Assessment of the uterine dose level in digital mammography exams including tomosynthesis

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ABSTRACT

Introduction: Conventional mammography is considered safe to be performed during pregnancy, but it presents some limitations that can be overcome using tomosynthesis. This exam can be done to women who don't know if they are pregnant. The objective is to evaluate the dose level in the uterus during mammography including tomosynthesis and assess the risk to the fetus. **Materials and Methods:** The mammograph used was Simens Mammomat Inspiration. It was also used a physical anthropomorphic phantom, PMMA plates and thermoluminescent dosimeters to measure entrance air kerma values on the breast and abdomen phantom in order to successively estimate the mean glandular dose (MGD) and the dose in the uterus. In order to accomplish these results, three-breast irradiation strategies that could be encountered in routine clinical examinations, were defined according to different exposure parameters. **Results:** In the second strategy the air Kerma was 3,37 times higher than the MGD in tomosynthesis and 3,24 times higher in 2D mammography mode. The calculated doses in the uterus varied between 0 and 0,015 mGy with the total estimated dose in the uterus equal to 0,048 mGy in the scenario where both breasts are examined. **Conclusions:** Regarding the breast, when the doses from the acquired projections in 2D mammography and tomosynthesis mode are compared, it was verified that there is no significant difference between the dose values obtained for both modes. For the dose in the uterus, the obtained dose values seem to indicate that the performance of mammography including tomosynthesis is safe during pregnancy.

KEYWORDS: Breast cancer, mammography, tomosynthesis, pregnancy

1. INTRODUCTION

Oncological disease is, in the middle of the 21st century, one of the most worrying diseases, not only for its incidence, but also for its high mortality. In fact, 1 in 5 men and 1 in 6 women develop some type of cancer throughout their lives [1]. According to the World Health Organization, cancer is thus the second leading cause of death worldwide and in 2018 it is estimated to have been responsible for the deaths of 9,6 million people [2]. In Portugal, regarding the percentage of deaths from malignant tumours, data from the National Institute of Statistics show that, in 2017, approximately 25% of deaths were caused by malignant tumours [3]. According to the latest data from 2018, also in Portugal, cancer is the second leading cause of death, after brain cardiovascular diseases [4].

Most frequent cancer incidences include organs such as lung, colorectal and female breast. This last one is the second most prevalent type of cancer, accounting for 25% of all cancers diagnosed, and is the leading cause of cancer death, ie 15% of deaths in the female population, worldwide [1]. In the United States of America, it was estimated that in 2017, 252710 new cases of female breast cancer would be detected [5]. In

the United Kingdom, the most recent data show that breast cancer is the most common cancer in women, accounting for 31% of cases [6][7]. Finally, in Portugal, breast cancer is the most common and deadliest cancer in women [8], representing 27,1% of new cancer cases in women in 2018 [9]. One type of breast cancer is pregnancy-associated breast cancer, which is expected to increase in incidence, particularly in the 35-45 age group [10]. Among various imaging techniques available today, mammography in both breast and pregnancy-associated breast cancer, plays an important role [11]. Nevertheless, given some limitations, especially for the second case [12], the association of the tomosynthesis technique with conventional mammography allowed to increase the diagnostic capacity.

According to Future Markets Insight, in the United States in 2016, it was expected that there would be an increase in the number of mammographs with tomosynthesis technique, as well as in Western Europe and Asia (excluding Japan). In fact, in the report, “Digital Breast Tomosynthesis Equipment Market: Global Industry Analysis and Opportunity Assessment, 2016 - 2026, it is estimated that during that period, the compounded annual global market growth rate will increase by 13,9% in revenues [13]. It is therefore expected that the number of mammographys including tomosynthesis will continue to increase, including in Portugal.

