ACTA IMEKO
ISSN: 2221-870X
December 2025, Volume 14, Number 4, 1 - 6

Development of a cyber-physical space from a radiation meter calibration laboratory for the digital twin process: Air kerma measurement on ionization chambers

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ABSTRACT
Significant resources have been invested in Metrology 4.0 with the advent of digital transformation. Cyber-physical systems (CPS) and digital twin (DT) technologies can be implanted in radiation applications, such as a calibration laboratory. Our objective was to create a pilot project of a CPS of a lab, with an air kerma measurement process as the DT, starting from a Monte Carlo simulation. The discrepancy between virtual and physical measurement results was approximately 10^{-6}, which is expected given the inherent characteristics of Monte Carlo codes applied to ionizing radiation. A workflow was developed to integrate Monte Carlo simulations within the DT framework. A pilot project of an interlaboratory comparison between two DT laboratories was developed based on the results of this paper.

Section: RESEARCH PAPER

Keywords: digital twin; air kerma; Monte Carlo; cyber-physical system; EGSnrc

Citation: E. M. Macedo, M. R. Nascimento, L. C. Pacífico, I. F. M. Garcia, J. S. Ferreira, M. V. T. Navarro, J. G. P. Peixoto, Development of a cyber-physical space from a radiation meter calibration laboratory for the digital twin process: Air kerma measurement on ionization chambers, Acta IMEKO, vol. 14 (2025) no. 4, pp. 1-6. DOI: 10.21014/actaimeko.v14i4.1971

Section Editor: Carlos Hall, PósMQI/PUC-Rio, Rio de Janeiro, Brazil

Received November 6, 2024; **In final form** October 14, 2025; **Published** December 2025

Funding: This work was supported by the Laboratório de Produtos para a Saúde do Instituto Federal de Educação, Ciência e Tecnologia da Bahia (Labprosaud/IFBA), Salvador, Bahia, Brazil.

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1. INTRODUCTION

Research, development, and innovation (RDI) in the metrology 4.0 area are necessary to support digital transformation and technological advancements in many areas, such as industry 4.0 and the medical 4.0 environment. In the area of ionizing radiation, in particular, some projects have been developed, mainly to "promote the infrastructure for legal metrology to support conformity assessment processes and market surveillance" [1]. Studies of personal dosimetry, dose prediction in radiotherapy, and clinical imaging, using innovative technologies such as Artificial Intelligence (AI) and Deep Learning, are being carried out with promising results [2].

In Brazil, some challenges make the metrological digital transformation process even harder, mainly related to the modernization of measurement systems and the integrating of professionals from multidisciplinary areas working in RDI. Another identified challenge is the risk associated with the difficulty in public individuals and end users accessing metrological information, such as calibration results and radiation qualities applied to field tests in interventional and diagnostic radiology. Efforts need to be directed towards mitigating these gaps and the new risks arising from such transformation [3]–[5].

A cyber-physical system (CPS) can be established within a calibration laboratory, enabling the simulation of its instruments and processes. The simulations can function in parallel as digital twins, contributing to a better projection of the physical system. This supports transformation efforts, as the CPS is continually improved through the ongoing measurement system modernization and integration into the digital environment.

1.1. Cyber-physical systems

CPS are "integrations of computation with physical process". They integrate elements controlled and monitored by embedded computers and networks generating and receiving data with feedback loops of influence variables [6]. This system consolidates computational, communication, and storage resources to reliably, securely, and efficiently monitor and control entities in the physical environment in real time [7].

Three fundamental aspects are considered essential in CPS [7]:

- Real space: the physical elements of a system;
- Object domain: sensors, actuators, or devices connected in a network with those components;
- Cybernetic/virtual space: the computational part that receives the data of the physical sensing, makes the control, and promotes the action in the domain of the objects.

In this scenario, the reliability of data obtained from the CPS becomes critical and must be continually assessed. Validation tests are suitable tools to do it.

1.2. Simulation and digital twins

Simulation has, as its primary conception, the act of manipulating concepts and exploring reality. It is considered the third alternative of scientific study, besides theory and experimentation. It can be understood as the technique of using models to study a particular system [8].

