Evaluation of Dosimetric Properties in Full Field Digital Mammography (FFDM)
Development of a New Dose Index

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Abstract: According to the World Health Organization (WHO), breast cancer is the most common cancer in women, constituting 29% of all cancers related to the female population. In this context, Full Field Digital Mammography (FFDM) is the reference imaging technique for breast cancer early detection and diagnosis and it is widely employed in screening programs. Therefore, the absorbed radiation dose for each examination shall be evaluated in order to ensure proper radiation exposures for the patient. In addition, the new European Directive 59/2013/EURATOM requires that dosimetric data referred to the radiation exposure should be inserted in the radiological report. For these reasons, we designed a multidisciplinary research project with the intention of realizing and validating a new method for calculating the Average Absorbed Breast Dose (2ABD) by the patient during a mammography procedure. The innovative aspect regards the availability of a quantitative and personalized dosimetric parameter, providing an index that is patient-specific rather than related to the X-ray machine output, directly related to the risk of radiation. Specifically, in this work we present our scientific approach as well as the initial results.

1 INTRODUCTION

Breast cancer is the most common cancer among women both in developed and developing countries and it is also the principal cause of death from cancer among women (De Santis et al., 2014; Ferlay et al., 2010). It affects 1 in 8 women in their lifetime, and represents 29% of all cancers related to the female population. Based on these data it is of fundamental importance to both do an early diagnosis and submit the patients suffering from this pathology to periodic checks, in order to offer appropriate treatments with the goal of reducing mortality.

FFDM (Full Field Digital Mammography) is a non-invasive high sensitive method for early stage breast cancer detection and diagnosis, and represents the reference imaging technique to explore the breast in a complete way (Dance et al., 2014). Hence, mortality from breast cancer can be reduced by mammographic screening (Myers et al., 2015). However, in a mammographic screening program healthy people are exposed to ionising radiation. Besides, the breast is a significant radiosensitive organ, so special care is required in the evaluation of the patient exposure (EUREF 2006). Additionally, the new European Directive 59/2013/EURATOM highlights the importance of controlling the doses delivered during radiological procedures and requires that a dosimetric data referred to exposure should be inserted in the radiological report (59/2013/EURATOM). The weight factor for breast tissue increased from 0.05 to 0.12 in the new directive, following the ICRP recommendations.

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In order to satisfy these necessities, this experimental work was accomplished with the ambition of identifying a quantitative and personalized dosimetric index to evaluate the radiation dose absorbed by each patient during a mammographic procedurebased on dosimetric measurements and mathematical calculations.

The current dosimetric index employed in estimating the radiation dose in mammography is the Average Glandular Dose (AGD) that is representative of the dose absorbed by glandular tissue. The most common algorithms for the AGD evaluation in mammography are based on the works of Dance (Dance et al., 1990) and of Wu (Wu et al., 1994). Both methods are based on incident air kerma ($k_{a,i}$) measurements and the AGD is obtained through an empirical expression by applying tabulated factors (Dance et al., 1990; Wu et al., 1994). The only measurable quantity in the AGD computation is $k_{a,i}$, which is an X-ray output related quantity rather than a patient dose related quantity.

Thus, we propose the Average Absorbed Breast Dose (2ABD), defined as the mean value of the energy imparted per unit of mass in a considered volume of interest, which could represent a more suitable physical quantity to evaluate patient exposure in a mammographic procedure.

In this paper, we present the 2ABD method, show the preliminary results obtained and discuss its potential impact on radiological workflow, further development of the whole project and other possible applications of the same method.

2 MATERIALS AND METHODS

The absorbed dose in mammography depends mainly on the quality of the beam and the breast thickness.

Following the mathematical definition, the 2ABD (mGy) for a specific total breast thickness t (cm) can be expressed as:

$$2ABD = \frac{1}{T}\int_0^t k_{a,i}\, e^{-\mu_{en} x} dx \qquad (1)$$

where μ_{en} is the energy absorption coefficient(cm^{-1}) and $k_{a,i}$ is the incident air kerma at the breast surface (mGy).

While the tube voltage (kVp), mAs, anode-filter combination and t are supplied by the mammographic device, $k_{a,i}$ and μ_{en} have to be assessed in order to compute the 2ABD. It is important to notice that μ_{en} depends on kVp and anode-filter combination, while $k_{a,i}$ depends on kVp, tube current-exposure time product (mAs), anode-filter combination and focus-to-breast surface distance. Therefore, an experimental evaluation of these dependences is required to ensure a reliable assessment of the 2ABD value.

In this first stage we employed a square water-equivalent phantom (1 g/cm^3) for breast tissue simulation. The phantom is composed of a set of slabs, which allow selecting a specific thickness.

