Monte Carlo Methods for Assessment of the Mean Glandular Dose in Mammography: Simulations in Homogeneous Phantoms

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Abstract: The rationale of this study is to perform a personalized dosimetry in digital mammography, using Monte Carlo simulations. We developed a GEANT4-based application that reproduces mammographic investigations editable in different setups and conditions. Mean Glandular Dose (MGD) is estimated for different compressed breast sizes and compositions. Breast compositions are obtained with homogeneous mixture of glandular and adipose tissues. The simulated setup reproduces the Hologic Selenia® Dimensions® Mammography System and the TASMIP$_M$ tool for deriving the photon fluence from the X-ray source has been employed. The influence of different skin models is also investigated, deriving the mean glandular dose in the breast using adipose tissue for different skin thicknesses, from 2 mm to 5 mm, and a dedicated composition found in literature with the specific thickness of 1.45 mm. We denoted different photon shielding properties on the MGD values.

1 INTRODUCTION

In European women, breast cancer is the leading cause of cancer death, causing one in six of all deaths from cancers in women. Screening mammography is a low-dose X-ray examination used to detect breast cancer, even at an early stage, when that cancer is too small to be felt as a lump. Digital Mammography (DM) represents the principal technique used to reduce this mortality rate and is recommended in women between 50 and 75. Since ionizing radiation is used in X-ray mammography investigations, there is a risk of contracting carcinogenesis associated with the absorption of X-ray in the mammary gland, which is considered to be the most radiosensitive tissue at risk.

A DM investigation is made by compressing the patient breast with a compression paddle and acquiring two digital images per breast, a cranio-caudal and a mediolateral oblique view, with a polychromatic X-ray source. The *Mean Glandular Dose* (MGD) is used for the evaluation of radio-induced cancer risk and, in principle, this value must be as low as possible, in agreement with the investigation image quality. Furthermore, patients have different compressed breast sizes and percentage of gland tissue, involving different MGD values associated to the investigations. Moreover, skin thickness and different mammography units also have important effects on radiation dose. Thus, accurate dosimetry is an important goal to achieve in X-ray breast imaging.

Dose in the gland tissue can't be measured directly, but the use of Monte Carlo (MC) simulations provides a valuable support. In MC simulations different variables can be investigated and some assumptions must be taken into consideration to estimate the dose delivered to the gland. It is necessary to create a personalized dosimetry able to evaluate glandular dose for different anatomical conditions and commercial mammography units.

The rationale of our study is to perform a personalized dosimetry in mammography, in which the MC simulations get closer to the real situations. Using a GEANT4 based code (https://geant4.web.cern.ch/), which is an object-oriented

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C++ toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. This code has been developed at CERN. We developed a GEANT4-based application, that reproduces mammographic investigations, editable in different setups and breast anatomies.

This study is part of the "RADIOMA" project (RADiazioni IOnizzanti in MAmmografia, ionizing radiations in mammography) and must be considered as a preliminary work.

2 MATERIALS AND METHODS

2.1 State of the Art

Monte Carlo methods are computational methods based on random sampling to obtain numerical results; multiple possible realizations of the phenomenon under examination are calculated, with the weight of the probability of such occurrence. The rationale is to run a high number of replications; the greater the number of the events (photons from the X-ray source in this case), the greater the accuracy of the simulation.

When MC simulations are adopted for research on dosimetry, some model assumptions must be followed, like breast shape, skin model, adopted materials, glandular tissue percentage, X-ray polychromatic source etc… Thus, these assumptions can seriously affect dosimetry values. For concise reference henceforward, the breast composition is referred to in terms of the glandular percentage by weight.

Dose to the breast starts in general from *incident Air Kerma* (K_{air}), air dose measurement, converted by dedicated coefficients to obtain a reference value of dose.

The European mammography dosimetry protocol employs the model proposed by Dance (Dance, 1990). In the MC simulations the breast is modelled as a semi-cylinder, with radius of 80 mm and variable height between 20 and 110 mm, with inside a homogeneous compound of adipose and glandular tissues surrounded by a 5 mm thick skin made by adipose tissue. The conversion factors calculated by the author are for a breast model of 50% glandularity and are tabulated as a function of the breast thickness and the *Half Value Layer* (HVL) of the X-ray beam. The formalism used to calculate the *Average Glandular Dose*, AGD, is

$$AGD = K_{air}\, g\, c\, s\,, \qquad (1)$$

where K_{air} is the incident air kerma without backscatter at the upper surface of the breast, g is the conversion factor for a 50% glandularity breast at the specified HVL, and c and s factors correct for breast composition and X-ray spectrum choice respectively.

