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Source strength determination in iridium-192 and cobalt-60 brachytherapy: A European survey on the level of agreement between clinical measurements and manufacturer certificates

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ABSTRACT

Background and purpose: Brachytherapy treatment outcomes depend on the accuracy of the delivered dose distribution, which is proportional to the reference air-kerma rate (*RAKR*). Current societal recommendations require the medical physicist to compare the measured *RAKR* values to the manufacturer source calibration certificate. The purpose of this work was to report agreement observed in current clinical practice in the European Union.
Materials and methods: A European survey was performed for high- and pulsed-dose-rate (HDR and PDR) high-energy sources (^{192}Ir and ^{60}Co), to quantify observed RAKR differences. Medical physicists at eighteen hospitals from eight European countries were contacted, providing 1,032 data points from 2001 to 2020.
Results: Over the survey period, 77% of the ^{192}Ir measurements used a well chamber instead of the older Krieger phantom method. Mean differences with the manufacturer calibration certificate were 0.01% ± 1.15% for ^{192}Ir and –0.1% ± 1.3% for ^{60}Co. Over 95% of *RAKR* measurements in the clinic were within 3% of the manufacturer calibration certificate.
Conclusions: This study showed that the agreement level was generally better than that reflected in prior societal recommendations positing 5%. Future recommendations on high-energy HDR and PDR source calibrations in the clinic may consider tightened agreements levels.

1. Introduction

Brachytherapy (BT) using photon emitting sources is mainly performed using either a single high dose-rate (HDR) or pulsed dose-rate (PDR) source, or multiple low dose-rate (LDR) sources. HDR sources are, with few exceptions, of high energy (>0.05 MeV) and LDR ones of low energy (<0.05 MeV). PDR sources are used for pulsed treatments and typically have the same design as HDR ones, but with lower source

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strength. In LDR treatments, several permanently implanted sources (seeds) are used with every patient treatment while a single HDR or PDR source is normally used repeatedly for months or years on multiple patients. For HDR and PDR BT, ^{192}Ir (half-life 73.8 days, mean photon energy 0.4 MeV) is the most common radionuclide while also ^{60}Co sources (half-life 1925 days, mean photon energy 1.25 MeV) are available. The reference quantity used in Europe for BT source strength is the reference air-kerma rate (*RAKR*) with units cGy h^{-1} at 1 m [1,2], while air-kerma strength, S_K in units of U (1 U = 1 μGy m^2/h = 1 cGy cm^2/h) is used in North America with the numerical value of *RAKR* being 10^4 more than the numerical value of S_K. *RAKR* plays a key role in dosimetry at the hospital level, since values of absorbed dose in absolute terms used in clinical BT treatment planning are directly proportional to it through the TG-43 formalism for dose calculation [3]. Standards for this quantity are setup and maintained within the international metrology community and requirements on traceability to such standards apply to BT similar to all other radiotherapy modalities [4]. Specifically, vendors issue BT source certificates including a determination of source strength using measuring equipment with traceability to such standards and experimental verification in the clinic of these certificates is regulated in most countries. This way, measurements of *RAKR* or S_K constitute the BT equivalent of external-beam reference dosimetry.

The established standards for dosimetric realization of *RAKR* differ depending on the dose rate [4,5]. Primary standards used to realize source strength measurement for LDR sources are based on free-air ionization chambers while for HDR and PDR ^{192}Ir sources such standards are based on a spherical graphite-walled large volume cavity ionization chamber and a lead-housing with a dedicated collimator [6,7]. Other ^{192}Ir standards are based on indirect methods for realization of *RAKR* [8]. The primary standard at NPL determines source strength values and instrument calibration coefficients with lower uncertainty (<1%) than the indirect ones (around 3%) at $k = 2$ [8–10]. The PTB provides a calibration for HDR ^{60}Co sources and reported on a quality correction factor, k_Q, aimed to transfer a ^{192}Ir calibration coefficient into one for ^{60}Co as derived from measurements with 35 well-type ionization chambers of two different chamber types [11,12]. Due in part to the logistics of HDR and PDR high-energy sources not being easily shippable and in part to the fact that high-energy sources are less sensitive to source design and manufacturing processes, a system similar to that setup for LDR sources by the AAPM does not exist [13]. It is nevertheless well recognized by the AAPM Task Group No. 56 Report [14] and by the GEC-ESTRO in the ESTRO Booklet #8 [15] that the manufacturer-issued *RAKR* certificate of each HDR and PDR source must be measured in the clinic using traceably-calibrated equipment. Updated GEC-ESTRO clinical recommendations for calibration traceability of HDR and PDR sources are currently in preparation, also collecting information on available resources of laboratories offering calibration services with traceability to international standards.

