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A device for quality evaluation of operational parameters in mammography X-ray tubes

Um dispositivo para avaliação de qualidade de parâmetros operacionais em tubos de raios X mamográficos

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Abstract
This work describes the development of a system designed to measure important operational parameters of mammography equipment, as kVp, tube current, exposure time, dose and half-value layer (HVL) in any field location. This system is based on a device with a Si semiconductor sensor, placed under the X-ray tube (over the unit table, for example), which detects the X-ray photons, yielding an electric current proportional to the beam intensity. This signal is driven to a digitizer card coupled to a notebook where a software provides the signal reading and treatment. The kVp measurement is based on the ratio of two signals, one filtered and other non-filtered (reference) from the same sensor. This kind of signal is obtained by detecting the sensor output during the X-ray exposure with a circular shaped aluminum wedge rotating over it. With a single exposure, the software allows to determine the actual parameters by this signal analysis. In addition, HVL in any field location can be determined by a previous developed computer simulation procedure. Calibration curves are stored so that the software compares the actual reading from the sensor X-ray exposures with the stored data to determine how accurate the tube under investigation is working. Development tests with a *Trex Medical Contour 2000* unit have shown that the system response is in agreement with calibrated devices used for checking the parameters. An advantage of this system is the possibility of storing a lot of information requested for quality assurance programs.

Keywords: kVp measurement, Quality assurance, Mammography, Half-value layer.

Resumo
Esse trabalho descreve o desenvolvimento de um sistema para medição de importantes parâmetros operacionais de equipamentos mamográficos, como kVp, corrente de tubo, tempo de exposição, dose e camada semi-redutora (CSR) em qualquer posição do campo. Esse sistema baseia-se num dispositivo com sensor semicondutor de Si, posicionado sob o tubo de raios X (sobre a mesinha do equipamento, por exemplo), que detecta os fótons e produz uma corrente elétrica proporcional à intensidade do feixe. Esse sinal é enviado a uma placa digitalizadora acoplada a um notebook no qual um software realiza sua leitura e tratamento. A medição da kVp se baseia na relação entre dois sinais, um filtrado e outro não (referência) a partir do mesmo sensor. Esse sinal é obtido detectando-se a saída do sensor sobre o qual gira uma cunha de alumínio circular durante uma exposição de raios X. Com uma única exposição, o software permite determinar os parâmetros pela análise desse sinal. Além disso, a CSR em qualquer posição do campo pode ser determinada a partir de um procedimento de simulação computacional desenvolvido previamente. Curvas de calibração são armazenadas para que o software compare a leitura real do sensor com os dados armazenados para determinar a precisão de operação do tubo sob investigação. Testes de desenvolvimento com uma unidade Trex Medical Contour 2000 mostraram que a resposta do sistema é concordante com dispositivos calibrados usados para verificar os parâmetros. Uma vantagem desse sistema é a possibilidade de armazenar uma grande quantidade de informações requisitadas por programas de controle de qualidade.
Palavras-chave: *Medição de kVp, Controle de qualidade, Mamografia, Camada semi-redutora.*

Introduction

Many factors contribute to radiographic imaging process. Nevertheless, many of them could affect the image contrast and, therefore, it could difficult the diagnosis. This is the main reason for the importance of developing quality assurance programs for radiological imaging systems. There are some important operational parameters involved in the X-ray beam generation. Examples of these parameters are the peak voltage (kVp) applied between the two electrodes in the tube, the half-value layer (HVL), the electrical current applied to the tube, the exposure time and the dose. In mammography, kVp evaluation is more significant due to the narrow energetic range of operation (from 25 to 40 keV, approximately). Therefore, investigation on the actual operational conditions of systems is necessary. This information could determine the efficacy of that equipment performance and could forward to reduce the number of false diagnoses due to poor quality images.

There are many methods designed to perform the radiographic system evaluation: by the transfer functions (Doi *et al.*, 1982; Schiabel, 2000), by phantoms (Ardran and Crooks, 1968; Caldwell and Yaffe, 1990), different techniques to measure individually some parameters (Haus and Yaffe, 2000; Karila, 1988; Muntz *et al*., 1978), and also methods based on computer simulations (Marques *et al*., 1999; Schiabel *et al.*, 1998). Most of the quality assurance programs still employ radiographic film as X-ray sensor, or, for dose investigations, ionization chambers (or similar devices). However, systems using films usually present several problems, since different radiographic films have different sensitivity, and there is no standardization on storage and development. This can affect largely the final results of quality evaluation. In addition to the subjective evaluation normally provided by these devices, the results usually take much time to be obtained, and also the tests demand some extra instruments in order to measure different parameters.

There is a large variety of other systems to be used in indirect kVp measurements. Among them, we could mention those based on Si semiconductors devices, like in Mahler and Lifshits' work (1984), where Si photovoltaic cells were placed under aluminum filters of different thicknesses, exposed to an X-ray beam.