Still, it is possible to state that tomosynthesis is a relatively recent technique and the number of studies evaluating the usefulness of the technique is not very high. In the American College of Radiology's Appropriateness Criteria® Breast Imaging of Pregnant and Lactating Women, (ACR) it is stated that there is no data on the usefulness of tomosynthesis, but given the physiological changes, patients may benefit from the characteristics of this technique for a better diagnosis [14]. Regarding dosimetry, the number of studies on the subject is also small. To date, only two studies addressing dosimetric characterization have been available. In the first study from 2015, the calculated doses for the various organs were obtained using Monte Carlo simulations using a female voxel phantom [15]. In the second, from 2018, the Entrance Surface Dose (ESD) was estimated by placing dosimeters in an anthropomorphic phantom, and the uterus was not one of the organs studied [16].

In addition to the cases reported so far, that is, women who need mammograms knowing they are pregnant, there are also cases of patients who are examined without knowing if they are. Although they are always asked in advance about the possibility of being pregnant, patients may discover pregnancy only after the exam. This may lead to the return of patients to imaging departments, where they express concern for the health of the fetus, the occurrence of any malformations that may derive from exposure to ionizing radiation to which they were submitted, and whether there is a need to terminate the pregnancy [17].

Thus, it is of utmost importance to make sure that a certain technique is safe to perform during pregnancy, whether known or not. Given the conventional mammogram, and the very low risk to the fetus, it is consensual that this exam is safe to perform during pregnancy. Although this is not yet clear regarding tomosynthesis, and in order to complement previous studies, the aim of this master's dissertation is to estimate the level of uterine dose in mammography exams including tomosynthesis and to assess the risk for fetus associated with this examination.

2. MATERIALS AND METHODS

2.1. Materials

The work required to carry out this dissertation was developed at the Portuguese Institute of Oncology (IPO), Francisco Gentil, Lisbon, specifically in the radiology department. It was necessary to use equipment present in that department but also materials from the C^2TN, a research unit of the Instituto Superior Técnico. In order to achieve the established objective, it

was intended to simulate a mammogram in a female patient, using an anthropomorphic physical phantom, in order to determine the mean glandular dose (MGD) in the breast and the dose that the uterus receives due to this irradiation.

The mammograph used to simulate the exam consisted of Siemens Mammomat Inspiration, present at the radiology department at IPO. This equipment can perform standard 2D mammograms and tomosynthesis and has PRIME (Progressive Reconstruction Intelligently Minimizing Exposure) technology included, solving the problem of scattered radiation in mammography [18]. The remaining Mammomat Inspiration components and specifications are shown in table 1.

Table 1- Mammomat Inspiration Technical Specifications.

Components	**Technical Specifications**
Detector technology	Direct conversion, amorphous selenium (aSe)
Detector size	24 cm × 30 cm
X-ray tube anode material	Tungsten (W)
Filter	0,05 mm of Rhodium (Rh)
X-ray tube movement	Continuous
Range of acquisition angles	- 24º a + 24º
Number of projections	25
Source-detector distance	65 cm

Since it is not possible to irradiate a real patient, the Alderson female radiotherapy phantom, with 155 cm in height and 50 kg in weight, was mounted and secured in a mobile-wheeled support. As the 8th week of pregnancy corresponds to the beginning of the most radiosensitive period of the embryo, and since at this stage of pregnancy the woman has not yet increased abdominal volume, the Alderson female radiotherapy phantom can thus replace a patient who is in an early stage of pregnancy. It was decided to remove the phantom holder, leaving only the movable base, and place the phantom on a table to facilitate its positioning in the equipment.

The Alderson radiotherapy phantom used has breasts that were chosen to be removed because it is not possible, given the size and material of the breasts, to compress them as if they were human breasts. In addition, there was the need of varying breast thickness in the irradiation plans created for the work. Therefore, PMMA plates of various thicknesses were used until reaching the desired breast thickness value and placed in the right breast position of the phantom. PMMA plates from C^2TN can be considered to replace the breast as there is a conversion of PMMA thickness to human breast thickness and glandularity.

