm^3), and material of collecting electrode is pure graphite type EK 50. Active chamber volume determined radiometrically by Yugoslav air kerma primary standard is 0.2535 cm^3 (9). Absorbed dose to water primary standard is realized with combined uncertainty better than 0.3 %, 1sfor ^{60}Co gamma beam (13,14). The first bilateral intercomparison of our primary standard happened in 1999 in Budapest. This comparison was stated as bilateral key comparison according to paragraphs T.8 and T.9 of Mutual Recognition Arrangements (9,15). Our primary standard was also used in important international intercomparison in 2001 in Sevres, France, which was organized by BIPM. Results of this intercomparison were presented in this paper and they are recognized as input true value of absorbed dose. Transfer of calibration is realized through calibration coefficient determination.

Calibration coefficient

It is necessary to pay special attention on new expression as well as explanation of calibration coefficient (formerly known as calibration factor in calibration terminology) (Allisy Roberts P. - Spasić-Jokić V., personal communication). There has been some confusion in the past over the use of various terms used for the calibration of radiation measuring instruments. The new term unites the terminology used by ICRU, IEC, and the ISO in a consistent manner. The definition of term calibration factor is quite clear in that it converts the indication of the instrument to give the conventional true value of the measurand and is dimensionless. Direct indication of the instrument has to be converted to the same units that measurand has by applying an instrument constant before the calibration factor is applied. In the case of ionizing chamber calibrations the instrument constant and the calibration factor are not identified separately but are applied together as the calibration coefficient that then has dimensions. In a typical situation, the instrument direct indication (*I*) would be normalized to the reference conditions[1] and corrected for any other factors to give $I_{corrected}$ and then multiplied by the instrument constant (*k*) to give the instrument indication converted to the measurand. The value of *k* will have dimensions. The instrument indication will now be in the correct units. However, it will normally need a calibration factor (C_f) to convert it to the conventional true value of the quantity. Thus the conventional true value (TV) of the measurement is given as a product:

$$TV = I_{corrected} \times k \times C_f. \quad (1)$$

RESULTS

Supplementary comparison of absorbed dose primary standard

The transfer ionization chamber ND 1006 has been calibrated in the BIPM in terms of absorbed dose to water in the ^{60}Co gamma beam. The calibration coefficient is given at 20˚C and 101325 Pa. The uncertainty represents one standard uncertainty. The transfer chamber is placed in waterproof sleeve in the BIPM water phantom of side 30 cm. Its axis is placed in the reference plain, at the depth of 5 gcm^{-2}. This depth includes the window of the phantom (PMMA 0.476 gcm^{-2}). The calibration coefficient N_{Dw} is determined using relation

$$N_{Dw} = D_w^*(I_w k p_f) \quad (2)$$

where D_w^* is the absorbed dose rate to water at the reference point, measured by the BIPM standard at a depth of 5 gcm^{-2} in water, I_w is the ionization current measured by the transfer chamber under BIPM reference conditions for air temperature and pressure, and k_{pf} is a correction factor applied to I_w for nonequivalence with water of the PMMA window of the phantom. Calibration coefficient in terms of absorbed dose in water, in ^{60}Co beam with absorbed dose rate of 2.73 mGy/s is given as $N_{D,w}$ = 122.7 ± 0.4 Gy/μC. It was stated as typical value for that type of chamber (17). Physical constants and correction factors used in BIPM ionometric determination of the absorbed dose rate and their estimated relative standard uncertainties are given in the Table 2 (17).

Table 2. BIPM calibration conditions and uncertainty budget

Performance	Value	Uncertainty (%) u_A	u_B
Physical constant			
Dry air density (273.15 K, 101325 Pa)	1.2930 kgm^{-3}	-	0.01
$(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c$	1.1125	0.01	0.14
Stopping power ratio $S_{c,a}$	1.0030	-	-
W/e [JC^{-1}]	3.97	-	0.11
Correction factors			
k_p pertubation correction	1.1107	0.05	0.17
k_{ps} polythene envelope of the chamber	0.9994	0.01	0.01
k_{pf} front face of the phantom	0.9996	-	0.01
k_{rn} radiation non-uniformity	1.0051	0.01	0.03
k_s recombination losses	1.0015	0.01	0.01
k_h humidity	0.9970	-	0.03
Mesurement of *I*/vρ		0.27	0.04
Relative standard uncertainty in D_w^*			
Quadratic sum		0.19	0.21
Combined uncertainty		0.29	

u_A represents the relative standard Type A uncertainty estimated by statistical methods
u_B represents the relative standard Type B uncertainty estimated by other means

Details concerning the calibration of our national primary standards are given in Table 3 (17). Estimated relative standard uncertainties associated with calibration coefficient for transfer ionization chamber ND 1006 in ^{60}Co gamma radiation are given in Table 4 (17).

Transfer of absorbed dose true value

Using the same formalism, value of Gray is transferred from the primary national standard for absorbed dose in water to secondary standards such as 0.6 cm^3 Farmer type chamber (e.g. NE 2571) officially stated as secondary standard ionization chamber. Calibration conditions in calibration transfer were the same as in BIPM. Transfer of absorbed dose measuring unit (Gray) was performed by means of calibration coefficient determination (18,19). The calibration standard was transferred by means of national absorbed dose secondary standard in the Primary laboratory of Federal Bureau of Measures and Precious Metals; afterwards, the transfer of calibration standard was carried on in our radiotherapy centers, beginning with the Institute of Oncology Sremska Kamenica, and than in the Military Medical Academy, Belgrade, the Institute of Oncology and Radiology of Serbia, Belgrade, and Oncology Clinic, Clinical Center, Podgorica.