A solid-state detector coupled to a Piranha multimeter (RTI-Electronics AB®) and calibrated termo-luminescent (TL) dosimeters have been employed in our measurements. The measurements were performed on the GE Senographe DS machine (GE Healthcare, Waukesha, WI, USA).

The first step of our work was the beam characterization in order to evaluate $k_{a,i}$ as a function of kVp, mAs, t and Focus-to-Image Distance (FID). We set a wide range of nominal kVp (24-34) and mAs (10-100) values and we measured $k_{a,i}$, kVp and mAs by placing the solid-state detector 6 cm from the chest wall edge in the centre of the flat support plate (t=0) with the compression paddle between X-ray tube focus and the detector. We chose the Rh-Rh anode-filter combination for all measurements.

We found the following relationship between $k_{a,i}$ and the other parameters:

$$k_{a,i} = (a \cdot kVp + b) \cdot mAs \cdot \left(\frac{FID}{FID - t}\right)^2 \qquad (2)$$

where the terms a and b were estimated fitting our experimental data. The dependence of the $k_{a,i}$ on kVp is linear as a first approximation and this relationship is valid only in the considered energy range. Repeated measurements of $k_{a,i}$ varying the kVp value were performed keeping fixed the value of mAs. Each measurement of $k_{a,i}$ was repeated five times and the average value was considered. The parameters a and b were obtained by fitting the experimental measurements to Eq. 2.

The second step was to determine the energy absorption coefficient μ_{en}. A set of experimental measurements was performed varying the kVp (range 22-34) and setting 40 mAs for the Rh-Rh anode-filter combination. The TL dosimeters were placed between the phantom slabs at specific depths to evaluate the absorbed dose for different phantom thicknesses (Fig. 1).

In order to estimate μ_{en} for each kVp value, the data were fitted according to the exponential attenuation law:

$$D(t) = D(0) \cdot e^{-(\mu_{en} \cdot t)} \qquad (3)$$

in which D(t) represents the absorbed dose measured by TL dosimeters at depth t. Repeated measurements varying the kVp value were performed in order to evaluate a possible dependence of the energy absorption coefficient μ_{en} from kVp.

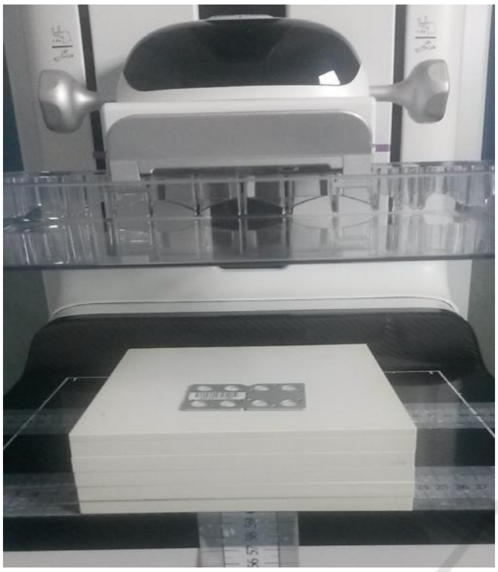

Figure 1: Experimental setup of water equivalent phantoms and TLDs: four different dosimeters were placed each time at the centre of the area irradiated by the beam. At each irradiation the thickness over the TLDs was increased, up to the maximum thickness of 5.5 cm.

Once $k_{a,i}$ and μ_{en} were derived as functions of the input parameters described above, we computed the 2ABD values in different clinical conditions and we compared them to the AGD values computed (for the Rh-Rh anode-filter combination) through the Dance and Wu methods. Uncertainties in AGD (using Dance and Wu methods) were estimated considering an overall 20% error (Hauge et al., 2013). The uncertainty in 2ABD was estimated considering the error propagation on a, b, kVp, t, FID and μ_{en}. The comparison between AGD and 2ABD took into account the overlap between data within their uncertainties.

3 RESULTS

In Fig. 2 we show the X-ray tube yield (i.e. $k_{a,i}$/mAs) as a function of kVp for the Rh-Rh anode-filter combination (Eq. (2)). As we said previously, the tube yield is approximately linear with respect to kVp in the energy range of interest. The repeatability of the kerma measurements (based on five repeated measurements for each value of kVp) is < 2% (standard deviation). a and b values allow to estimate the incident air kerma $k_{a,i}$ for any breast thickness t, mAs and kVp values (Eq. 2).

In Table 1 we compare $k_{a,i}$ measured values and $k_{a,i}$ computed values. The good agreement between the measured and calculated values allows the evaluation of $k_{a,i}$ by Eq. 2 for each mammographic equipment. Notice that the determination of *a* and *b* permits to obtain $k_{a,i}$ without directly measure it.

