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: Even more energy has been invested in metrology 4.0 since the Digital Transformation arrived. Cyber-physical systems (CPS) and Digital Twin (DT) technologies can be implanted in radiation applications, such as a calibration laboratory. The objective here is to create a pilot project of a CPS of a lab with an air kerma measurement process as DT, starting from a Monte Carlo simulation. The difference in virtual and physical measurement results was about 10^{-6} times, which is the source of a deep posterior investigation. A workflow was designed to transform the Monte Carlo simulations in the DT.

Keywords: Digital Twin. Air Kerma. Monte Carlo. EGSnrc. Cyber-physical system.

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. Specifically in the ionizing radiation area, some projects have been developing, 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 technology such as Artificial Intelligence (AI), 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 challenge identified is the risks associated with the difficulty of public individuals and final users in 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 from such transformation [3–5].

A Cyber-Physical System (CPS) can be created from a calibration laboratory, and its instruments and processes simulated. The simulations can work in parallel as Digital Twins and contribute to better projecting the physical system. This can help that transformation once the CPS is constantly improved as measurement systems are modernized and integrated into the digital environment.

1.1. Cyber-Physical systems

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

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

- Realspace: the physical elements of a system;
- Objects domain: are sensors, actuators, or devices with those components connected in a network;
- 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 related to data obtained from CPS becomes critical and needs to be constantly pursued. Validation tests are suitable tools to do it.

1.2. Simulation and Digital Twin

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

Digital Twin Technology (DT) is the development of a faithful copy, in digital media, of any environment. According to the Center 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 both 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 to highlight is that simulations usually don't benefit from having real-time data. But digital twins are designed around a two-way flow of information. That feedback system generates insights from data evaluation, which are shared with the physical twin. In other words, Digital Twin has 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.

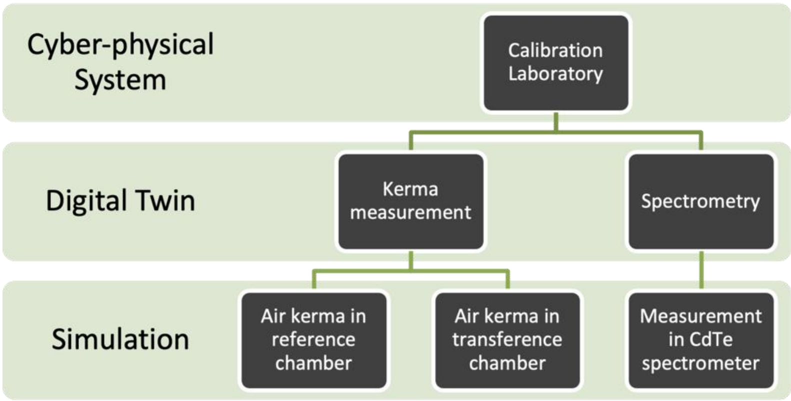

Figure 1. Digital elements hierarchy pyramid.

1.3. Objective
This study aims to create a pilot CPS from a calibration laboratory (Labprosaud/IFBA) and prospects how its simulated instruments, meters, and processes can work as Digital Twins, contributing to continuously improving its physical processes.

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 [11,12].

The Monte Carlo code used in the simulation was EGSnrc, with the egs_phd application [13].

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, aluminum (4 mm, counting Al equivalent inherent filtration), and cooper (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 on Metrologia 2021 Conference proceedings. 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 able to perform virtual measurements under ISO N 60 radiation quality conditions [14,15].

2.2. Setup for the physical air kerma measurement
The apparatus for air kerma measurement under ISO N 60 quality is the same one used for spectrometry, except for the radiation detector and its distance from the x-ray source [14].

The standard ISO 4037 recommends the setup illustrated in Figure 2 [11,12].