Table 3. BIPM calibration conditions and uncertainty budget

Performance	Value
Positioning of transfer chamber	
Reference plain – source distance (filed size)	1 m (10 cm x 10 cm)
Depth in water	5 gcm^{-2}
Chamber sleeve thickness	1 mm
Radial non-uniformity influence	less than 10^{-4}
Collecting voltage	
Value	200 V
Polarity (polarity effect)	positive (neglected)
Charge measurement and leakage	
Relative value of correction for current leakage	2 x 10^{-4}
Ambient conditions	
Relative humidity	53% (no correction applied)
Air temperature	20°C
Water temperature	20°C
Stability od air and water temperature during the measurements	better than 0.01°C
Reproducibility of measurements	
The short -term relative standard uncertainty of the mean value of 90 measured values	2 x 10^{-4}
Measurement of charge	BIPM electrometer

Table 4. Uncertainty budget (16)

Uncertainty component	U_A [%]	U_B [%]
Absorbed dose rate in water D_w^*	0.20	0.21
Ionization current of transfer chamber	0.02	0.02
Position	0.02	-
Depth in water	0.02	0.06
Uncertainty of $N_{d,w}$		
Quadratic sum	0.20	0.22
Combines uncertainty		0.30

Metrology regulatory papers

Primary standard development as well as international comparisons gave us legitimacy to change previously prescribed metrological conditions and calibration manual in radiotherapy. Thanks to some members of Ionizing Radiation Metrology Commission the new regulatory papers were brought and they represented the compilation of international documents and recommendations such as Organisation Internationale de Metrologie Legale OIML Document No.21 (Secondary Standard Dosimetry Laboratories for the Calibration of Dosimeters used in Radiotherapy, 1990), International Atomic Energy Agency Technical Report Series IAEA TRS 381 (The Use of Plane-parallel Ionization Chambers in High-energy Electron and Photon Beams, 1997), IAEA TRS 374 (Calibration of Dosimeters used in Radiotherapy, 1994), and IAEA TRS 398 (7). In accordance with these metrological conditions and calibration manual we adjusted our metrology regulatory papers to international recommendations (21).

Calibration manual

Calibration manual can be used for the calibration of ionizing chambers of following beam qualities (7, 20): (a) Low-energy X rays with generating potentials up to 100 kV and HVL of 3 mm Al (the lower limit is determined by the availability of standards); (b) Medium-energy X rays with generating potentials above 80 kV and HVL of 2 mm Al; (c) ^{60}Co gamma radiation (mean energy of gamma line of 1.25 MeV); (d) High-energy photons generated by electrons with energies in the interval from 1 MeV to 50 MeV, with $TPR_{20,10}$ values between 0.50 and 0.84; (e) Electrons in the energy interval from 3 MeV to 50 MeV, with a half-value depth, R_{50}, between 1 g/cm^2 and 20 g/cm^2; (f) Protons in the energy interval from 50 MeV to 250 MeV, with a practical range, R_p, between 0.25 g/cm^2 and 25 g/cm^2.

The principal scheme of Metrological Manuel consists of (20): (1) Beam qualities relevant for radiotherapy; (2) Calibration coefficient in terms of absorbed dose to water; (3) Calibration conditions; (4) Standard equipment and reference beams; (5) Correction factors applied to ionization chambers; (6) Certificate contents.

Calibration certificate consists of following basic elements (20): (1) Referent beam quality; (2) Calibration depth in phantom; (3) Ionization chamber reference point; (4) Calibration coefficient in terms of absorbed dose; (5) Expanded uncertainty; (6) Users beam quality correction factor.

Working sheets

The absorbed dose to water in an external therapy beam is determined by ionometric measurements under standard conditions and by calculations according to formalism and data provided by a Dosimetry Protocol (Code of Practice) (7). It is imperative that the modes of calculation and basic data have to be strictly adhered to (21). A number of spreadsheets for absorbed dose calculation have been developed. The main goal is to provide a means to: (1) Perform the calculation accurately without forgetting any of factors; (2) Minimize the possibilities of calculation errors; (3) Perform calculation in a logical and consistent manner; (4) Perform the calculation quickly without loss of reliability; (5) Provide a clear, uniform and unambiguous printout.

CONCLUSION

Absorbed dose to water is the quantity of main interest in radiation therapy. Since this quantity relates closely to the biological effects of radiation it was the subject of efforts in metrology assurance. It was also recognized as a priority in long-term metrology plans and programs. The development of primary standards of absorbed dose to water for high energy photon and electron beams offers possibility of reducing the uncertainty in the dosimetry of radiotherapy beams and it has been primary laboratory major goal pursued by the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (Section I). Over the past few years in our country it was established an ionometric standard for the measurement of absorbed dose to water, using ^{60}Co radiation compared in international comparisons (12). Our primary standard laboratory provided calibration in terms of absorbed dose to water is radiation quality of ^{60}Co gamma rays, but also in high energy users beam. Extended calibration in high-energy beam qualities is in stage of developing the necessary techniques (12). Metrology and radiotherapy practice are in the period of the beginning of implementation of IAEA Code No.398 so it is necessary to provide users with calibration factors both in ^{60}Co reference beam in authorized laboratory and in user's particular beam after careful beam calibration by secondary standards. All necessary correction factors have to be applied and incorporated in chamber factor so that users only have to correct instrument reading of pressure, temperature, and humidity conditions different from reference values. It is also necessary to concentrate all efforts on experimental determination of the beam quality dependence factors k_{qq0} for all types of ionization chambers used in therapy dosimetry (mostly NE 2571 and similar farmer type chambers) for beam qualities applied in our radiotherapy centers (12). With this approach it will be possible to help our radiotherapy centers to implement new Code of Practice as fast as it possible, and to change previous air kerma practice in a painless manner.

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[1] *The reference conditions are those defined conditions under which the calibration is valid.*