The US protocol follows the Wu's method (Wu, 1991; Wu, 1994), in which the breast shape is a semi-cylinder but with a semi-elliptical cross-section. The breast model has a 5 mm thick skin layer of adipose tissue (indeed, skin thickness was considered to be 4 mm until the new 2016 ACR Digital mammography quality control manual), while the inner part is a homogeneous mixture of adipose and glandular tissues; the reference relative amounts of glandular tissue are 0%, 50% and 100%. The *Mean Glandular Dose*, MGD, is obtained multiplying K_{air} by a factor denoted as *normalized glandular dose* (DgN)

$$MGD = K_{air}\, DgN\,. \qquad (2)$$

Using Monte Carlo simulations, the authors tabulated DgN values for breasts as defined above and for X-ray spectra derived from a molybdenum target and molybdenum filter, varying the phantom breast thickness from 3 to 8 cm.

The maximum dose limits for the "standard breast" (Yaffe, 2009) are, in digital mammography, per view, 2.5 mGy in EU protocols and 3 mGy in US protocols.

In the last years, a trend has emerged to extend and perform protocols and research groups are proposing their models and methods (Sechopoulos, 2012; Traino, 2017; Sottocornola, 2018). The rationale of our study is to perform a personalized dosimetry in mammography, in which the MC simulations get closer to the real situations, simulating real mammography investigations executed with the Hologic Selenia® Dimensions® mammography system. For personalized dosimetry we mean the objective to evaluate both different breast anatomies and commercial mammography systems, with other anode/filter combinations, that of course traduces in different glandular dose values.

The GEANT4-based application developed by our group reproduces mammographic investigations in different setups and breast anatomies. The code provides, in the same run, simulation of mean glandular dose and incident air kerma at the upper surface of the breast (backscatter photons are excluded from the computation). This led to a reduction in the simulation times. Using an Intel Core™ i7 8700 CPU @ 4.30 GHz (12 threads

available), 32GB of RAM, multithreading mode performs 10^8 events in approximately 10 minutes.

2.2 Code Validation and Characteristics

The code was validated according to the prescription of The American Association of Physicists in Medicine, AAPM Task Group 195 (Case III, for mammography purposes). The code showed discrepancies from the reference data of 0.6% with both monoenergetic and polyenergetic X-ray beams in MGD scoring, which is computed by

$$\mathrm{MGD} = \sum_{\mathrm{j}} \frac{\mathrm{G_j(E)} \times \mathrm{E_j^{dep}}}{\mathrm{m_{gland}}}, \quad (3)$$

where $G_j(E)$ is the G-factor introduced by (Boone, 1999) evaluated for the energy of the *j*th interacting photon, E_j^{dep} the energy deposition of this photon and m_{gland} the glandular mass. For Air Kerma scoring, results are in agreement with data in literature (Sarno, 2017), using

$$\mathrm{K_{air}} = \sum_{\mathrm{i}} \frac{\mathrm{E_i} \times \left(\frac{\mu_{\mathrm{en}}}{\rho}(\mathrm{E_i})\right)_{\mathrm{air}}}{\mathrm{S}}, \quad (4)$$

where E_i is the energy of the *i*th incident photon passes through the scoring surface *S*, $(\mu_{en}/\rho)_{air}$ is the air mass energy absorption coefficient at the energy E_i (Hubbel, 1995). K_{air} computation let to obtain estimates of dose conversion coefficients to be used or compared with data in literature (Boone, 2002; Nosratieh, 2015).

This kind of validation is useful due to the opportunity to compare results with those given by other groups, that use different MC codes (Gholamkar, 2016) but the same methodology used in the protocols.

Furthermore, other research groups propose their physical phantom models, create to validate their MC code, using, for example, TLD dosimeters (Wang, 2017; Nigapruke, 2010).

2.2.1 Implemented Geometry

A semi-cylinder was used to simulate a compressed breast, with a radius of 10 cm, variable heights that correspond to the different compressed breast thicknesses, from 2 cm to 10 cm in 1 cm increment, and 5 breast compositions, 0% 12.5% 25% 50% and 100% glandular fractions. Different glandular fractions are obtained mixing properly adipose and glandular tissue, from data provided by (Boone, 1999), in order to obtain homogeneous mixtures with desired glandularities (Dance, 2016; Sarno 2018).