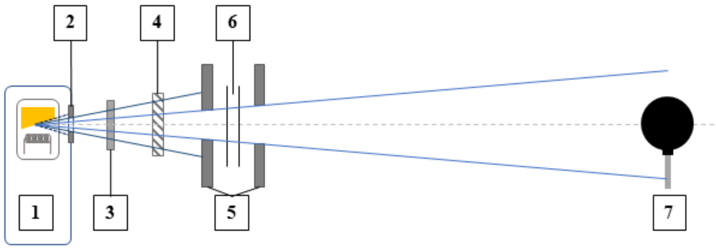

Figure 2. ISO 4037 recommended setup [12].

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: aluminum and cooper 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 webline electrometer measures the charge or current generated from the ion chamber.

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

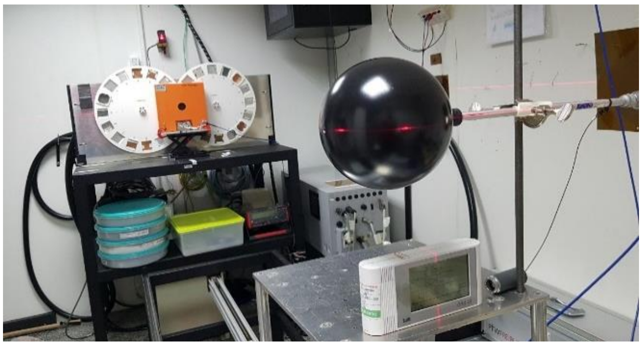
Figure 3. Physical air kerma measurement setup on Labprosaud/IFBA [16].

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% until 24 cm diameter.

For open air ion chamber, a correction factor for air density, k_{TP}, must be applied according to equation 1 [17]:

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

The reference air kerma, $K^{ref}_{a,\mathrm{N60}}$, for ISO N 60 radiation quality is obtained from: (ISO 4037-3)

$$K^{ref}_{a,\mathrm{N60}} = \frac{N^{ref}_{H,60}}{h^*_N(10; N60)} M^{ref}_{60} \,.\, k_{TP} \tag{2}$$

Where:
$N_{H,60}^{ref}$ 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 same scenario used for the virtual measurement of the ISO N 60 spectrum was used on beam production of the beam used on 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 [14].