Approximately in the last 15 years, the researches on radiation sensors devices have grown, particularly on the use of semiconductors with this purpose (Rikner and Grusell, 1987; Willetts *et al*., 1989). Willetts *et al*. (1989), for instance, have proposed an electronic instrument designed to quality assurance measurements in diagnostic radiology. However, few parameters can be evaluated and each one is dependent on a particular set of X-ray sensors.

Nowadays, modern commercial instruments, like NERO® (Victoreen Inc. – http://www.elimpex.com/companies/victoreen/8000.htm) or Barracuda® (RTI Electronics – http://www.rti.se), using microprocessors for processing, evaluating and displaying in liquid crystal screens the results of this kind of measurement, are in use by professionals involved in QA measurements in diagnostic radiology. They can usually perform measurements on kVp, exposure time, and dose. However, additionally to a very high cost (not less than US$ 11,000), these instruments have, at least, one important limitation: kVp, and HVL measurements are influenced by the heel effect. Indeed, information on what field region the radiation is being detected is important because the detected intensity in strongly dependent on the field location and the distance from the source where the sensor is placed.

As the radiation intensity along the field is not uniform due to the photons filtration by the target material when they are emitted, there is a variation in the beam intensity depending on the photon emission direction. This variation can be up to 30% from the anode side to the cathode side along the tube axis direction, which can affect significantly the measurements of parameters as kVp, HVL and dose. HVL is important for evaluating the beam energy characteristics since the larger is that thickness, the more energetic is the corresponding radiation. The experimental method commonly used for HVL determination – based on that proposed in the 60s by Trout, Kelley and Lucas (Trout *et al*., 1960; Vieira *et al*., 1999) – states that the measurement has to be made in the center of the field for a well-collimated beam; however this does not take into account the beam intensity variations along the entire field, caused mainly by the heel effect. Furthermore, one unique measure in a single location cannot consider the beam relative quality in other field locations.

Therefore, the purpose of this work is the description of a simple and accurate instrument designed to determine the most important operational parameters of mammographic systems, and, in addition, the HVL in all field locations from one unique X-ray exposure. The device can be placed on the table available in the equipment, preferably in the field center. The instrument is based on a system composed by: a) a semiconductor sensor which converts the X-ray photons detected into electrical current; b) a device for supporting the sensor, with a wedge moved by a motor; c) a digitizer card (PMCIA type II) to convert the analog signal from the sensor into digital; and d) a notebook, where the evaluation can be performed by a software developed in LabVIEW®. The signal from the sensor is digitized and conveniently stored in the notebook memory. From a previous calibration, this signal can provide information on the kVp – from a comparison between a "filtered" and a "reference" signal, both obtained simultaneously during the X-ray exposure –, the mA, the exposure time, the dose, and the HVL. This later is determined initially for the center and, thus, for all desired field locations, by means of a computer simulation program (Vieira *et al*., 1999).

Methods

Figure 1 shows the device developed for determining X-ray tube parameters as kVp, for example. A continuous aluminum wedge is placed just above a silicon sensor with a given X-ray sensitive area (1.57 mm^2). This wedge has 0.15 mm of minimum thickness and 1.95 mm of maximum thickness. As seen in Figure 1b, it is circular and the linear projection of its complete length has 72 mm. It is coupled to a mechanical device able to rotate it toward its thickness growing, driven by a DC motor. The single sensor placed under the wedge is able to provide a signal called *reference*, as well as the signal attenuated by the aluminum wedge during the same exposure. Figure 1c illustrates the device placed under a mammography X-ray tube.

During an X-ray exposure, the signal from the sensor is digitized by a digitizer card (DAQ Card-1200, National Inst. Corp.) in order to export it to the notebook; at the same time, the support mechanism rotates the wedge above the sensor, synchronized with the exposure start. Thus, the recorded signal has a constant reference value which decreases as the wedge is rotated up to reach its maximum thickness.

Determining kVp

After convenient amplification, the signal from the sensor is digitized and stored in the notebook. The waveform is illustrated in Figure 2. Therefore, the ratio between its largest peak (corresponding to the non-filtered sensor output, when it has received direct X-rays) and its second peak (corresponding to the output filtered by 0.15 mm Al) can be verified. These values allow to determine a graph corresponding to the ratio between the signal V_A (non-filtered – refer-