Digital twin technology (DT) involves creating an accurate digital replica of any environment. According to the Centre for Digital Built Britain, DT is "a realistic digital representation of assets, processes or systems in the built or natural environment". It must represent physical reality at a level of accuracy suited to its purpose, considering the quality of the data on which the twin is based, the fidelity of the algorithms, the validity of the assumptions, and the competence of the code to represent it digitally, besides the quality of presentation of the output [9].

Simulations and digital twins utilize digital models to replicate a system's processes. The difference between the two is related to scale: a simulation typically studies one process, while a digital twin can run any number of useful simulations to study multiple processes [10]. Another difference worth highlighting is that simulations usually do not benefit from having real-time data. However, digital twins are designed around a two-way flow of information. This feedback system generates insights from data analysis, which are then shared with the physical counterpart. In other words, digital twins have more significant autonomous potential in the processes [10].

Figure 1 illustrates the hierarchy relation among these items in a calibration laboratory of ionizing radiation meters. The CPS is the laboratory's macrostructure, which shelters some DTs inside it. Computer simulations are responsible for feeding the DTs with virtual data, while physical sensors do this with data from the physical environment.

1.3. Objective

This study aims to create a pilot CPS from a calibration laboratory (LabPROSAUD/IFBA) and prospect how its simulated instruments, meters, and processes can work as digital twins, contributing to continuously improving its physical processes.

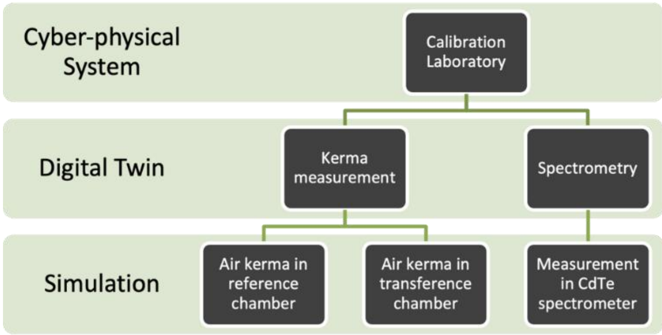

Figure 1. Digital elements hierarchy pyramid.

2. MATERIALS AND METHODS

2.1. Characterizing virtual apparatus for ISO N Radiation Quality

The first step for the air kerma measurement simulation is establishing a virtual apparatus, similar to the physical one, guided by ISO 4037 series requirements [11]–[13].

The Monte Carlo code used in the simulation was EGSnrc, with the egs_phd application [14].

The spectral requirements for ISO N 60 radiation quality are mean energy between 45.6 keV and 50.4 keV (5 % of tolerance relating to the 48 keV mean energy), and resolution between 30.6 and 41.4 % (15 % of tolerance relating to the 36 % of resolution). Those features shall come from a tungsten anode, aluminium (4 mm, counting Al equivalent inherent filtration) and copper (0.6 mm) of additional filtration, and distance measurement of 1.0 m–3.0 m [11], [12].

Those requirements have already been established in a previous work published by Macedo. The results have shown mean energy of 47.2 keV and spectral resolution of 33 % for the corrected spectra obtained in both physical and virtual laboratories. They comply with standard requirements and could be considered capable of performing virtual measurements under ISO N 60 radiation quality conditions [15]–[18].

2.2. Setup for the physical air kerma measurement

The apparatus for air kerma measurement under ISO N 60 quality is the same as the one used for spectrometry, except for the radiation detector and its distance from the x-ray source [12].

The standard ISO 4037 recommends the setup illustrated in Figure 2 [11]–[13].