In Fig. 3 we show D(t) as a function of depth t for different kVp values. Data were fitted with Eq. (3) and the μ_{en} for each kVp was obtained. The experimental data confirm the exponential trend of the beam intensity as a function of the phantom thickness.

Numerical results are presented in Table 2. The energy absorption coefficients μ_{en} vary slightly with kVp. For this reason, the average value was considered, as shown in Table 2[1].

Once evaluated a and b values and the energy absorption coefficient μ_{en} the 2ABD can be calculated according to Eq. 1.

In Table 3 we compare the 2ABD and AGD values in clinical situations. Five mammograms were selected from the PACS (Picture Archiving and Communication System) and the data needed to compute the AGD through the Dance and Wu methods were extracted. The most used kVp values were chosen for each anode/filter combination. For each kVp value the most frequent thickness was considered. From Tab. 3 we observe a good agreement between 2ABD and AGD in every considered conditions. The two methods provide results that are consistent within the uncertainties.

4 DISCUSSION

The 2ABD, defined as the mean value of energy imparted per unit mass in a considered volume of interest, represents a suitable physical quantity to evaluate the patient exposure in a mammography procedure. In fact, we notice a good agreement between the 2ABD values and the AGD values computed through the Dance (Dance et al., 1990) and Wu (Wu et al., 1994) methods for the clinical situations considered in this work (Table 3).

Our method requires kVp, mAs and breast thickness values as input parameters, for a specific anode-filter combination. These parameters can be

[1]The difference between 2ABD computed by considering the kVp dependence of μ_{en} and the 2ABD computed considering the average value of μ_{en} was negligible.

easily obtained or selected by the operator before the mammographic exam. Therefore, the 2ABD index

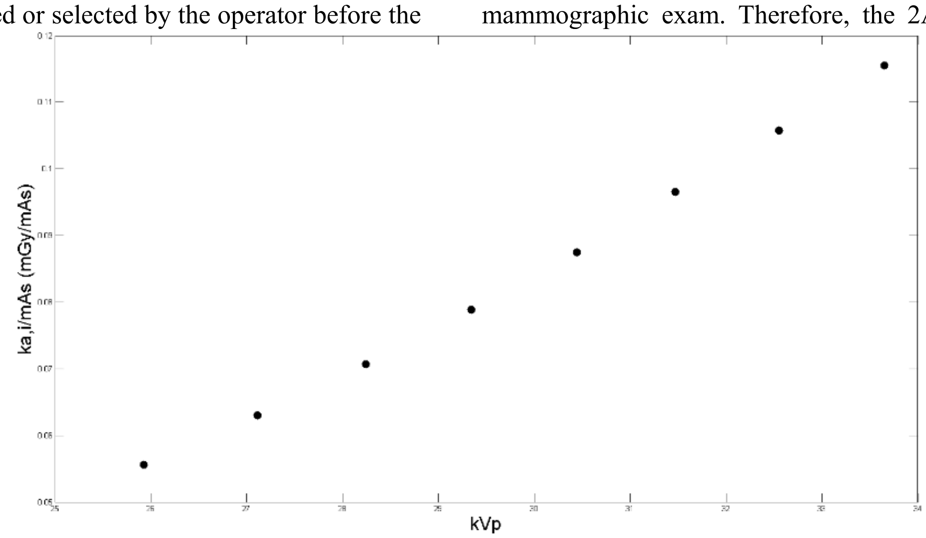

Figure 2: X-ray tube yield ($\frac{k_{a,i}}{mAs}$) as a function of kVp for the Rh-Rh anode-filter combination. Data were fitted using Eq.(2) with a=(0.0078±0.0002)$\frac{mGy}{mAs \cdot kVp}$ and b=(-0.149±0.006)$\frac{mGy}{mAs}$. Five measurements were averaged and the standard deviation was computed in order to evaluate the precision of our experimental data.

Table 1: Comparison between $k_{a,i}$ (mGy) measured and calculated for different experimental settings. Five measurements were averaged and the standard deviation was computed in order to evaluate the precision of our experimental data.