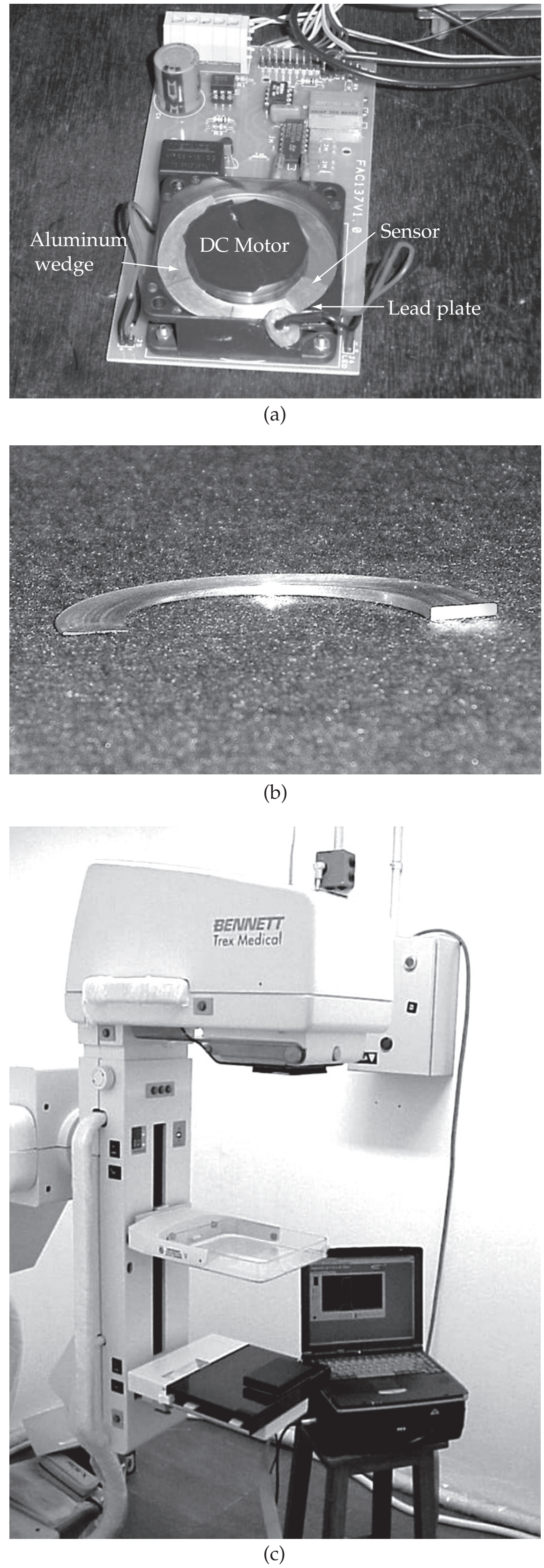

Figure 1. a) sensoring support device; b) continuous aluminum wedge; and c) sensor device placed under the X-ray tube.

ence) and the signal V_B (filtered) – in analogy to Mahler and Lifshits' work (1984), called as "transfer ratio" (T.R.) – and the kVp which was effectively applied to generate that beam. Thus, the actual radiographic equipment kVp value can be measured directly from the curve, as illustrated by the system software window shown in Figure 3.

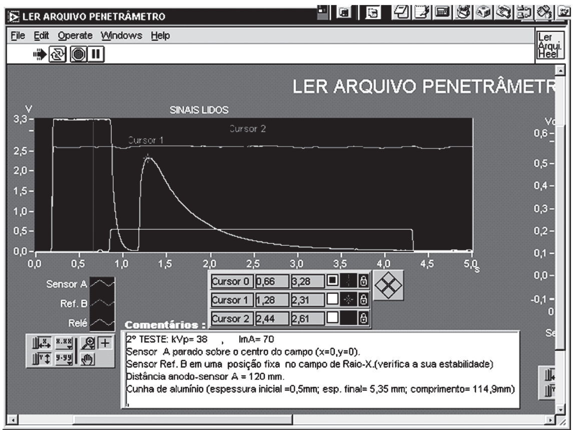

Figure 2. Illustration of the software output screen showing the signal from the sensor during an X-ray exposure. Cursors allow checking the amplitudes along the curve, which determines V_A and V_B.

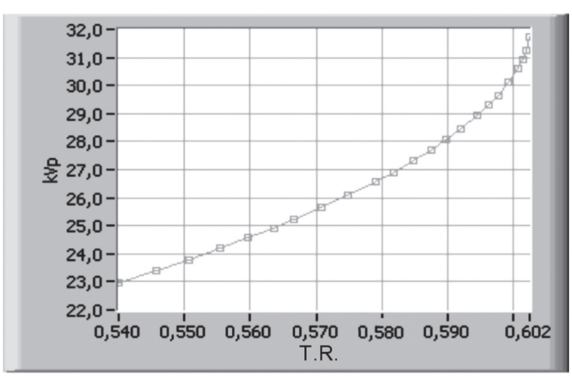

Figure 3. Graph showing the transfer ratio (T.R.) as a function of tube voltage (kVp) variation as it could be seen in a window at the software screen.

