Use of a high-resolution 2D diode array for electronic brachytherapy quality control

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Abstract: Quality control in radiotherapy is essential to ensure treatment safety and accuracy. Our goal is to evaluate the efficacy of quality control of an electronic brachytherapy system, performed with a 2D diode array, and to propose new methods involving this tool. We have performed a variety of tests regarding system's reproducibility, sensitivity and stability, and computed the gamma index and gamma pass rate to compare dose distributions. We have been able to determine our array's resolution both in position and dose (at least 1 mm and 1%, respectively), and presented strategies to perform an electronic brachytherapy system's quality control implementing this device.
Keywords: x-ray source, electronic brachytherapy, quality control, gamma index, 2D diode array.
SDGs: Good health and well-being; Industry, innovation and infrastructure.

I. INTRODUCTION

Brachytherapy is a form of 'near therapy'. Instead of traditional radiotherapy, where mega-voltage photons are emitted from beams around and outside the patient, an ionising radiation source is positioned inside the patient near the tumor, and therefore irradiation comes from within. Since radiation is attenuated by tissue absorption and scattering and is inversely proportional to the squared distance, this means that a higher dose can be delivered to the treatment area, and that the surrounding organs are exposed to a lower dose. Brachytherapy can use either a radionuclide or an electronic x-ray source. In this work, we will use the latter. The purpose is to evaluate the efficacy of quality control (QC) of an electronic brachytherapy (EB) system, performed with a 2D diode array, and to propose new methods involving this tool.

II. MATERIALS AND METHODS

The equipment this work focuses on is the Elekta Xoft® and the SRS MapCHECK®.

The Elekta Xoft® [1–3] is an electronic brachytherapy system used to provide treatment for a variety of tumors. It is most frequently utilized for breast intraoperative radiotherapy. It consists of an x-ray source (the Xoft Axxent® X-Ray source) and a control unit. It also incorporates several applicators that provide a channel through which the source is inserted, enabling targeted treatment. In this work, no applicators will be used. The x-ray source is connected via a high voltage cable to the control system. Unlike radionuclide x-ray sources, it does not need to be kept in a shielded container, given that radiation stops as soon as the operating voltage is shut off. The source is also connected to a refrigeration system for cooling, which in turn allows a higher possible dose, minimizing heat damage. A mechanical arm enables source insertion through the treatment catheter. The input data of this device consist of two columns: dwell position and irradiation time. The Elekta Xoft® system also includes an electrometer and a well-chamber used for calibration.

The SRS MapCHECK® [4] is a high-resolution 2D diode array. It is clinically used for Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy quality assurance. The treatment plan is recalculated on a detector array embedded in a phantom, which serves as a substitute for the patient. The phantom is then irradiated using a lineal accelerator (LINAC) to verify the system's capability to deliver the planned dose distribution accurately. This process ensures the treatment machine can reproduce the intended dose with precision before it is administered to the patient. To the best of this author's knowledge, this is the first time a 2D diode array will be used as a quality control tool for an electronic brachytherapy device.

The array size is 77 × 77 mm, centered at (0,0) mm, with upper and lower limits of ± 38.5 mm in both the x and y axes. It consists of 1013 SunPoint® 2 Diode Detectors. The detector spacing is 2.47 mm and the active detector area is 0.48 × 0.48 mm^2. The output data in this work is given for 1.75 mm increments, as a 45 × 45 matrix, with the detected dose values in grays (Gy). The matrix is connected via cable to a computer containing the SunCHECK® Patient software, from which we can start and stop measurements and save the obtained data.

The system set up is as follows: the source is mounted on the Elekta Xoft®'s robotic arm, which is then placed atop the matrix in the needed coordinates. In this work, the source will irradiate for a fixed position.

In order to establish the quality controls of our equipment, the following tests have been performed:

- Reproducibility: to firstly assure the system can be satisfyingly recreated.
- Sensitivity: to establish the system's resolution in both position and dose.
- Stability: to determine if the system is constant over time.

Images of the several system components and an example of their set-up can be found in the Supplementary Material section.

A. Acquired data

The acquired data consist on a 45 × 45 matrix dose distribution, with a dose value for each 2D index, and therefore a total of 2025 values. The source is positioned in the center of the array, at (0,0). Fig. 1 shows an example of a dose distribution.