To measure the dose in the anthropomorphic physical phantom, the TLD-100 H (LiF: Mg, Cu, P) Harshaw EXT-RAD dosimeters, with a circular shape and 5 mm in diameter, were used. The TLDs were reset the day before irradiation and readings were taken the next day using the Harshaw 6600 reader. A specific time-temperature profile was predefined to avoid any contribution from non-dosimetric peaks [19]. The measurement system was previously calibrated in terms of Kerma in the air using an ISO Narrow 80 (N80) spectrum at the Ionizing Radiation Metrology Laboratory of the Instituto Superior Técnico. The final uncertainty of the measurements taken is approximately 17% and is a combined uncertainty considering the contribution of detector efficiency, stability correction factor and reader calibration factor. 119 dosimeters were used and 116 of these were irradiated, with the remaining 3 serving to record the background dose. However, background dose subtraction was not performed as its value was negligible.

Figure 1 shows the phantom, the PMMA plates and the dosimeters positioned on the equipment.

Figure 1- Anthropomorphic phantom and positioning of dosimeters on PMMA plates in the first irradiation plan.

2.2. Work phases

The first phase of the work consisted of a phase of collecting and registration of mammography-related data, including tomosynthesis. Complete examination data was recorded, i.e. women who underwent 2D mammography and bilateral tomosynthesis or, in case this was a small number of cases, examinations as complete as possible. Totally, data coming from 60 exams was collected.

After collecting and analysing the data obtained in the first phase of the work it was possible to define three irradiation plans that would apply to the phantom. From the dosimetric point of view, the worst-case scenario for the patient, and consequently for the fetus, is to perform bilateral 2D mammography and tomosynthesis so this was the case considered in the 2nd irradiation plan. However, since the number of dosimeters was finite and limited, it was decided to apply irradiation plans to the right breast only. Because specific acquisition parameters were set to apply to the plans, the automatic exposure control mode was disabled so that the parameters could be set manually. The irradiation conditions of the defined plans are presented in table 2, 3 and 4.

Table 2- Irradiation conditions applied in the 1st plan.

1st Plan	
Voltage	28 kV
Exposure	160 mAs
PMMA thickness	5 cm
Projection	craniocaudal
Acquisition mode	tomosynthesis
Number of dosimeters	7 TLD in the abdomen + 3 TLD in the breast
Number of repetitions	3

Table 3- Irradiation conditions applied in the 2nd plan.

2nd Plan (with 4 subsets)	
Voltage	34 kV
Exposure	250 mAs
PMMA thickness	5 cm
Projection	Craniocaudal + mediolateral oblique
Acquisition mode	Mammography 2D + tomosynthesis
Number of dosimeters	6 TLD in the abdomen + 1 TLD in the breast
Number of repetitions	3

Table 4- Irradiation conditions applied in the 3rd plan.

3rd Plan	
Voltage	34 kV
Exposure	250 mAs
PMMA thickness	7 cm
Projection	Craniocaudal
Acquisition mode	Tomosynthesis
Number of dosimeters	2 TLD in the abdomen
Number of repetitions	1

To determinate the MGD, the following equations were used for 2D digital mammography (2.1) [20] and tomosynthesis (2.2) [21]:

$$DGM_{DM} = K \times g \times c \times s \quad (2.1)$$

$$DGM_{T} = K \times g \times c \times s \times T \quad (2.2)$$

where, K corresponds to the air Kerma measured with the dosimeters and the factors g, c, s and T used are presented in table 5.