The main signal shown in Figure 2 can be divided in two parts: the first is the rectangular initial pulse, with approximately constant maximum amplitude, corresponding to the exposure time with the "uncovered" sensor; the second is the signal which decreases from a maximum peak about 0.25 s after the rectangular pulse, corresponding to the exposure time with progressive and constant increase in the aluminum filter thickness. This time of 0.25 s with no signal corresponds to a small thin lead plate passing above the sensor in order to be a reference for the filtered signal beginning. The definition of V_A and V_B values for the T.R. calculation can be obtained by running with the cursors on the signal in Figure 2, where the little windows just under the waveform present the values for the illustrated example: 3.28 V for cursor 0 positioning (V_A) and 2.31 V for cursor 1 (V_B). The waveform at the upper is a reference registered by another silicon sensor, with purposes only to confirm the stability during the X-rays exposure. The rectangular waveform at the bottom of the window is generated by a small key (under the plate supporting the mechanism for wedge spinning) which denotes the start and the end of displacement. This last signal is used in order to provide an automatic conversion of the time scale presented in Figure 2 into a distance scale.

The graph illustrated in Figure 3 is obtained automatically. Indeed, the signal curve shown in Figure 2 is a single part of the complete signal at the input of the notebook digital card, since the same signal arises several times during the same time interval – according to the X-ray detector device arrangement previously shown in Figure 1. This feature however has created an extra difficulty in the treatment software development due to the need of isolating, among the repeated signal curves, one representing all the essential characteristics to the calculations. The original sensor output signal has additionally another characteristic: as the wedge is spinning over the sensor and the X-ray beam can be triggered randomly in any moment during this spinning, the signal acquisition could register, also randomly, the "free peak" and the curve produced by the wedge absorption. The "free peak" corresponds to the pulse produced when there is no filter over the sensor.

Therefore, a routine in the software was implemented in order to isolate only one signal curve corresponding to the wedge absorption plus the "free peak", since the T.R. should determine the ratio between the maximum voltage values read for each of these curves. The following steps were performed to separate these signals:

a) Since the acquired curves are stored in matrix format by the software, the process identifies the beginning and the end of the reading, which generates the "separate curve" (Figure 4a);
b) The transitions in the curves courses (Figure 4b) are obtained by calculating the derivative curves;
c) Each peak of the positive part of these transitions corresponds to the beginning and to the end,

respectively, of a set formed by wedge curve and "free peak"; and

d)The indexes corresponding to the first and second transitions are obtained for the "separate curve" and thus the region of interest can be also separated, which leads to the curve displayed at the bottom of Figure 4.

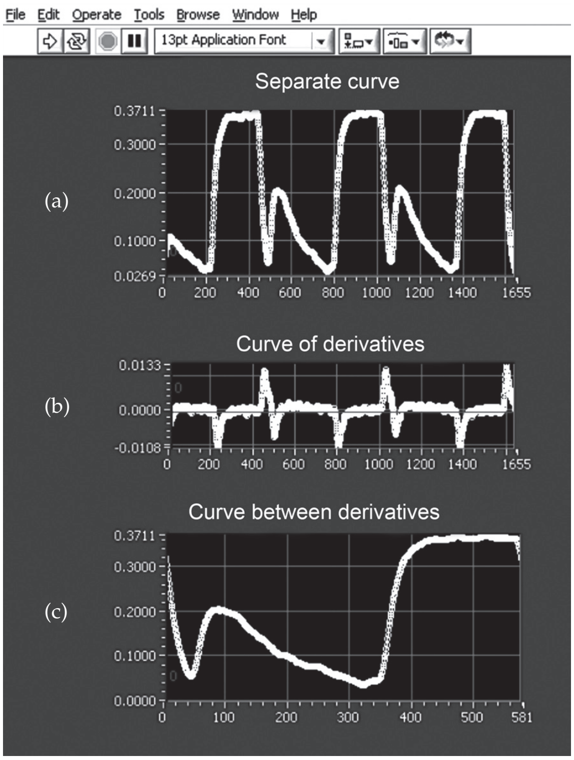

Figure 4. Curves extracted from the sensor signal for isolating the main curve, illustrating the "free peak" (pulse from the non filtered sensor) and the wedge absorption curve (signal from the sensor while the wedge is spinning over it): a) separate curve; b) signal corresponding to the derivative from the curve displayed in (a); and c) curve corresponding to the region of interest with the peaks to be used in T.R. calculation.

By repeating this process, each part of this last curve can also be separated, as shown in Figure 5. By determining the ratio between their respective maximum values, the T.R. can be obtained. Performing T.R. calculations for several kVp values simultaneously with measurements performed with calibrated Barracuda® device, two matrixes are obtained, allowing to produce the R.T. x kVp graph as shown previously in Figure 3, as well as the related table, illustrated in Figure 6. The experimental (measured) value is registered in that table, so that one can easily determine the kVp as function of R.T. independently on the graph, as shown also in Figure 6.