A skin thickness of 5 mm of adipose tissue was introduced to the model and two polycarbonate compression paddles, upper (2.8 mm thick) and lower (4.1 mm thick).

As prescribed by the AAPM TG195 protocol, a box made by water is used to consider the scattered radiation from the patient body (Figure 2).

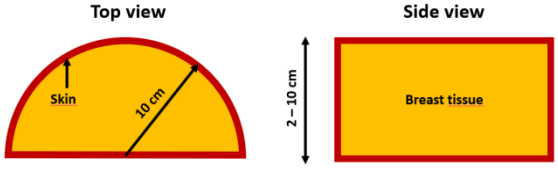

Figure 1: Breast model adopted. The semi-cylinder radius is fixed to 10 cm, the range thickness is 2-10 cm while the skin is investigated changing its thickness.

2.2.2 Polychromatic Source

The X-ray source is positioned following the Hologic Selenia® Dimensions® mammography system geometry. The X-ray beam simulates a craniocaudal view and it is produced by a focal spot of 0.3 mm^2 at a source-to-image receptor distance (SID) of 70 cm.

Since real mammographic exams involve a polychromatic X-ray beam source, in order to obtain data that are comparable with real investigations, in the MC code a polychromatic spectra can be set as a *macro* file, in which every energy bin is weighted with its relative photon fluence; this weight is used in the computation as a statistical probability to produce an incidence photon in its energy bin. Thus, we use $TASMIP_M$, algorithm for tungsten anode material, provided by (Boone, 1997), to produce photon fluences referring to the Selenia® Dimensions® system, to assess glandular dose in digital phantoms. The algorithm provides spectra for the voltage applied ranging from 18 to 40 kV; spectral information is released at 500 eV intervals starting from 5.5 to 40 keV, with energy bins centered in 5.5, 6.0, 6.5…

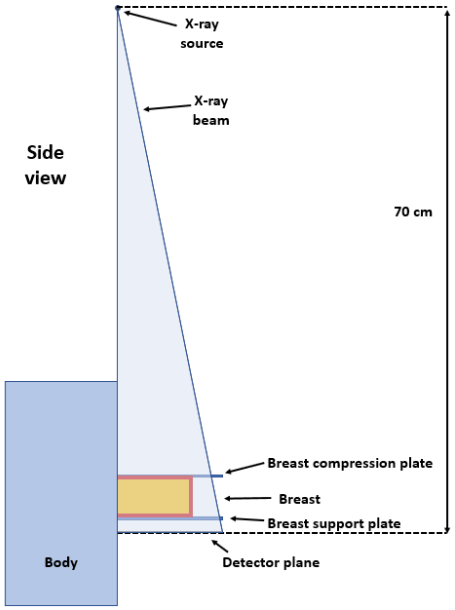

Figure 2: Simulation geometry adopted. Source to detector plane distance is set to the SID of the Hologic Selenia® Dimensions® system.

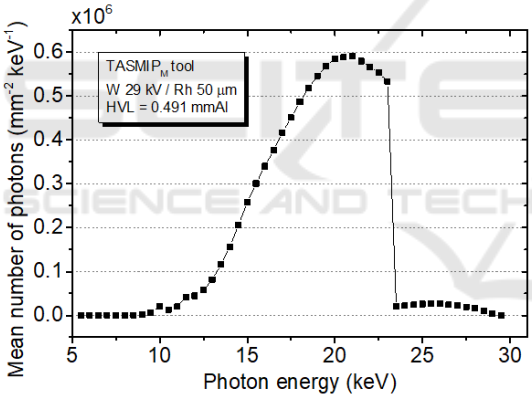

Figure 3: Example of spectra obtained using TASMIP$_M$ algorithm, in W/Rh anode/filter combination @ 29 kV. Spectra is normalized to unit Air Kerma.

2.2.3 Physics List

According to the prescriptions provided by the report of AAPM Task Group 195, the "Option4" PhysicsList was used in GEANT4, for the constructors and instances that consider the physics processes; this model is designed for any application requiring high accuracy of electrons and it uses the most accurate standard low-energy models. The production threshold ("range cut") fixed for the secondary particles is expressed in terms of the distance travelled by the particles in the medium (skin or breast tissue), converted by GEANT4 in terms of energy; e.g. the range cuts of 1 mm for photons and 1 µm for electrons correspond respectively to about 2.55 keV and 0.99 keV in 25% glandular breast tissue. For energies involved in these cases Rayleigh, photoelectric, Compton and bremsstrahlung are simulated.