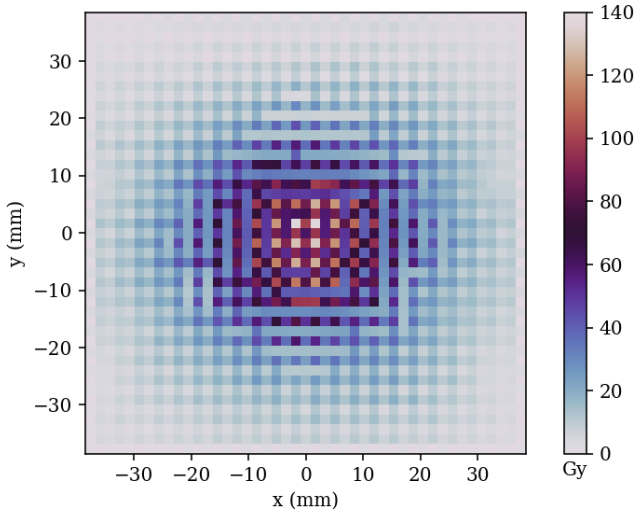

FIG. 1: Example of a dose distribution displayed as a colormap, with its corresponding colorbar, for an irradiation time of 60 s.

B. Gamma comparisons

The analysis tool used in this work to compare dose distributions is the gamma index (γ). Gamma is a "numerical quality index that serves as a measure of disagreement in the regions that fail the acceptance criteria and indicates the calculation quality in regions that pass" [5]. Through two parameters, distance to agreement (DTA) and dose-difference (DD), and their selected passing criteria (Δd_M and ΔD_M, respectively), it compares two dose distributions. It uses one as a reference to which the other is compared, and indicates whether the latter passes the accorded DTA and DD criteria ($\gamma \leq 1$), and determines its accuracy: the lower the gamma index value, the higher the accuracy.

Clinically, the measured dose distribution is used as a reference to which the calculated distribution is compared, although the gamma index can compare any two distributions. In this research, both the compared distributions are measured dose distributions, and the reference dose distribution will be selected according to each analysis' needs. For this study, the following passing criteria were chosen: $\Delta D_M = 1\%$ and $\Delta d_M = 1$ mm, since we will evaluate wether the system is sensible to 1% dose increments and 1 mm position differences. Further development on the definition and calculation of the gamma index can be found in [5].

In this work, gamma has been calculated via an existing gamma function from the 'pymedphys' Medical Physics Python library [6], in the `gamma` module: `gamma_shell`. The output of this function is a 2D matrix with the gamma value for each point of the distribution. An example of such a gamma representation can be found in Fig. 2.

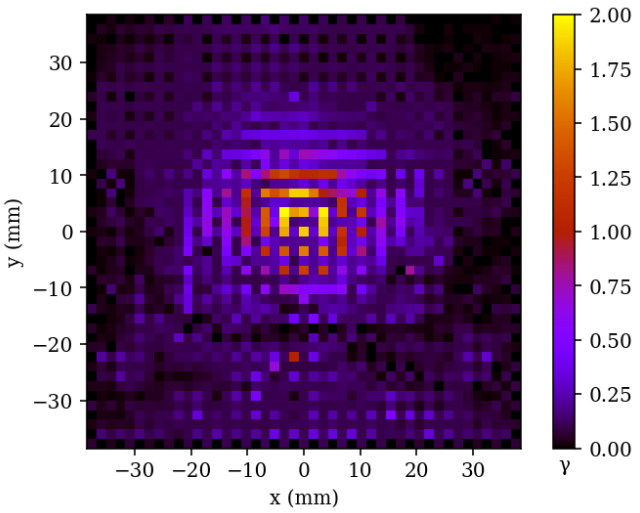

FIG. 2: Example of a gamma index 2D matrix displayed as a colormap, with its respective colorbar, for an irradiation time of 60 s.

Results can also be displayed in the form of an histogram, as portrayed in Fig. 10a in the Supplementary Material section.

C. Gamma pass rate

In order to effectively present the gamma comparison's results and the compared dose distributions' quality, data is presented via the pass rate. The gamma pass rate (GPR) determines the percentage of points in a gamma 2D matrix that successfully pass the evaluation, that is, that are $\gamma \leq 1$. An existing function of the above mentioned 'pymedphys' Medical Physics Python library and in the same `gamma` module, `calculate_pass_rate`, is used for this calculations. For this study, a GPR $\geq$ 95% will be appointed successful, given the reproducibility test results (detailed in the next section), and following the recommendations of the hospital experts, given there are no established criteria for this.