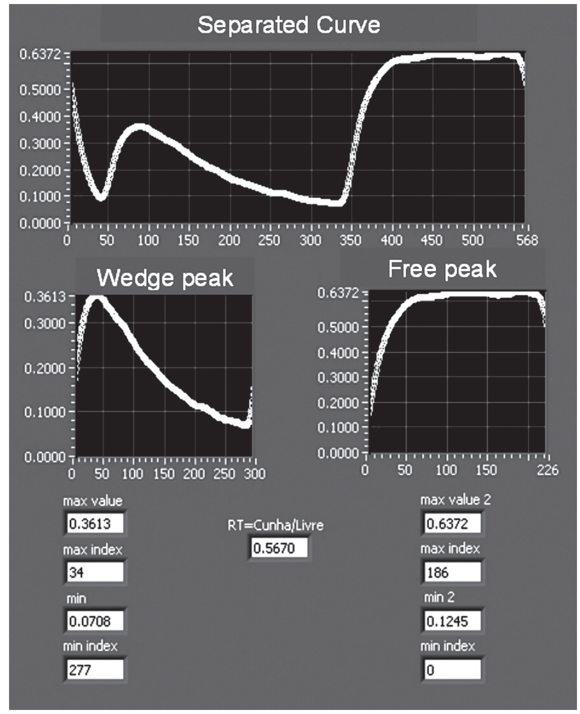

Figure 5. Separation of two parts of the curve isolated by the process shown in Figure 4 (*wedge curve* and *free peak*) in order to calculate the T.R. In the illustration, the maximum value measured for the wedge curve was 0.3613 V and for the free peak, 0.6372 V, giving a T.R. of 0.567.

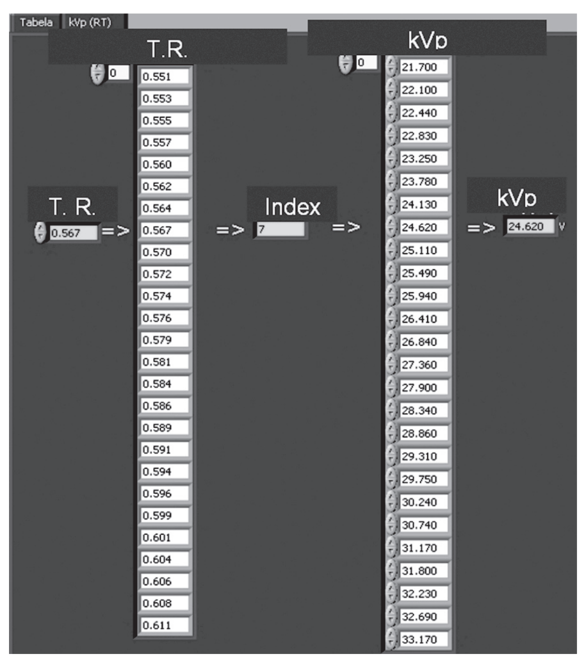

Figure 6. Notebook window showing the table with the relation between T.R. and kVp according to the reading of curves (Figure 5). Taking into account the value 0.567 for T.R. displayed in Figure 5, the correlate kVp can be found.

The first evaluations have demonstrated that the T.R. variation with the tube current is neglected in this energy range so that T.R. can be considered constant with the current increase. For 30 to 40 kVp range, for example, T.R. has decreased less than 5% in average against 230% of variation in the tube current range.

Determining the half-value layer

Another important information which can be obtained from the waveform shown in Figure 2 is the HVL, at the very location where the sensor is. Therefore, from the determination of signal V_B, for example, the cursor can be moved on the screen along the decreasing wave up to find the amplitude V_C, corresponding exactly to $V_B/2$. As the software converts the time scale in distance scale, the determination of the distance from the maximum peak (V_B) to the value V_C is easily achieved. As the aluminum wedge size is known, the determination of the aluminum thickness responsible for the beam intensity attenuation in that location can be given by:

$$HVL = (0.025\, d + 0.150)\ [\text{mm Al}] \qquad (1)$$

where d is the distance automatically measured by the software; the factor 0.025 is the ratio (1.80/72.00), since the linear projection of the curved wedge shown in Figure 1(b) is 72.00 mm long with thickness ranging from 0.15 mm up to 1.95 mm (see Figure 7).

The HVL value in any other field location can be found by simulation procedures (Vieira *et al.*, 1999), following equation (2), which gives the radiation spectrum of intensity I_0 yielded inside a Mo target for an X-ray tube:

$$I_0(E) = 0.579 \cdot 10^{11}\ (E_0 - E)\ [\text{keV/mAs} \cdot \text{Sr}] \qquad (2)$$

where E_0 is the maximum photon energy (numerically equal to the kVp), E is the photon energy where the intensity should be calculated, mA is the tube current, s the exposure time, Sr the solid angle of the X-ray beam emission (in stereorad), and range (in keV) is the interval between the energies (Vieira *et al.*, 1999).