3 RESULTS

With the simulation setup described in the previous section, MGD and K_{air} were obtained. For monoenergetic beams, we decided to focus in the energy spectrum between 8 keV and 40 keV, with 0.5 keV step, range in which photons are produced by mammography X-ray tubes. Figure 4 shows the MGD per generated photon, for a 5 cm thick breast with 50% glandular fraction and a 5 mm thick skin made by adipose tissue. For monochromatic purposes we used 10^7 simulated events. The simulation model considers the energy deposited in the breast tissue, excluding skin; thus, at lower photon energies, the skin "shields" the breast tissue and the delivered dose is low.

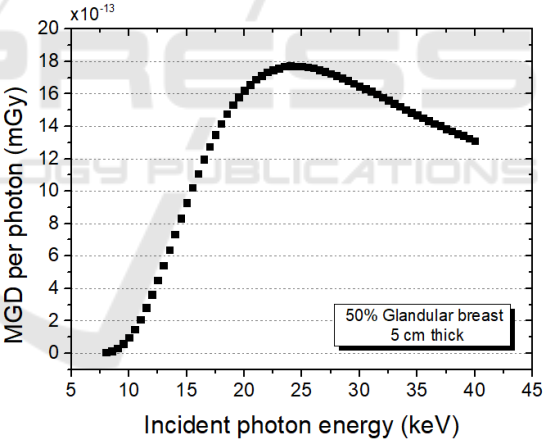

Figure 4: Dose per photon delivered to glandular tissue to a 50% glandular breast and 5 cm thick, due to both the primary and the secondary radiation. Each point in the graph represents one simulation run with a monochromatic beam with 10^7 simulated events.

At increasing photon energies, X-ray beam penetrates the skin layer and deposits dose, up to a maximum of about 23 keV; then, the total dose to the glandular breast reduces, due to the decreasing energy-absorption coefficient.

Of course, we concentred our efforts on polychromatic spectra; for polyenergetic beams we simulated 10^8 primary events. In Figure 5 it is represented the mean glandular dose versus

compressed breast thickness for the same X-ray beam source and 0%, 50% and 100% glandular tissues. MGD values decrease while increasing compressed breast thickness and/or glandular fraction, due to a major glandular mass in the equation (3).

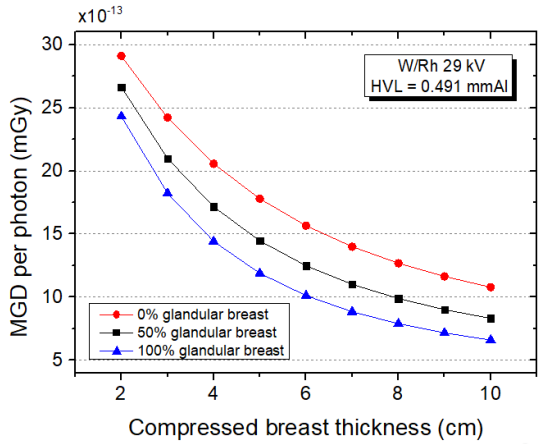

Figure 5: MGD per photon vs. compressed breast thickness for different glandularities in W/Rh configuration @ 29 kV. Each point on the graph refers to a single simulation with 10^8 events.

Furthermore, *beam quality*, in terms of *half value layer* (HVL, units of mm Al) has to be considered (Sobol, 1996). Spectra provided by algorithms are not correct at all, because of the uncertainty of the filter thickness (usually estimated by the manufacturer on about 10%) and, of course, due to the algorithm adopted approximations. This may lead to either an overestimation, or underestimation, of low energy, or high energy, of photons, and a consequent mismatch on dose assessment. To avoid this circumstance a beam quality estimate has to be performed.

Once one knows the experimental value, the rationale is to try to reach the correct HVL value on the algorithm varying the filter thickness. Figure 6 shows the dependence of MGD from the half value layer of the radiation; a *harder* beam (i.e. a relatively major number of photons with higher energy) delivers more glandular dose to the breast.