Table 5- Correction factors used in the calculation of DGM

Parameter	1st Plan	2nd Plan 2D	2nd Plan Tomo
PMMA thickness (cm)	5	5	5
HVL (mmAl)	0,56	0,60	0,61
g factor	0,240	0,261	0,261
c factor	1,135	1,134	1,129
s factor	1,042	1,042	1,042
T factor	0,966	N.A.*	0,966

*N.A. – Not applicable

Estimating the dose in uterus will be possible by taking advantage of the data used to calculate the MGD in each plan. Thus, initially, a relation between the air Kerma values, recorded by the dosimeters placed on the PMMA plates, and the MGD, for 2D mammography and tomosynthesis calculated later, was established. Then, this relation between air Kerma and dose was be applied to estimate the dose in uterus. This way, it is possible to extrapolate the estimated dose received by the uterus and to assess the risk to the fetus.

3. RESULTS AND ANALYSIS

3.1. Mean glandular dose

For the 1st irradiation plan, the air Kerma was 3,65 times higher than the MGD value. For the 2nd irradiation plan, the air Kerma was 3,37 times higher than the MGD, in tomosynthesis mode, and 3,24 times higher than the MGD, in 2D mammography mode. To better analyse the results obtained, the graph in figure 2 was constructed, which compiles the total MGDs obtained in the first plan and in the four sets of irradiations of the second plan.

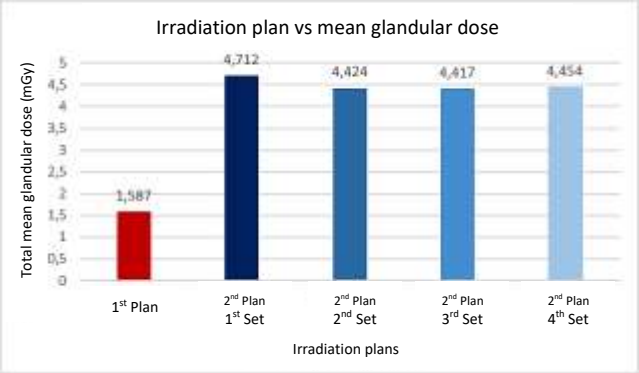

Figure 2 - Comparison of mean glandular doses obtained in the various irradiation plans.

The first plan aimed to validate the doses obtained for average irradiation conditions and thus compare these results with values present in the literature. The dose value obtained, performing a tomosynthesis under the defined conditions, delivers a 1,6 mGy MGD. Based on the literature [22,23], the available values are close to the obtained value, which allows to assume that, for the remaining irradiation plans defined under different conditions, the results obtained with the IPO equipment will be equally reasonable.

Regarding the second irradiation plan, the first finding is that the MGD values are very close in all sets, with the main difference between the first and the second plan dose values. This difference between the plans, since the PMMA thickness was the same, is due to the increase in voltage from 28 to 34 kV and exposure from 160 to 250 mAs.

Within the second irradiation plan, the first set, which consists of the craniocaudal projection in 2D mammography mode, has the highest dose value of the four irradiation sets, 4,712 mGy. Comparing directly with

the second set, that is, the same projection but in tomosynthesis mode, the DGM is lower, 4.424 mGy, corresponding to a decrease of approximately 6,1% in the dose value. Although, theoretically, it is expected that the dose resulting from the tomosynthesis would be higher than the 2D mammography dose, the opposite result can be justified by the presence of PRIME technology available to reduce the dose to the patient.

Comparing the sets where the acquired projection is the mediolateral oblique (MLO), the behaviour previously verified was not repeated. That is, the third set of irradiations, in which the MLO projection was acquired in 2D mammography mode, has a lower MGD value than the fourth set, in which the same projection was acquired but in tomosynthesis mode. Although the dose in the fourth set is higher, it corresponds to an increase of only 0,83%. Thus, although the dose has not decreased from the 3rd to the 4th set, the increase has not reached 1%, so it can be considered that the dose remained approximately the same.

It is also important to remember that, for the sake of saving resources, it was decided to perform irradiations only for the right breast. Thus, considering the worst-case scenario, that is, the need to perform 2D mammography and tomosynthesis in all projections bilaterally, the final total dose received by the patient's breasts is the sum of the individual doses of each acquisition, multiplied by 2, thus conferring a final MGD of approximately 36 mGy.