Anode-filter	FID (cm)	t (cm)	kVp	mAs	$k_{a,i}$ calculated	$k_{a,i}$ measured
Rh-Rh	63.5	5	29	50	4.65 ± 0.6	4.80 ± 0.01
Rh-Rh	63.5	3	27	40	2.67 ± 0.4	2.83 ± 0.01
Rh-Rh	63.5	4	28	45	3.57 ± 0.5	3.70 ± 0.01

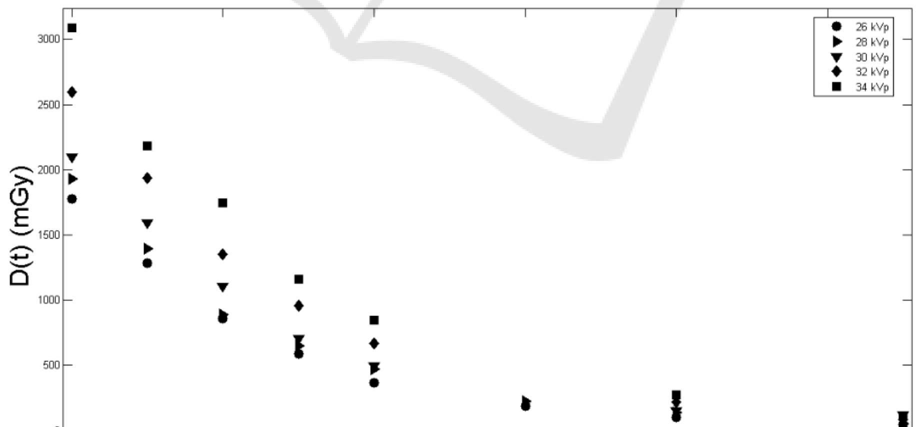

Figure 3: Absorbed radiation dose at different depths in the water-equivalent phantom for different kVp values.

Table 2: μ_{en} values for different kVp and average value of μ_{en} for the Rh-Rh anode-filter combination.

kVp	26	28	30	32	34	μ_{en_avg} (cm^{-1})
μ_{en} (cm^{-1})	0.74±0.05	0.72±0.05	0.69±0.09	0.66±0.04	0.63±0.06	0.69±0.06

Table 3: Comparison between 2ABD and AGD values in different clinical situations.

Age (y)	Glandularity (%)	t (cm)	kVp	mAs	AGD (Dance)(mGy)	AGD (Wu) (mGy)	2ABD (mGy)
63	33	5	28	48	1.0±0.2	1.0±0.2	1.1±0.2
59	33	5	29	58	1.4±0.3	1.4±0.3	1.4±0.3
45	35	6	29	73	1.5±0.3	1.5±0.3	1.6±0.3
57	21	6	30	63	1.5±0.3	1.6±0.3	1.5±0.3
60	12	7	30	75	1.7±0.3	1.7±0.3	1.6±0.3

could be easily computed and employed as dosimetric index for each mammographic procedure (i.e. for each patient) and recorded in the radiological report. In addition, the computation could be conveniently automated and this could be advantageous in order to comply with the European Directive 59/2013/EURATOM. Notice that $k_{a,i}$ can be computed directly from Eq. 2 once kVp, mAs, FID and t are known and therefore, to assess 2ABD, a direct measurement of $k_{a,i}$ can be avoided.Furthermore, Table 3 does not show evident discrepancy between AGD and 2ABD values, although a different set of radiation exposure and patient-specific parameters was involved in each mammographic procedure. Thus, 2ABD could be employed as surrogate of AGD.

However, our model has some limitations. In fact, this model could be improved taking into account the X-ray tube yield variations for different anode-filter combinations among different mammographic devices, which can affect the $k_{a,i}$ evaluation. Moreover, breast composition should be considered and a correction factor might be applied for the μ_{en} assessment. In addition, different phantoms with different shapes could be used so as to better simulate the breast. Besides, in order to comprehensively validate this model, the method should be tested in different clinical conditions on different mammographic devices. Moreover, breast composition should be considered and a correction factor might be applied for the μ_{en} assessment. Breast density is being studied in many epidemiological works also related to screening programs (Freer 2015, Berg 2016). We are also realizing image processing software able to automatically analyse clinical images to evaluate the breast composition, based on both a classical approach (comprising a pre-processing step, a pattern recognition step, a classification step and a segmentation step) and novel approaches based on machine learning methods.

As a further development, this method could be also applied to the tomosynthesis, an advanced imaging technique that allows the reconstruction of a three-dimensional view of the breast, overcoming the projective (two-dimensional) imaging approach limitations.

5 CONCLUSIONS

In conclusion, in this work we proposed the 2ABD as a reproducible and easily computable dose index to assess the radiation dose absorbed by the patient during a mammography procedure. According to our preliminary results, the 2ABD could be employed as dosimetric index to be inserted into the radiological report as required by the European Directive 59/2013/EURATOM. The development of this new dose index is a part of a whole project finalized to optimize the dose in mammographic procedures, give a correct information about the risk related to ionizing radiation and maintain high adherence to screening programs.

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