Since mammary gland is considered to be the tissue at risk, one has to consider skin as a shielding tissue. The greater the thickness, the greater the shielding. Unfortunately, in literature there are bucking studies about skin thickness and composition. The EU and US protocols used until the 2016 different skin thickness, of 5 mm and 4 mm respectively, made by adipose tissue. The reason is that skin is composed by three parts, starting from outside to inside by epidermis, dermis and hypodermis. It is not possible to differentiate them in

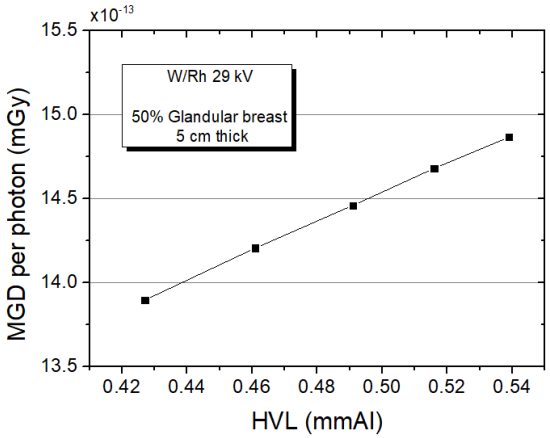

Figure 6: MGD vs. HVL. Different HVL values are obtained varying the Rh filter thickness from 40 to 60 µm with 5 µm step.

a clear manner, because thickness and distribution are very variable, but it is evident that dermis and hypodermis are mainly composed by adipose tissue. Nevertheless, only the epidermis, the outer layer, is evident from breast Computed Tomography (bCT) images (Huang, 2008), which has a higher density from adipose tissue. This involves different skin attenuation and shielding. Because of its obvious presence in the TC slices, other research groups (Sarno, 2017; Massera, 2018) tend to consider the epidermis layer in their respective studies, whose average thickness is 1.45 ± 0.30.

We wanted to investigate the effect of various skin models on MGD values, changing thickness and compositions, simulating, as previously, monoenergetic and polyenergetic beams. In Table 1 five types of skin model adopted are reported, whose surround the same 50% phantom glandularity to form five different 5 cm thick digital phantoms.

Table 1: Skin models adopted. These models are associated to 50% glandular and 5 cm thick digital breast to form five different phantoms.

Skin model	Skin thickness	Skin composition	Density [g/cm^3]
#1	1.45 mm	Skin (Boone, 1999)	1.09
#2	2 mm	Adipose tissue	0.93
#3	3 mm	Adipose tissue	0.93
#4	4 mm	Adipose tissue	0.93
#5	5 mm	Adipose tissue	0.93

Obviously, a thicker skin traduces in a major photon shielding of the mammary gland, but models #1 and #5 (which is adopted by EU protocol), due to the different skin compositions and thicknesses,

deserve a brief comparison. In Figure 7 different shielding properties are denoted. For low energies, the first breast model is less shielded by its (thin) skin, showing slightly higher MGD values; a reverse situation appears for higher energies; this may be attributed to the property of the thicker skin to "become a secondary radiation source" at increasing energies, because of the probability of the Compton effect (in the skin) increase at the expense of the photoelectric effect (Sarno, 2017). These results have been also found by Massera et al. (Massera, 2018), who used PENELOPE, another Monte Carlo code, to produce MGD values for monochromatic beams.

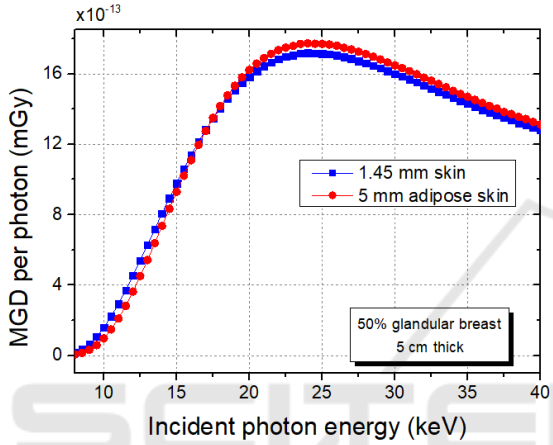

Figure 7: MGD vs. photon energy for monoenergetic beams ranging from 8 to 40 keV, for phantoms #1 and #5.

In order to better outline this behaviour with polychromatic beams, we reproduce two W/Rh kilovoltage configurations, 22 kV and 29 kV. It is evident in figures 8 and 9 that, for the same skin composition, the thicker is the skin, the lower is the dose to the gland; nevertheless, if we consider the #1 and the #5 skin models, we see that the last shields more the breast tissue at @ 22 kV (Figure 8), but less @ 29 kV (Figure 9). This result confirms the previous statement in the monoenergetic investigation.

4 DISCUSSION

The aim of this project is to obtain a personalized and accurate dosimetry for X-ray digital mammography, for different breasts sizes and composition and commercial mammography units commonly used.