3.2. Dose in the uterus

For the first irradiation plan, that is, with 28 kV, 160 mAs and 5 cm PMMA, the dosimeters placed in the phantom's abdomen did not measure any air Kerma value. Based on these results, it is assumed that in these conditions, the dose in uterus is negligible and therefore, the fetus exposure is minimal.

For the first set of irradiations of the 2nd plan, in which 34 kV, 250 mAs and 5 cm of PMMA were applied, only some of the dosimeters recorded air Kerma values, namely those on the left side of the phantom abdomen, numbered and marked with arrows in figure 3.

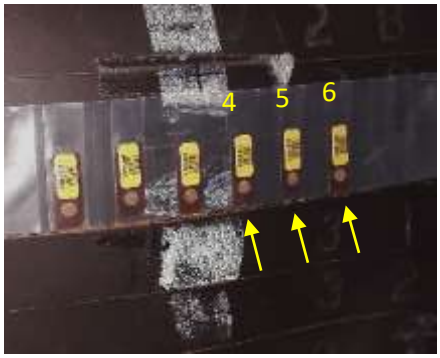

Figure 3- Identification of the dosimeters that registered air Kerma values in the phantom.

The dose received by the uterus, in this set, is equal to 0,008 mGy. As the examination was performed for the right phantom breast, the left side of the detector has no PMMA plates. For this reason, it is expected that X-ray photons can reach the leftmost dosimeters in the phantom, more easily.

For the 2nd set, with the same acquisition conditions as the first set, but in tomosynthesis mode, there is a greater number of dosimeters that recorded data compared to the previous set. The estimated dose for the 2nd set is approximately 0,015 mGy.

Like observed in the results of the 1st irradiation plan, also in the 3rd set of the 2nd plan, the dosimeters placed in the phantom did not measure air Kerma values, so it can be considered that in this situation the dose in the uterus is negligible and the fetal exposure is minimal.

The results obtained in the 4th set of irradiations are not very different from those obtained in the previous set, with only one of the dosimeters recording an air Kerma value of 0,07 mGy, which gives a dose in the abdomen, approximately equal to 0,001 mGy.

Considering all data for the second irradiation plan, a complete examination of the left and right breast will give the uterus an approximate total dose of 0,048 mGy. Figure 4 shows the comparison of the results obtained for the second irradiation plan. For a better

association of the results with the sets, the colours used in the graph of figure 2 were maintained.

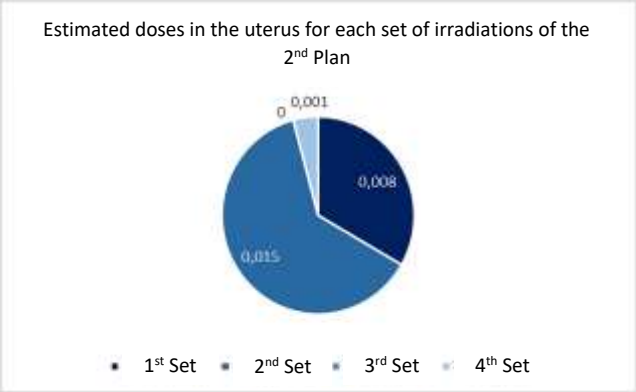

Figure 4- Estimated dose values, in mGy, in the uterus for each set of irradiations.

From figure 4, it is visually easier to understand how each irradiation set contributes to the calculated total dose. Thus, the 2nd set is the one with the highest contribution, followed by the 1st set and then the 4th.

Both the values for the first and second irradiation plan seem to indicate that the dose in uterus is very close to zero, with dose values often very low. These results are in agreement with the results of the literature consulted for comparison (15).