III. RESULTS AND DISCUSSION

A. Reproducibility

Ten measurements were performed in the same day in order to determine the reproducibility of the system, that is, if there are perceptible differences in measures taken considering no changes except for the required tests of the Elekta Xoft® (i.e., priming, calibration and pullback test). These are mandatory for every patient's treatment, which, in our study, translates to every measurement. The priming test is performed by creating circulation in the tube that connects the cooling system to the x-ray source, to ensure no bubbles can be found; calibration is mandatory for every treatment to account for temperature and pressure adjustments, and the pullback test is performed to assure there are no obstacles in the path the x-ray source follows as it moves, once it is placed atop the robotic arm. This means the source has to be inserted in the well-chamber for calibration, positioned in the mechanical arm during the pullback test and re-centered atop the matrix for every measurement. The average of this ten measures is used as an initial reference state (IRS). GPRs are calculated for each measure, using the IRS as reference. The results are presented next:

TABLE I: Gamma pass rates (GPRs) for the ten initial dose distribution measurements, each compared to their average.

Measure	1	2	3	4	5
GPR (%)	100.00	99.75	99.65	99.26	99.95
Measure	6	7	8	9	10
GPR (%)	98.37	99.80	99.95	99.95	95.75

GPRs are considered to be sufficiently high to assure our system can be reliably replicated.

B. Sensitivity

It is important to determine the system's sensitivity to make sure it is sufficient for position and dose stability quality control.

1. *Position sensitivity*

Measures were performed between -5 mm and +5 mm, with $\Delta x = 1$ mm (increment in position), three repetitions for each, for a total of 33 measurements. Each measure, which includes the above mentioned necessary tests of the Elekta Xoft®, took between 5 to 10 minutes, for a 1 minute irradiation time. The reference dose distribution for this test is the corresponding to the central position, that is, when the source is positioned in the center of the matrix ($\Delta x = 0$ mm). The GPR was computed for each measure, and the results for each position were averaged to introduce a standard deviation related error. Results are presented in Fig. 3.

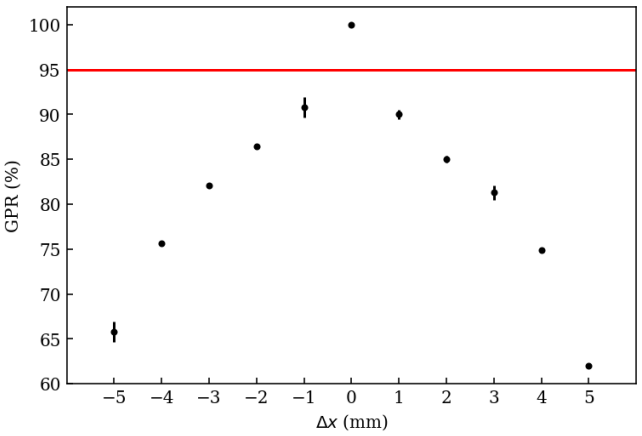

FIG. 3: Gamma pass rates (GPRs) and errors for the selected 1 mm increments and passing criteria, for a ± 5 mm interval, with a convenient 95% horizontal line indicating the limit percentage tolerance.

As showed in Fig. 3, since both for ± 1 mm the gamma index is already below the defined 95% minimum tolerance, we can state that the system is sensible to 1 mm position shifts. As expected, the GPR is lower for bigger position shifts, that is, the dose distribution increasingly differs from its reference as distance to the central positions increases. The fairly stable and symmetrical decrease of the gamma index indicates that this tool is effective to evaluate position sensitivity. Moreover, we can predict a positioning shift by checking the GPR, and viceversa.

However, we would ideally expect the graph to be vertically symmetrical with a constant decline. This can be explained simply by taking into account that 1 mm increments can't be perfectly performed by the human eye. Since the gamma index is so sensible to such small positioning deviations, a certain human error is inevitable.

2. *Dose sensitivity*

Given that the Elekta Xoft®'s irradiation's input is the dwell position and time, in order to determine the 1% dose increment needed for the dose sensitivity evaluation, it is necessary to compute the corresponding time increment responsible for it. Therefore, measurements were performed for several values of time to obtain a dose-time lineal estimation. Three separate measures were made for each time value. The resulting graphic can be found in the Supplementary Material section.