Use of air-filled, vented well-type ionization chambers in the clinic and secondary standard laboratories has been recommended because of their robustness, stability, and simplicity in setup [16]. An alternative measurement technique is recommended by the German society for Medical Physics (DGMP), consisting of a PMMA phantom, named the Krieger-phantom, housing a thimble ionization chamber [17,18]. Current societal recommendations establish that differences between clinic-measured *RAKR* (or S_K) values and the manufacturer certificate should be within 5% [14,15].

Uncertainties of secondary/tertiary standard's calibration coefficients and vendor issued source certificate are lower for HDR-PDR ^{192}Ir and HDR ^{60}Co than for LDR sources. Therefore, it has been suggested in the literature that the current *RAKR* relative difference limit of 5% could be reduced given that clinics and manufacturers respect the measurement conditions specified on the instrument calibration certificates and follow good practice protocols [19]. Additionally, differences in calibration coefficients for different types of ^{192}Ir sources are small compared to those for low energy sources [20]. *RAKR* measurement corrections due to source geometry, derived using Monte Carlo calculated factors, of about 0% to 2%, may be applied to further reduce *RAKR* measurement differences between various ^{192}Ir sources [21]. Such factors are not yet available for all source types (notably short length PDR sources) and all well-type chambers or the Krieger phantom setup.

The current study presents the results of a survey performed by the BRAPHYQS WP21 group of GEC-ESTRO to assess the level of agreement between *RAKR* values as measured in the clinic to verify values reported on source manufacturer certificates for ^{192}Ir and ^{60}Co HDR and PDR BT sources. The survey included clinics throughout Europe, including BRAPHYQS and GEC-ESTRO committee members where HDR and PDR BT is routinely used.

2. Material and methods

Eighteen clinics from eight European countries were contacted to achieve enough statistics and provide basic sample stratification to avoid potential bias due to the use of a particular methodology, clinical practice, or national regulations. Data on HDR ^{192}Ir, PDR ^{192}Ir, and HDR ^{60}Co sources were reported, together with general information about the clinical practice followed for each set of measurements. Data collection included changes during the period reported in instrumentation, calibration certificate, or procedure. Participating clinics were requested to submit their measured values ($RAKR_{\mathrm{CLINIC}}$) together with corresponding values on manufacturer certificates ($RAKR_{\mathrm{MANU}}$). Percentage differences between these were reported as:

$$\left(\frac{RAKR_{CLINIC}}{RAKR_{MANU}} - 1\right) \times 100\ (\%) \tag{1}$$

The number of data points thus obtained were 970 for ^{192}Ir (294 for PDR and 676 for HDR) and 62 for ^{60}Co over the period 2001–2020. In the case of ^{192}Ir, the number of values obtained was large enough to recover the expected normal distribution, hence a Gaussian fit was performed. Not all participants provided the same level of detail, two clinics did not provide detailed lists of measurements, instead providing their mean, standard, and maximum deviations. Those values were combined with the corresponding ones obtained in the fit by a weighted average (mean) and weighted sum in quadrature (standard deviation). A histogram of the *RAKR* differences reported was produced for both radionuclides. The *RAKR* interval where more than 95% ($k = 2$ for a normal distribution) of data points resided was considered a conservative estimate of differences expected between *RAKR* from clinical user measurements and vendor certificates.