Regarding the 3rd irradiation plan, the two dosimeters used registered an air Kerma value equal to 0,10 mGy. This plan can be directly compared to the 2nd set of the 2nd Plan of irradiations, but as the number of dosimeters in the 3rd plan is lower, it is only possible to compare the air Kerma values recorded by the dosimeters placed in the same position in both irradiations. The placement of dosimeters in the third plan, corresponds very closely to the position of dosimeters 3 and 4 (figure 3) placed in the phantom, along the entire second plan. In the 2nd set, the air Kerma values, for dosimeters 3 and 4, ranged from 0,07 to 0,13 mGy. The mean air Kerma values for dosimeter 4 are even equal to 0,10 mGy. Based on these results it can be stated that increasing the PMMA thickness from 5 cm to 7 cm did not have a major influence on the air Kerma values recorded by the dosimeters.

4. CONCLUSIONS

The use of ionizing radiation is an important and often fundamental tool for the diagnosis of various conditions and pathologies. In fact, in situations such as breast cancer, where early diagnosis is essential for a more positive prognosis, the use of ionizing radiation is widely justified. Proof of this is, for example, the more than 3 million mammograms that have been done in Portugal under the Portuguese League against Cancer screening programs.

Mammograms performed in this context may result from the woman's own willingness and initiative or by sending invitations to apparently healthy women to perform these exams. Despite its advantages, the effectiveness of mammography in detecting early-stage breast cancer may present a small but not negligible risk of the appearance of breast tumours or cancer in other exposed organs. Still for screenings, it is not uncommon for a woman to be called a second time for an exam repetition, if the first one is not sufficiently clear. Since it is possible to start mammograms at age of 40 and remembering that more women over 40 are getting pregnant, it is not impossible for a woman to have a mammogram while not knowing to be pregnant. Since the most critical time, during which radiation exposure should be avoided, is between the 8th and 15th gestational week, corresponding to the first trimester, this is the most probable time when exams are performed without the woman being aware of the pregnancy. As the number of exams increases, so does the awareness, concerns, and misconceptions about the risk to foetuses and patients examined with medical imaging. Because people are afraid of what they do not know, lack of knowledge about the area and misconceptions can lead to excessive and unnecessary anxiety among patients, delays in diagnosis and treatment or even improper termination of pregnancy.
Although justified, because their benefit is greater than the risk they add, it is necessary to ensure that these practices are also optimized, to ensure that the patient

receives no more dose than is strictly necessary for the exam considered. Therefore, it is important to see what these optimizing conditions translate to in situations such as those of a pregnancy, whether known or unknown. This verification is even more important when new techniques or technologies are introduced in the market, such as tomosynthesis.

The issue of risk to the fetus, associated with low doses and particularizing for low LET (Linear Energy Transfer) radiation, is another aspect that is not adequately clarified. The data available for the study of this risk are based on data on atomic bomb survivors and therefore associated with considerably higher doses than those received under radiodiagnosis. On one hand, any dose value, even a value within the low dose range, may be capable of increasing the risk to the fetus. On the other hand, the establishment of this dose-response relationship based on the high-dose results is considered to be a rough approximation that is not yet, truly proven, given the complexity of the low-dose carcinogenic capacity *versus* naturally and spontaneous cancers developing in the human being. Thus, it is important to continue the study of this subject and to deepen the models that evaluate the impact of low doses at the intrauterine level. As there is no consensus, we should always follow the principles of radiological protection and keep the doses to the fetus as low as reasonably achievable, preferably throughout pregnancy.

Nevertheless, the same technological development that allows increasing knowledge about low doses, simultaneously allows the development of more and more specialized equipment to give patients the lowest possible dose, without compromising image quality, such as PRIME technology, present in the equipment used. About tomosynthesis, as mentioned, it is a relatively recent imaging modality, so there are still some studies to be done and therefore, the information available on certain aspects is not yet widely clarified and disseminated. Despite this, tomosynthesis is becoming, in some places, the preferred method for the diagnosis of breast cancer and this raises the question whether it will be advantageous to replace 2D mammography with tomosynthesis, if it avoids repetition of exams due to interpretation doubts. For this reason, it is important to make sure that just as 2D mammography is considered safe to perform during pregnancy, so is tomosynthesis. In this sense, the present dissertation aimed to answer this same question, that is, to confirm that tomosynthesis is safe to perform during pregnancy.