A simple lineal regression is adjusted to this data, with $R^2 = 0.999998$. For a $\Delta D = 1\%$ dose increment, we find

that we need $\Delta t = 0.6$ s (increment in time). Therefore, measures were performed for a $\pm$ 3.0 s interval (corresponding to the accorded $\pm$ 5% dose interval) around the reference time of 60.0 s, with $\Delta t = 0.6$ s. Again, for each value of time, three measures were repeated to account for system uncertainty.

In this test, the reference dose distribution corresponds to the 0% dose increment, to which the rest are compared. The GPR was computed for each of these, then averaged for each set. In Fig. 4 we represent these, with their error bars, as a function of their respective dose % increment.

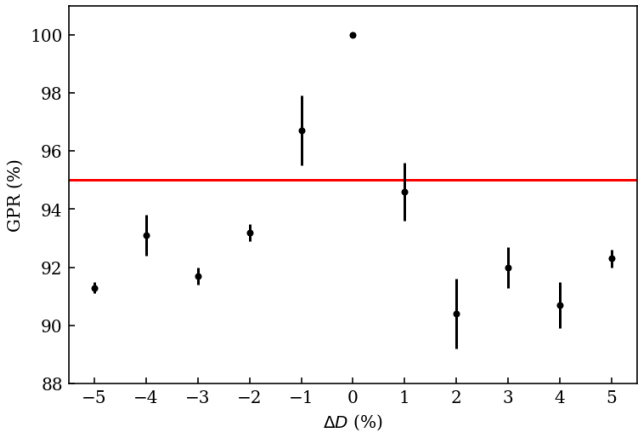

FIG. 4: Gamma pass rates (GPRs) and errors for the selected 1% dose increments and passing criteria, for a $\pm$ 5% interval, with a convenient 95% horizontal line indicating the limit percentage tolerance.

As is observable, a 1% dose increment can not be appreciated through a GPR evaluation. Further proof of this is the instability for higher dose percent differences, as we would otherwise expect there to be a monotone decrease, such as the one presented in Fig. 3.

We can conclude that the GPR is not a useful tool to evaluate dose sensitivity. A different tool is hereby proposed: comparing the maximum value of the dose distribution for each dose increment. If the 2D array can resolve this 1% dose difference, we would expect to obtain a lineal adjustment to fit the obtained data.

The maximum value of each dose distribution matrix was susbsequently found, using the `numpy.max` attribute of a numpy array in Python. These were averaged for each set, and the results are presented in Fig. 5.

As predicted, a lineal tendency is clear, which demonstrates that the maximum value of a dose distribution is a good substitute to its output. The equation of this lineal adjustment is:

$$D_{max} = a \times \Delta D_{\%} + b \tag{1}$$

Where a, the slope, is $a = 1.34 \pm 0.03$ Gy and b, the reference dose, is $b = 142.18 \pm 0.09$ Gy. Comparing b with

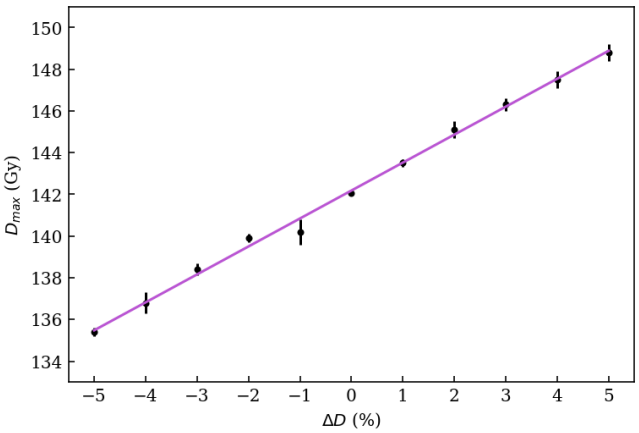

FIG. 5: Maximum value of the dose distribution (D_{max}) for each 1% dose increment (ΔD), with the corresponding errors and lineal adjustment.

the maximum dose for the reference 0% matrix, $D^{ref}_{max} = 142.04$ Gy, we can state that, given that their discrepancy of 0.14 Gy is smaller than twice the error, the results are compatible.