Knowing the location x in the field where the HVL should be calculated, the angle θ regarding the photons emission is obtained (Vieira *et al.*, 1999), and thus the path of the photon inside the target, $S(\theta)$, is given by:

$$S(\theta) = \frac{d \cdot \cos(\Phi)}{sen(\theta + \Phi)} \qquad (3)$$

where Φ is the target inclination angle, d is the depth of radiation production and θ is the angle between the central axis and the axis of the single ray, which determines its position on the image plane.

The beam intensity I, after filtered by the target material, is given by equation (4) (Vieira *et al.*, 1999):

$$I = I_0\, e^{-\mu/\rho\, S(\theta)} \qquad (4)$$

Determining time exposure and dose

The reference signal width allows determining the exposure time, since the signal acquisition is synchronized with an automatic trigger at just the beginning of X-ray beam exposure. Adequate sensor sensitivity calibration allows the emission of a signal with appropriate amplitude as soon as it is reached by the first X-rays photons. This signal disappears as soon as the radiation is off. This is registered and conveniently stored by the software into the notebook as the waveform shown in Figure 8. Still, this "mode" reg-

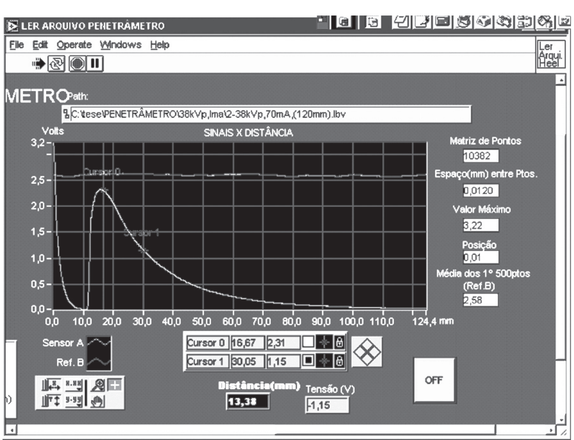

Figure 7. Software output screen showing the signal from the sensor during an exposure. The time scale was converted into distance scale. The cursors show the linear distance of the wedge displacement corresponding to V_B and to $V_B/2$.

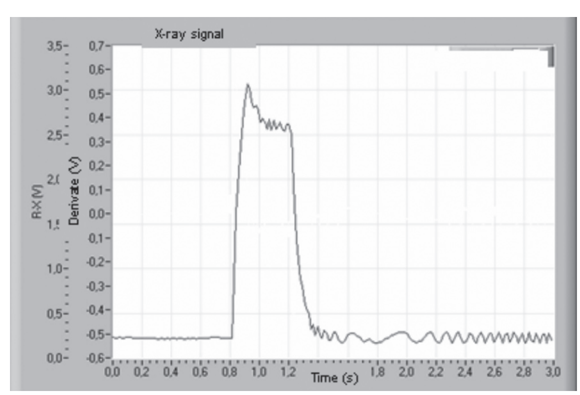

Figure 8. Sensor signal waveform recorded by the software. Its width provides the exposure time calculation.

isters the waveform yielded by the X-ray generator, which can also provide information about the X-ray spectrum quality.

In order to eliminate the subjectivity corresponding to the visual evaluation of the signal shown in Figure 6, an algorithm was introduced in the software in order to calculate the derivative at each point on the curve; these results are larger when scanning the ascendant or descendant parts of the curve. From this calculation, the maximum derivative values are found, as for the ascendant as well as for the descendant parts. These values are the inflexion point at each part; the first and the second inflexion points define the two points in the time axis so that the effective exposure time is calculated as the difference between these two values.

Thus the software displays the accurate value corresponding to the time the sensor was reached by the X-ray beam during that exposure.

The dose determination can be performed by using another calibration curve. An integration circuit is simulated by the software. The input signal for this "circuit" comes from the non-filtered sensor. While this signal is applied to the circuit input, it is continuously integrated up to a maximum value, obtained when the X-ray is turned off. This value is thus compared to the previous mentioned calibration curve, which indicates the relation between the output signal voltage and the dose (given in mGy). Dose values forming this calibration curve are obtained from a calibrated dosimeter during the system development. The simulation circuit scheme for this evaluation is shown in Figure 9.

Tests Results

kVp and HVL measurements

The tests performed with the signal acquisition device were based on the procedures described previously. It was placed under the X-ray beam so that the main sensor was located in the field center, 65 cm from the focal spot, as shown in Figure 1c. The aluminum wedge spins completely over the sensor during each exposure. A previously calibrated *Trex Medical Contour2000* mammography unit was used, and the reference and filtered signals were recorded. Then, the calibration curves were plotted for this device and the T.R. values were calculated as a function of kVp. Table 1 shows the results of output signals V_A (non-filtered) and V_B (filtered) for a range of kVp and mA.