Starting with the MGD results, the 36 mGy result is a relatively high value, considering that the breast is one of the most radiosensitive organs. However, it is necessary to remember that the results obtained presuppose the acquisition of a complete, bilateral examination and under maximum conditions. Not all women are suspected of having disease in both breasts and so, don't need to get left and right images, nor need to set a voltage of 34 kV. However, when comparing the doses of projections acquired in 2D mammography mode and tomosynthesis mode, it appears that there is no significant difference in the value of the obtained doses. That is, having mammography including tomosynthesis advantages over 2D mammography, and being both dosimetrically comparable, then it may be preferable to perform the former rather than the latter.

Regarding the dose to the uterus, resulting from the complete bilateral examination under maximized conditions, its calculated value was approximately 0,048 mGy. As mentioned for MGD values, given the extreme conditions under which the examination was performed, it is likely that the dose in the womb will be even lower. In fact, in the 1st Plan with average conditions, the air Kerma values were so low that were not detectable by the dosimeters used, leading to the conclusion that the dose received by the uterus is very low at least less than the dose threshold detectability of TLDs. In addition, since radiation-attenuating phenomena will occur from the womb to the fetus, the fetal dose will also be very close to zero.

With respect to the use of shields, such as lead aprons, these are typically present in radiology departments and are usually offered to patients when their pregnancy is known. However, in 2011, the American Association of Physicists In Medicine published on its website a communication addressed to the public and health professionals, informing about the usefulness of this type of apron. It is stated in this communication that the dose in uterus is often considered immeasurable and that, therefore, the use of lead apron is not necessary or recommended. In general, the uterus and fetus are only exposed to scattered radiation and since we are already in the presence of PRIME technology equipment that reduces this type of radiation, the use of the apron is no longer so relevant. However, since its use does not interfere with the exam or the quality of the images, it should be provided to the patient, in case she makes this request.

Regarding this work, it is necessary to highlight some issues that may have conditioned the results obtained. HVLs of the mammograph should have been measured in order to use actual values inherent to the equipment, instead of using values available in the literature like how was done in this case. Regarding the 3rd irradiation plan, ideally the same number of dosimeters that was used in the 2nd plan should have been used in the phantom's abdomen. Thus, the comparison of the results obtained between the two plans becomes limited, since it is not possible to fully understand the influence of the increase in breast thickness for the dose at the uterus level. However, this was not possible given the limitation on the number of dosimeters available for this study. Another limitation, associated with future work that can be developed, is related to the structure of the phantom. The phantom used represents a female patient with a “standard” body. However, the height and body composition of the patients is very variable. At the abdomen level, there are patients who have a higher percentage of fat mass and others with a higher percentage of lean mass. Thus, in the future, further evaluation of uterine doses could be performed in real patients to understand to what extent the difference in body composition may influence the dose received by the uterus. Moreover, it would also be interesting to be able to compare the results obtained under the same acquisition conditions, but with different equipment such as GE, Hologic or Philips or even to verify if there are significant differences in the dose values obtained, depending on the choice of anode / filter combinations.

Nevertheless, this work contributed to obtain further clarification about the dosimetry associated with tomosynthesis. To date, there is no other study in the literature that has used an anthropomorphic physical phantom to perform measurements in the abdomen area as if it was a real patient. Thus, and considering that further studies are evidently necessary to prove these results, the dose values obtained seem to indicate that mammography including tomosynthesis is equally safe to perform during pregnancy and thus, may be, at any time, one of the options to consider for breast cancer diagnosis.

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