This is possible because the resolution of the detector array is high enough (i. e., the detectors are sufficiently close) so that the approximate maximum value is always detected, despite the high dose gradients present in the distribution.

From the lineal adjustment's slope (a) and a reference dose (b), we can estimate a % dose increment for a maximum dose value, and viceversa.

C. Stability

As an example of a practical application of the maximum dose value method, introduced in the Dose Sensitivity section, the stability over time of the Xoft Axxent® X-Ray source was evaluated. Therefore, several measures were taken during a month long period (measures were performed seven days, three times each day) to account for changes in the source's output. The maximum dose of the output matrices was computed, then averaged for each set, as can be seen in Fig. 6.

The resulting relative error of each of these compared to their average is never >1%, which indicates that the source is stable. This is due to the fact that the irradiation times, for their corresponding dwell positions, are corrected before treatment (during the calibration test), according to small daily output's deviations. This ensures the measured dose remains stable.

Additionally, GPRs were computed and averaged for each of these days (here, the reference dose distribution is the IRS). The results are presented in Fig. 7.

GPR is not above the defined 95% tolerance for each of these days. This can be explained taking into account that, as previously mentioned, a millimetrical error in

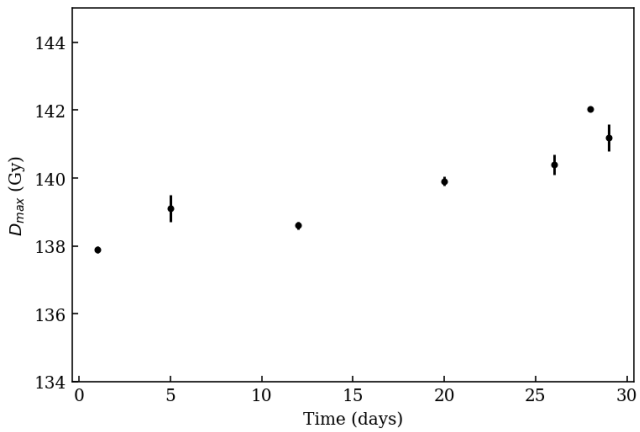

FIG. 6: Maximum value of the dose distribution (D_{max}) with the corresponding errors, measured during several days.

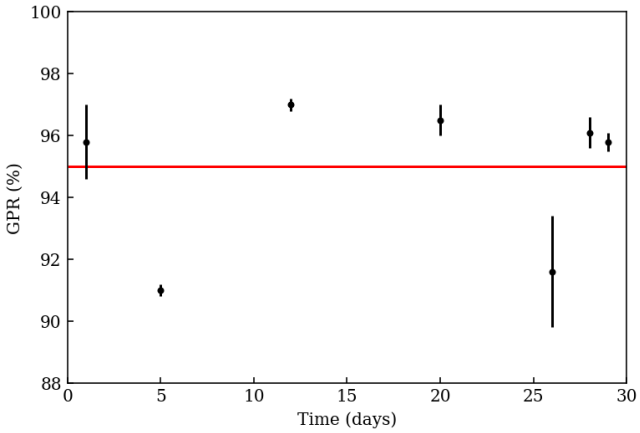

FIG. 7: Gamma pass rates (GPRs) for the selected passing criteria, computed for the same dwell position and irradiation time during several days, with the corresponding errors and a convenient 95% horizontal line indicating the limit percentage tolerance.

position can cause the GPR to drop considerably, which was probably what occurred on days 5 and 26 of this test. This is further proof that the GPR test is not effective in dose sensitivity evaluations. Gamma index might only be satisfying when used on systems of high positioning precision.

IV. CONCLUSIONS

According to our study, the use of high-resolution 2D matrices can be satisfyingly implemented in quality control of electronic brachytherapy equipment.

We have proved, via the GPR, that our system has position sensitivity of at least 1 mm.

We have demonstrated, by substituting the array's output for its maximum value, that our system is sensible to dose deviations of at least a 1%.

Therefore, the gamma index and the maximum dose value can be included in quality control tests for position accuracy and dose stability, respectively.

Areas for future research could include utilizing our positioning QC evaluation to verify the x-ray source's positioning is reproducible in intricate situations, such as those regarding a curved applicator, which is common when inserting the source in the balloon applicator for breast tumor related treatments.