According to Figure 2 number positions, the instrumentation used was:

- Position 1: ISOVOLT Titan E 160M2, an X-ray tube with a tungsten anode and inherent filtration of 1 mm Be;
- Position 2: lead primary collimator;
- Position 3: PTW shutter;
- Position 4: aluminium and copper additional filtration;
- Position 5: pre- and post-monitor chamber collimators;
- Position 6: transmission chamber as a beam monitor (PTW TM-786);
- Position 7: reference chamber, a PTW 1-liter spherical ion chamber (TM32002), calibrated in terms of ambient equivalent dose, $H^{*}(10)$, at PTB. A PTW Unidos

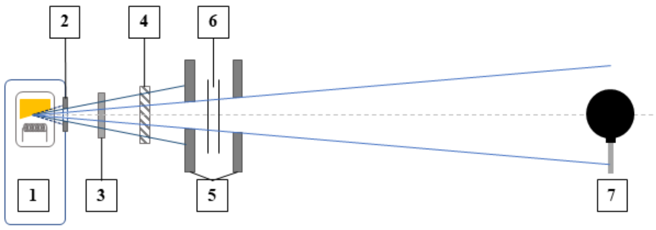

Figure 2. ISO 4037 recommended setup.

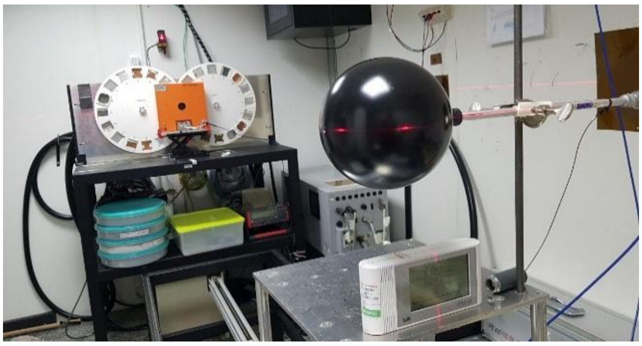

Figure 3. Physical air kerma measurement setup on Labprosaud/IFBA [18].

webline electrometer measures the charge or current generated from the ion chamber.

The experimental setup established on Labprosaud/IFBA is shown in Figure 3.

The $H^*(10)$ reference value was obtained with the reference chamber positioned 2.5 m far from the source, with a 4 mA of tube current. The field geometry at this point is a 30 cm diameter circle, with an air kerma inhomogeneity lower than 5 % to 24 cm diameter.

For the open air ion chamber, a correction factor for air density, k_{TP}, is calculated from a measured temperature (T, in °C) and air pressure (P, in kPa), which must be applied according to equation 1 [12], [19]:

$$k_{\mathrm{TP}} = \frac{(273{,}15 + T)}{293{,}15} \cdot \frac{101{,}325}{P} . \qquad (1)$$

The reference air kerma, $K_{a,\mathrm{N60}}^{\mathrm{ref}}$, for ISO N 60 radiation quality is obtained from equation (2) [13]:

$$K_{a,\mathrm{N60}}^{\mathrm{ref}} = \frac{N_{H,60}^{\mathrm{ref}}}{h_N^*(10; N60)} \cdot M_{60}^{\mathrm{ref}} \cdot k_{\mathrm{TP}} , \qquad (2)$$

where:

- $N_{H,60}^{\mathrm{ref}}$ is the reference system calibration coefficient, in terms of $H^*(10)$;
- M_{60}^{ref} is the uncorrected measure of the reference system;
- $h_N^*(10; N60)$ is the conversion coefficient from air kerma to ambient dose equivalent for ISO N 60 radiation quality.

2.3. Setup for the virtual air kerma measurement

The scenario used for the virtual measurement of the ISO N 60 spectrum was also applied for the production of the beam used for kerma measurement, which can be seen in Figure 4. Structures from 1 to 5 are fixed in this cyber-physical laboratory, and the radiation detector changes according to the desired application [15].

Elements shown in Figure 4 include: 1. X-ray focus; 2. primary collimator; 3. aluminium and copper filtration;

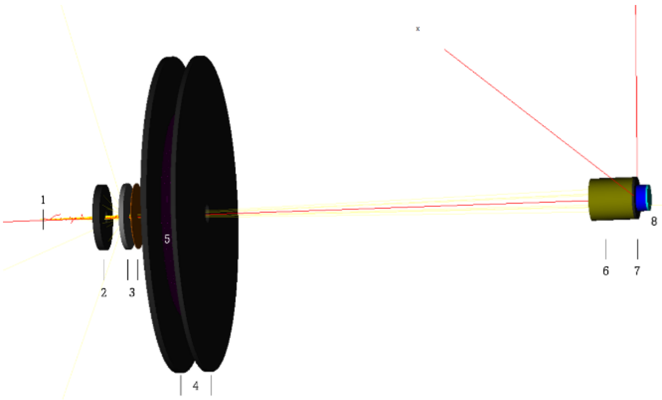

Figure 4. The simulated scenario of N60 spectrometry on EGSnrc [14].