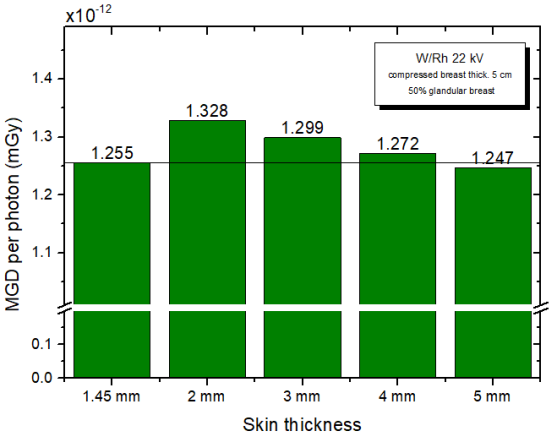

Figure 8: Dose delivered to glandular tissue versus different skin thicknesses and compositions. 1.45 mm thick skin has a different elemental composition (Boone, 1999), while from 2 mm to 5 mm skin is made by adipose tissue. Simulations refer to a low-energy examination.

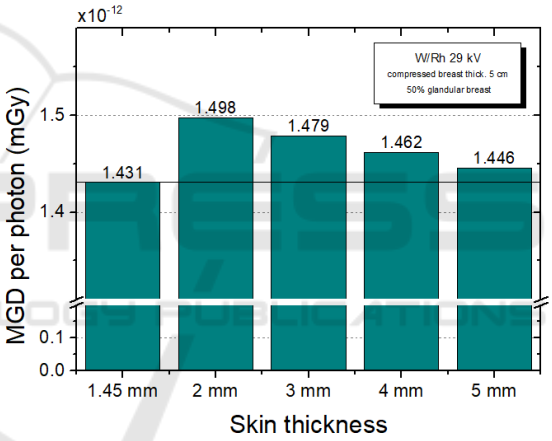

Figure 9: Dose delivered to glandular tissue versus different skin thicknesses and compositions. Simulations refer to a higher energy examination.

We developed, and opportunely validated, a GEANT4 Monte Carlo code for dosimetry in mammography; adopting some geometry assumptions and an external algorithm (Boone, 1997; Hernandez, 2017) for deriving spectral information for mammography X-ray tubes, the code is able to replicate different mammography setups for different geometries and conditions, and different anatomical women breasts.

In order to assess the Mean Glandular Dose in digital phantoms for typical mammography investigations, we used the TASMIP$_M$ tool to reproduce photon fluences referring to the Hologic Selenia® Dimensions® system, adopted in the Department of Radiology, University Hospital "Azienda Ospedaliero-Universitaria Pisana", Pisa.

We derived the dependencies of the Mean Glandular Dose changing breast anatomy and X-ray beam; MGD decrease with both the increase of compressed breast thickness and glandular percentage. Important dependency is represented by the HVL value (radiation beam quality), which can lead to an overestimation of the glandular dose in case of "harder" spectra. The rationale is to know the HVL experimental value and to find the correct MGD value referring to the specific radiation.

An important variable not yet permanently defined in literature is the assessment of skin thickness and composition. EU and US protocols used, until 2016, respectively 5 mm and 4 mm thick skin (now US protocol employs the 5 mm thick skin), made by adipose tissue but, Huang et al. (Huang, 2008) found a different skin thickness in breast CT investigations. A comparison between digital breast phantoms with different skin showed of course different MGD values. At low-energy investigations skin 1.45 mm thick "shields" less glandular tissue, respect to the 5 mm adipose skin, while for higher energies shields more. This may be attributed to the property of the thicker skin to "become a secondary radiation source" at increasing energies, because of the probability of the Compton effect (in the skin) increases at the expense of the photoelectric effect (Sarno, 2017). The choice of an appropriate model of a digital breast phantom can be a critical aspect and we reserve the right to continue investigating it.

In the last years, Digital Breast Tomosynthesis (DBT) is spreading in clinics and represents an evolution of mammography; this technique let the X-ray tube to move in an arc over the compressed breast, acquiring multiple images from different angles. Images are then reconstructed by a computer forming three-dimensional images. 3D techniques minimize tissue overlaps that can hide cancers above the normal overlapping.

We will improve our MC code implementing the tomosynthesis set-up for dosimetry purposes.

To achieve the experimental verification of the MC results, and improve the personalized dosimetry, our efforts are focused on the creation of physical phantoms with similar properties of the real breast, like, of course geometry, but primarily X-ray attenuation.

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