3. Results

Defining *RAKR* differences according to Eq. (1), mean differences for ^{192}Ir sources of 0.01% with a standard deviation of 1.15% were found. This was for 750 and 220 clinic measurements using well-type ion chambers and Krieger phantoms, respectively. Hence, values outside 3% corresponded to less than 5% of the reported values. Although this behavior was independent of the measurement technique (well chamber or Krieger phantom datasets), Gaussian-fits performed on each dataset independently yielded standard deviations of 1.0% for the well chamber and 1.5% using the Krieger phantom (Fig. 1).

For ^{60}Co BT sources, where normality of the distribution of *RAKR* differences could not be assumed due to the limited number of data points, all *RAKR* difference values were within a ± 3% interval with a mean value of –0.1% and standard deviation of 1.3% (Fig. 2).

4. Discussion

Current recommendations establish that the *RAKR* value measured by a medical physicist during clinical practice must agree within 5% to that reported in the source calibration certificate provided by the

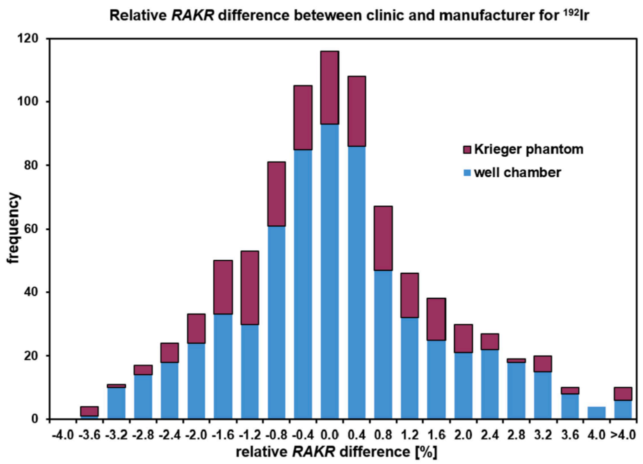

Fig. 1. Frequency distribution of percentage differences between $RAKR_{\mathrm{CLINIC}}$ and $RAKR_{\mathrm{MANU}}$ for ^{192}Ir (mean = 0.01%, standard deviation = 1.15%).

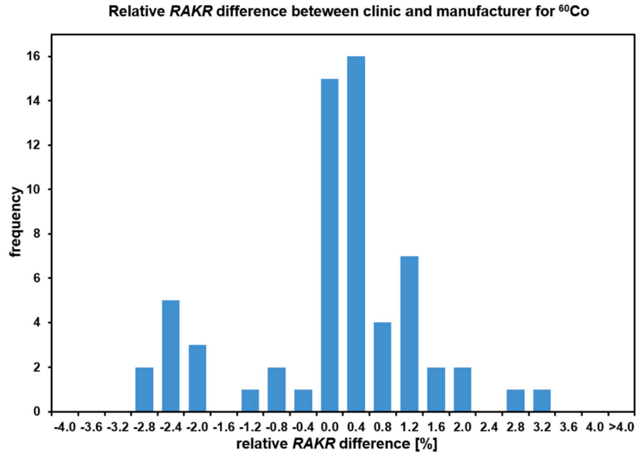

Fig. 2. Frequency distribution of percentage differences between $RAKR_{\mathrm{CLINIC}}$ and $RAKR_{\mathrm{MANU}}$ for ^{60}Co (mean = –0.1%, standard deviation = 1.3%).

manufacturer [9,10]. This survey found that such a value underestimates the quality of *RAKR* measurements at European clinics. It is clear that in the period 2001–2020, more than 95% of the HDR/PDR source strength measurements performed in the sampled European centers agreed within 3% with the BT source manufacturer calibration certificate.