4. monitor chamber collimators; 5. monitor chamber; 6., 7., and 8. spectrometer.

The active volume of reference PTW 1-liter spherical ion chamber (TM32002) was designed according to its technical specification for the virtual air kerma measurement. There were two concentrical spheres of polyoxymethylene and a 1000 cm³ air volume between them. Figure 5 shows the technical design [20].

The Monte Carlo code used in the simulation was EGSnrc, with the egs_kerma application [21]. Figure 6 shows the simulation of the lab apparatus (point 1), same as Figure 5, and the measuring volume (point 2).

The highlights of the simulation code are:

- Source definition with egs_collimated_source;
- Air region inside the chamber selected as "scoring regions" element;
- "Scoring region masses = 1.20479", in grams, calculated from an air density of $1.20479 \cdot 10^{-3}$ g/cm³, for an active volume of 1000 cm³;
- Forced detection ("FD geometry") option used to optimize interactions on ion chamber;
- Mass-energy absorption coefficients from "emuen_rho_air_1keV-1.5MeV.data" [21].

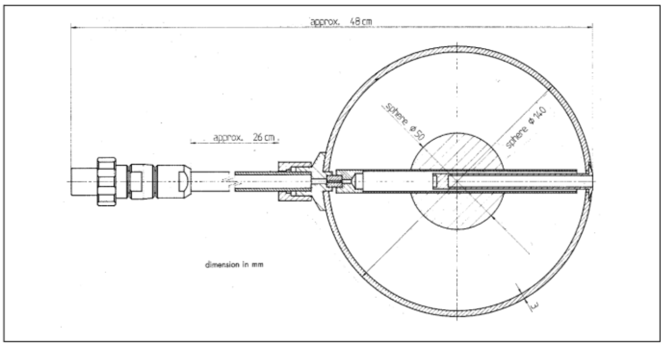

Figure 5. 1-liter chamber technical design [20].

Figure 6. 1-liter chamber simulated.

Collision kerma for medium m, K_m, is computed by summing up the individual contributions of N photons crossing the scoring volume V_m using equation (3) [21]:

$$K_\mathrm{m} = \sum_{i=1}^{N} \omega_i \cdot \frac{l_i}{V_\mathrm{m}} . E_i . \left(\frac{\mu_\mathrm{en}}{\rho}\right)_{\mathrm{m},i} , \quad (3)$$

with l_i the path crossed by the i^th photon of statistical weight ω_i through the scoring region.

2.4. Digital twin for air kerma measurement

The pilot DT system of air kerma measurement will be designed from the Monte Carlo simulation described in 2.3. It consists of a two-way flow of information that first occurs when sensors provide relevant data to the system processor ("Physical Sensing"), and then happens again when insights created by the processor are shared back with the source object ("Information Actuation"). This workflow is illustrated in Figure 7.

The variables obtained on the physical system that will feed the virtual one are listed below:

- Air kerma: air kerma measurements from reference ionization chamber;
- Ambient temperature: used to correct the air density inside the chamber;
- Atmospheric pressure: used to correct the air density inside the chamber;
- Humidity: used as a control variable inside the X-rays room, values within a specific interval;
- Radiation quality: beam characterization, quantified from spectrometry variables, such as mean energy;
- Distance source-to-detector;
- Field area at the reference irradiation point;
- Tube voltage;
- Tube current.

The database produced from those variables will allow the analysis of relationships between two or more quantities. Some correction factors are examples of the expected output of DT data analysis. Reproducibility and correlations among variables can also be considered.