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I would like to thank my advisors, Dr. Carles Muñoz and Dr. Roser Sala, for their knowledge and guidance, and the Medical Physics and Radiation Protection Department of Institut Català d'Oncologia at Hospital Dr. Josep Trueta, for allowing me to use their equipment and facilities. Special thanks to my family and friends, for their support throughout this work.

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Ús d'una matriu de díode 2D d'alta resolució per al control de qualitat de la braquiteràpia electrònica

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Resum: El control de qualitat en radioteràpia és essencial per a garantitzar un tractament segur i eficaç. L'objectiu d'aquest treball és evaluar l'eficàcia del control de qualitat d'un equip de braquiteràpia electrònica, realitzat amb una matriu de díode 2D, i proposar nous mètodes que incloguin aquesta eina. Hem dut a terme un conjunt de proves respecte de la reproducibilitat, sensibilitat i estabilitat del sistema, i calculat l'índex gamma i la taxa d'aprovació gamma per comparar distribucions de dosi. Hem pogut determinar la resolució de la nostra matriu en posició i dosi (almenys d'1 mm i d'un 1%, respectivament), i hem presentat estratègies per realitzar un control de qualitat d'un equip de braquiteràpia electrònica implementant aquest dispositiu.
Paraules clau: font de raigs x, braquiteràpia electrònica, control de qualitat, índex gamma, matriu de díode 2D.
ODSs: Salut i benestar; Indústria, innovació, infraestructures.

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de les desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	
3. Salut i benestar	X	12. Consum i producció responsables	
4. Educació de qualitat		13. Acció climàtica	
5. Igualtat de gènere		14. Vida submarina	
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures	X		

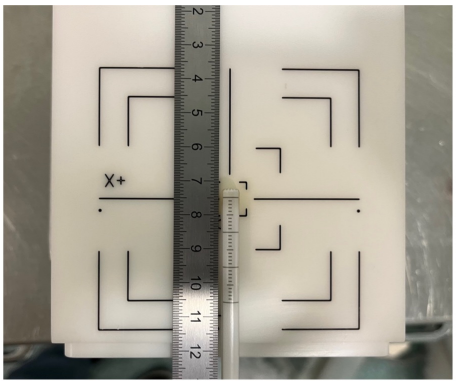
SUPPLEMENTARY MATERIAL

(a) X-Ray Axxent® source.

(b) Elekta Xoft® control unit.

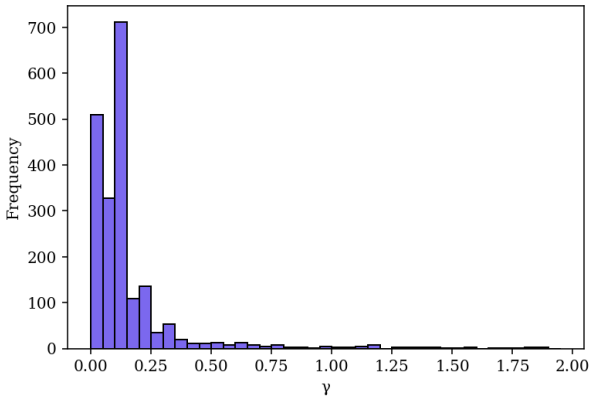
FIG. 8: Elekta Xoft® system.

(a) SRS MapCHECK®.

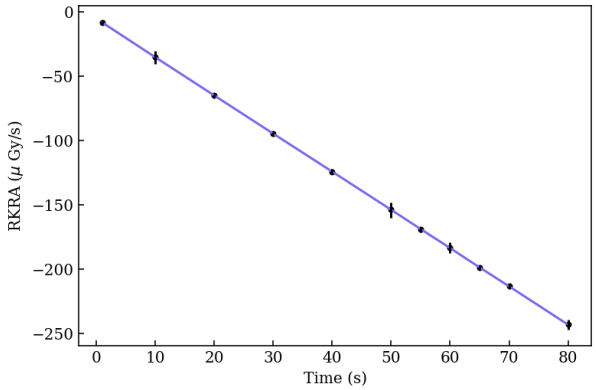


(b) Example of a system measurement.

FIG. 9: Material and set-up image for source positioned at the center of the matrix.



(a) Example of a histogram representation. Frequency of the gamma index values for a selected bin interval of 0.05.



(b) Reference air kerma rate (RAKR) for each value of time, and its corresponding errors and lineal adjustment.

FIG. 10: Supplementary graphs.