The largest differences reported were 9.1% and 3.0% for ^{192}Ir and ^{60}Co, respectively. A reduced number of outliers were found in the data sample. Of those, only three measurements present differences larger than four standard deviations (>4.6%). One center presented larger systematic differences in older results (before 2010) compared to more recent results. If those values were removed from the analysis, the number of measurements within 3% would increase to 99%. A different methodology to approach this problem would analyze institutional results individually. Unfortunately, we were faced with long temporal series (about 20 years in some cases) where the uncertainties changed with time whenever the protocols were actualized. Therefore, it is clear that the data from every single clinic does not always correspond to randomly distributed results around a central value, and hence trying to extract a single mean value and a standard deviation for every clinic might lead to a misleading statement. An example of such pattern for one clinic is shown as Supplementary Material (Suppl. Fig. S1).

There are many sources of uncertainty and errors that may have contributed to the *RAKR* differences observed in this study. Briefly, experimental uncertainties may be divided into two categories: those that are well known and clearly specified, the most important being calibration uncertainties stemming from measurement setup, and systematic errors in the measurement methods or an undetected equipment malfunction. These sources of uncertainty and errors are included within the *RAKR* differences from the previous section.

There are some sources of clinic-related uncertainties that might or might not be folded into the results of the survey. The most relevant ones are differences in source type used at instrument calibration and measurements [20,21], and sub-optimal practice or non-compliance to the conditions stated in the instrument calibration certificate. An example would be placing the well chamber close to the floor or a wall where typical enhancement of about 3% has been reported, instead of being positioned in the center of the room on a on low-scattering device with more than 30 cm from the floor or wall [19].

Although a complete analysis on the protocol followed at each of the institutions participating in this survey is beyond the scope of the present manuscript, it is possible to make general comments. Well-type ion chambers are known for their long-term stability [22], but are more susceptible to room-scattering conditions than the Krieger phantom as the latter is surrounded by a significant amount of PMMA. Furthermore as both instruments contain large amounts of material (air or PMMA), it is important they have reached thermal equilibrium with the other instrumentation, i.e., thermometers and pressure gauges. It is also important to ensure the correct source position inside the well chamber or Krieger phantom. Ideally, the clinical user should maintain a historical record of previous source strength measurements to identify possible systematic error and subsequently correct said measurements.

RAKR is determined with an ion chamber as $RAKR = I_{\mathrm{corr}} \cdot \mathrm{N}_{\mathrm{RAKR}}$, where I_{corr} is the measured current corrected for influence quantities and N_{RAKR} is the ion chamber calibration coefficient. The N_{RAKR} bears the largest contribution to the total uncertainty of *RAKR* measurement as it stems from the realization of the quantity at a standard laboratory, while the I_{corr}, measured in the clinic or by the manufacturer, contributes less. Clinics are recommended to follow the *RAKR* difference obtained with the manufacturer over time as such ratio can be expected to vary within the combined uncertainty of the two current determinations around a number set by possible differences in calibration coefficient determination [19], and other potential systematic uncertainties. Logically, every uncertainty budget is affected by the protocol implemented in the corresponding calibration laboratory. Such uncertainty can differ significantly across institutions. Typically, calibrations at the NPL using a primary standard are associated with reduced uncertainty (0.8% at $k = 2$) relative to calibrations based on indirect interpolation techniques such as 2.6% at $k = 2$ at the University of Wisconsin ADCL, or 3.0% $k = 2$ at VSL [19].

A protocol used in some of the clinics participating in this survey and enforced by some particular national regulations is to measure all sources twice, once when received and a second after some time, typically a few weeks or when removed from the institution by the vendor (in both cases corrected by the corresponding radioactive decay). Such a procedure allows the user to immediately determine any possible measurement error or equipment malfunction that might have arisen in between measurements and therefore guaranties reproducibility.

Summarizing, high dosimetrical accuracy is fundamental to radiation therapy. For HDR and PDR ^{192}Ir and HDR ^{60}Co sources, the mean difference between *RAKR* values measured at the hospital level and those reported in the source certificates were less than 0.1%, being more than 95% of values reported within 3%. These results will be included in the upcoming GEC-ESTRO recommendations on high energy, HDR and PDR source calibrations in the clinic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2021.07.007.

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