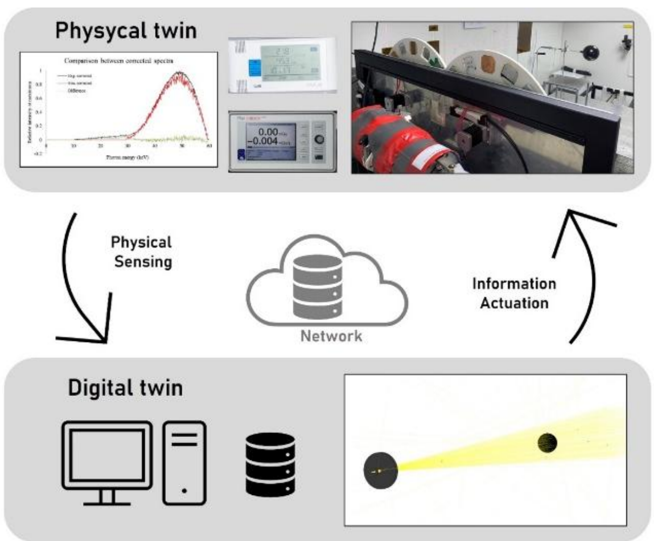

Figure 7. Diagram of loop feedback in air kerma measurement.

3. RESULTS AND DISCUSSION

As a preliminary result, kerma simulation in the virtual laboratory was obtained. The virtual PTW 1-liter ion chamber measures 4.3×10^{-13} Gy/mAs.

The variables obtained on physical simulation, and replicated in the virtual system, were:

- Air kerma: 2.3×10^{-7} Gy/mAs;
- Ambient temperature: 21.0 °C;
- Atmospheric pressure: 101.05 kPa;
- Humidity: 56.6 %;
- Radiation quality: mean energy of 47.2 keV and spectral resolution of 33 %;
- Distance source-to-detector: 2.5 m;
- Field area at the reference irradiation point: 24 cm diameter;
- Tube voltage: 60 kV;
- Tube current: 4.0 mA.

A discrepancy in air kerma measurements was observed between the physical and digital twin systems. The ISO N 60 setup of the virtual laboratory was established [15], however, kerma measurements did not have the same performance.

Since the physics of electromagnetism is not included in the EGSnrc Monte Carlo code, it is not possible to simulate an exposure based on mAs values that would produce the expected number of electrons and, consequently, X-ray photons in a real exposure. This limitation exists in this study and in other studies using Monte Carlo computational simulations. To address this issue, the authors estimate correction coefficients to adjust the simulated values relative to experimental values, or use air kerma data estimated from the generated X-ray spectra. This information was discussed by Macedo (2023) [22], based on previous studies by other authors [23]–[28].

The workflow described in Figure 7 is the expected result of pursuing the development of a cyber-physical calibration laboratory and a digital twin of the components of air kerma measurements.

A pilot project of a digital twin calibration laboratory was proposed by Macedo using the presented CPS in an application of interlaboratory comparison [22].

4. CONCLUSION

Building cyber-physical systems and implanting digital twin concepts in their processes is challenging. Developing those technologies in a radiation laboratory environment also has its obstacles. The virtual air kerma measurement system was chosen for its level of recognition, since it is widely disseminated in calibration laboratories around the world.

The results show that this work's objective was partially reached, since the difference between virtual and physical air kerma measurements form the field of investigation as next steps. The good agreement between physical and virtual spectrometry in the last work indicates that the virtual air kerma can be obtained with better accuracy.

The designed workflow has the conceptual basis for transforming the Monte Carlo simulations into a digital twin system, including the loop feedback of data in its operation.

AUTHORS' CONTRIBUTION

Mr. Matheus R. Nascimento, Mr. Leonardo C. Pacífico, and Mr. Igor F. M. Garcia contributed to investigation and methodology, Ms. Jeovana S. Ferreira to writing – review and editing, and Mr. Marcus V. T. Navarro and Mr. José G. P. Peixoto to supervision.

ACKNOWLEDGEMENT

To the Instituto de Radioproteção e Dosimetria – IRD/CNEN, Laboratório de Produtos para a Saúde Labprosaud/IFBA, and the Sociedade Brasileira de Avaliação de Riscos e Benefícios em Saúde (SBAR). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. Thanks also to all participants of the IRTech research group.

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