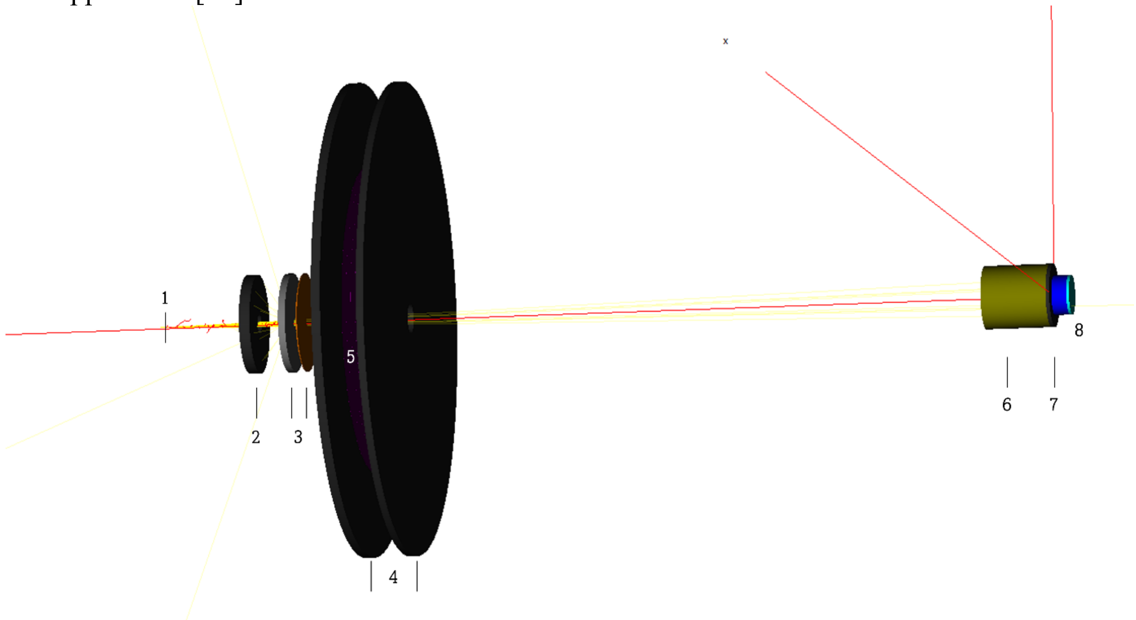

Figure 4. The simulated scenario of N60 spectrometry on EGSnrc [14].

Elements in Figure 4: 1. X-ray focus; 2. primary collimator; 3. aluminium and copper filtration; 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. Two concentrical spheres of polyoxymethylene and a 1000 cm³ air volume between them. Figure 5 shows the technical design [18].

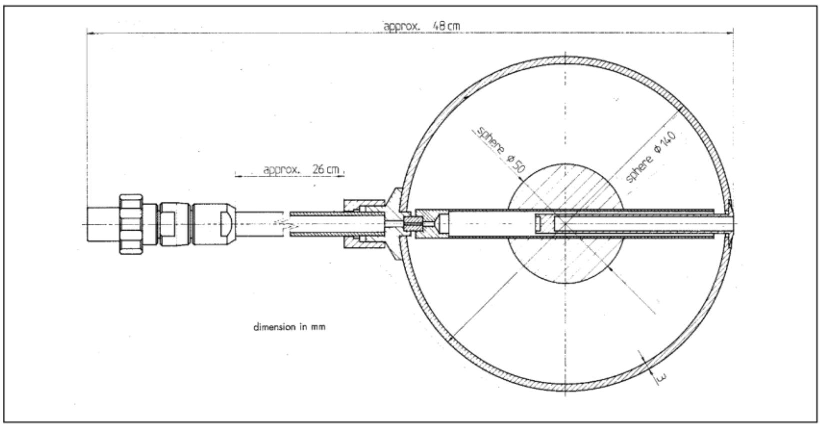

Figure 5. 1-liter chamber technical design [18].

The Monte Carlo code used in the simulation was EGSnrc, with the egs_kerma application [19].

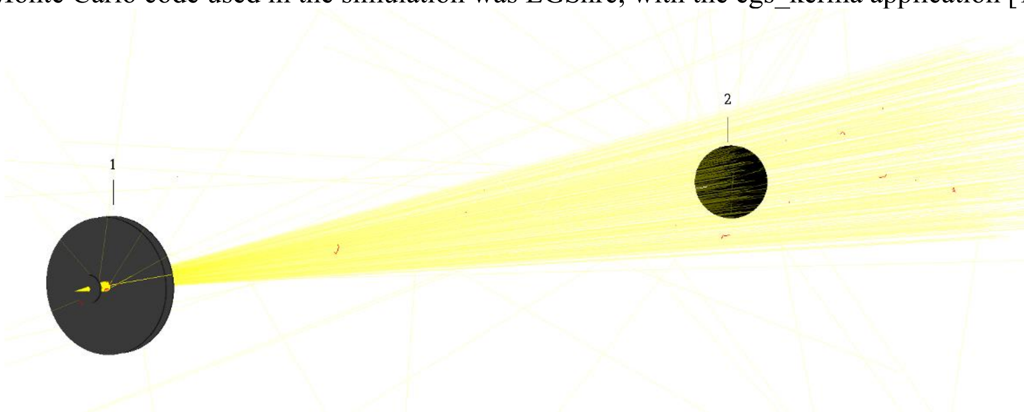

Figure 6. 1-liter chamber technical design [18].

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 1.20479E-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” [19].