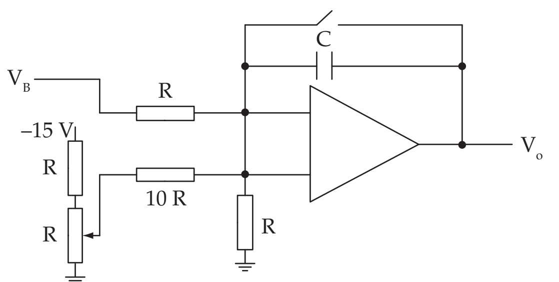

Figure 9. Simulated integrator circuit for dose determination.

Table 1. Measurements for V_A and V_B for different kVp and tube currents considering exposures in the mammography equipment *Trex Medical Contour 2000*. Values for V_A and V_B correspond to the average of readings. Standard deviations for these data are indicated.

kVp	mA	V_A [V]	V_B [V]
24	40	0.165 ± 0.007	0.080 ± 0.005
24	50	0.355 ± 0.007	0.155 ± 0.007
24	60	0.740 ± 0.014	0.315 ± 0.007
24	70	0.990 ± 0.012	0.380 ± 0.000
26	40	0.215 ± 0.007	0.100 ± 0.005
26	50	0.470 ± 0.000	0.200 ± 0.005
26	60	0.915 ± 0.020	0.385 ± 0.004
26	70	1.390 ± 0.000	0.550 ± 0.014
28	40	0.260 ± 0.000	0.120 ± 0.000
28	50	0.605 ± 0.007	0.270 ± 0.000
28	60	1.145 ± 0.007	0.490 ± 0.012
28	70	1.837± 0.099	0.745 ± 0.038
30	40	0.355 ± 0.007	0.160 ± 0.000
30	50	0.820 ± 0.007	0.360 ± 0.002
30	60	1.645 ± 0.007	0.720 ± 0.002
30	70	2.244 ± 0.007	1.045 ± 0.008
32	40	0.420 ± 0.005	0.200 ± 0.004
32	50	0.970 ± 0.000	0.435 ± 0.006
32	60	2.010 ± 0.014	0.885 ± 0.017
32	70	2.605 ± 0.007	1.360 ± 0.014
34	40	0.485 ± 0.007	0.225 ± 0.010
34	50	1.151 ± 0.032	0.530 ± 0.010
34	60	2.146 ± 0.040	0.965 ± 0.038
34	70	2.945 ± 0.005	1.740 ± 0.013
36	40	0.610 ± 0.005	0.285 ± 0.007
36	50	1.350 ± 0.010	0.630 ± 0.015
36	60	2.562 ± 0.035	1.310 ± 0.022
36	70	3.120 ± 0.021	2.045 ± 0.027
38	40	0.735 ± 0.005	0.345 ± 0.007
38	50	1.640 ± 0.012	0.760 ± 0.002
38	60	2.775 ± 0.030	1.530 ± 0.035
38	70	3.280 ± 0.000	2.310 ± 0.008
40	40	0.815 ± 0.007	0.390 ± 0.003
40	50	1.840 ± 0.023	0.872 ± 0.015
40	60	2.830 ± 0.017	1.565 ± 0.007

The data shown in Table 1 therefore allow the T.R. calculation. In addition, based on the response curves obtained from the tests – as that in Figure 7 – the values corresponding to the HVL could also be determined. Table 2 shows the average value for T.R. – from V_B/V_A ratio – for each kVp value used during the tests, as well as the HVL average values.

Table 2. Average T.R. and HVL calculated for each kVp, as results from the data in Table 1.

kVp	Average T. R.	Average HVL [mm Al]
24	0.416	0.983
26	0.425	0.995
28	0.437	1.024
30	0.447	1.036
32	0.467	1.028
34	0.482	1.036
36	0.515	1.046
38	0.535	1.055
40	0.553	1.067

Figure 10 illustrates an example of a typical sensor response-curve, obtained experimentally with the system, according to some of the data registered in Table 1. Figure 11 shows the T.R. as a function of kVp for the mammography operation range.

Figure 12 shows the relation between kVp and the HVL measured in aluminum thickness. The equation for the best fit curve to the experimental data for the graph in Figure 9 is:

HVL = 0.88067 + 0.00467 kVp
(Correlation: 0.949)

a) 40 mA → $V_A = -0.889 + 0.042$ kVp
(Correlation: 0.990)

b) 50 mA → $V_A = -2.004 + 0.094$ kVp
(Correlation: 0.993)

c) 60 mA → $V_A = -2.669 + 0.142$ kVp
(Correlation: 0.989)

d) 70 mA → $V_A = -2.986 + 0.170$ kVp
(Correlation: 0.988)

Dose measurements

Based on the procedures described above, in the same sensor location, the amplitudes of the sensor output signal were measured for exposures of 1.0 s. Data, for some kVp and tube currents, are shown in Table 3.