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 the equation 3 [19]:

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

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

2.4. Digital Twin of 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 also can be considered.

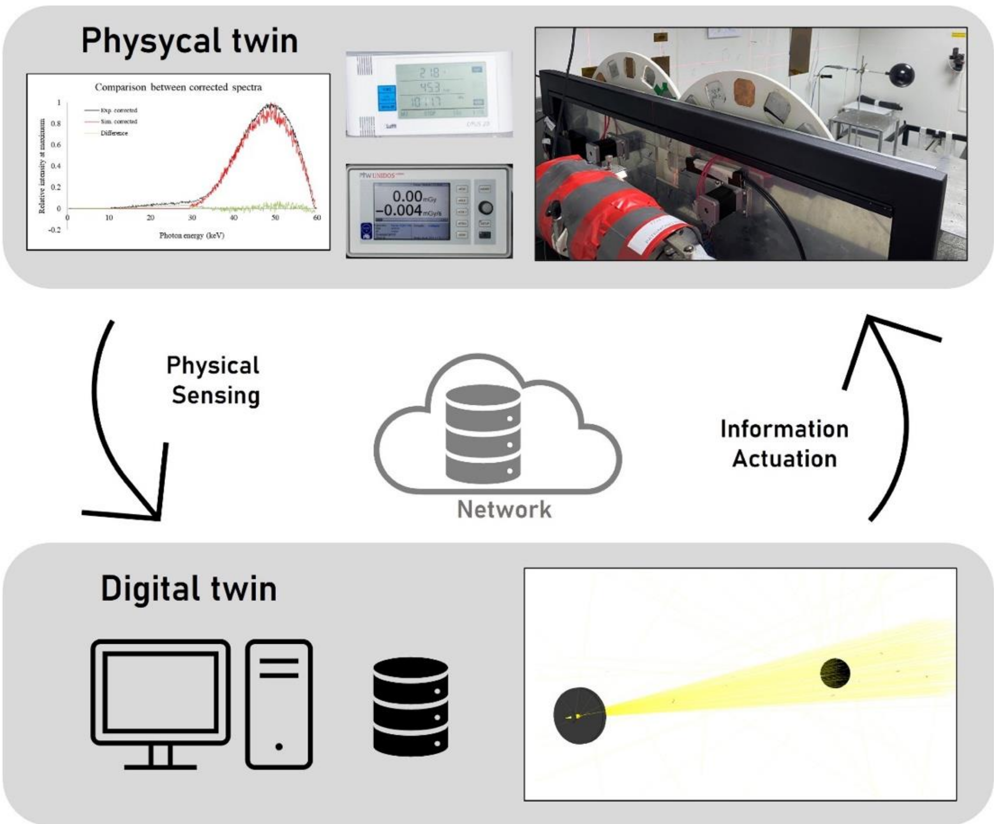

Figure 7. Diagram of loop feedback in air kerma measurement.

3. Results and Discussion

As prelims results, kerma simulation in the virtual laboratory was obtained. The virtual PTW 1-liter ion chamber measure $4.3x10^{-13}\ Gy/mAs$.

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

- Air kerma: $2.3x10^{-7}\ Gy/mAs$;
- Ambient temperature: $21.0\ °C$;
- Atmospheric pressure: $101.05\ kPa$;
- Humidity: 56.6 %;
- Radiation quality: Mean energy: $47.2\ keV$ 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 difference in air kerma measurement was observed between the physical and digital twin. The next step of this work is to investigate the cause of this shift. The ISO N 60 setup of the virtual laboratory was established [14]. But kerma measurements had not the same performance.

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

4. Conclusion

Building cyber-physical systems and implanting Digital Twins concepts in their processes is challenging. Developing those technologies in the radiation laboratory environment also has its obstacles. The virtual air kerma measurement system was chosen by its level of knowledge once it is widely disseminated in calibration laboratories around the world.

The results show that this work's objective was partially reached once the difference between virtual and physical air kerma measurements is the field of investigation of the 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 workflow designed has the conceptual basis for transforming the Monte Carlo simulations in the Digital Twin system, including the loop feedback of data in its operation.

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