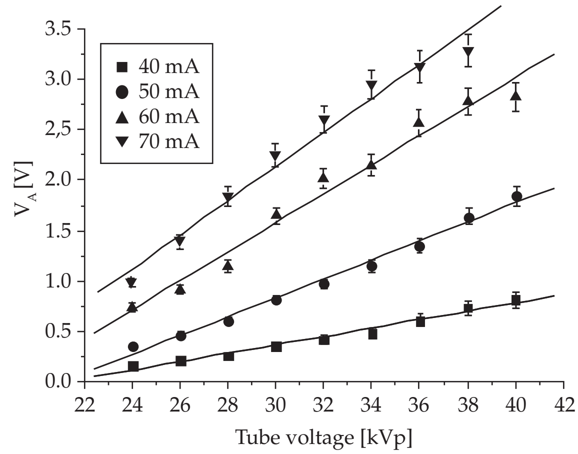

Figure 10. Graph illustrating the relation between the output V_A and kVp for the equipment under test for 4 different and constant values of tube current.

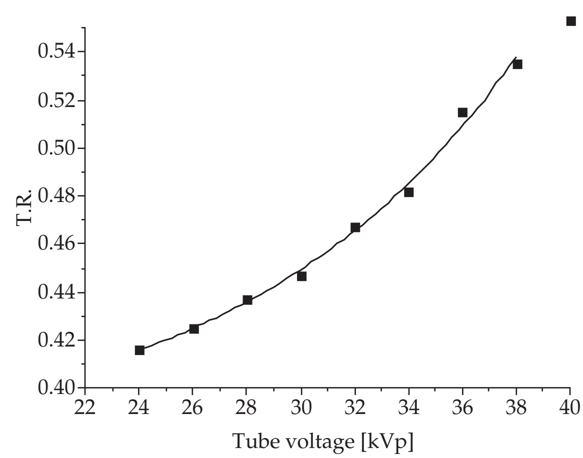

Figure 11. Graph illustrating the kVp as a function of the T.R. for the equipment under test: T.R. = $0.22756 + 0.07377 \cdot e^{kVp/29.37408}$.

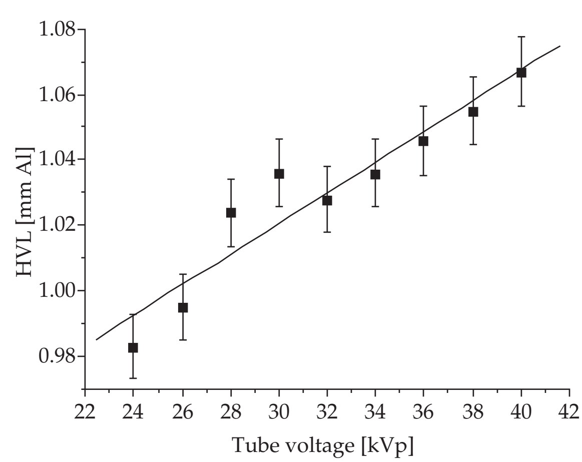

Figure 12. HVL variation (mm Al) relative to kVp for the mammography equipment under investigation.

Table 3. Results from dosimeter circuit tests: values obtained from measurements corresponding to the output signal in the dosimeter circuit as a function of some kVp and tube currents. (VD = sensor output in V; It = tube current; kVp = tube voltage)

kVp	V_D [V]		
	I_t = 35 mA 0.2 s	I_t = 140 mA 0.2 s	I_t = 160 mA 0.3 s
24	0.04 ± 0.007	0.13 ± 0.001	0.18 ± 0.001
28	0.05 ± 0.007	0.24 ± 0.001	0.31 ± 0.001
32	0.08 ± 0.014	0.37 ± 0.001	0.49 ± 0.001
34	0.10 ± 0.007	0.45 ± 0.001	0.60 ± 0.007

Data in Table 3 are converted into the values of dose (in mGy) displayed at Table 4. They correspond to the dose applied to the sensor under the tube, as its positioning shown in Figure 1, and they were also evaluated by comparison with measurements performed by a commercial calibrated instrument (Barracuda®). The comparisons are shown in Table 5 as well as in Figure 13.

Table 4. Dose values D (in mGy) after conversion for each condition considered in Table 3.

kVp	D [mGy]		
	I_t = 35 mA 0.2 s	I_t = 40 mA 0.2 s	I_t = 160 mA 0.3 s
24	0.63	2.83	3.73
28	0.98	4.36	5.73
32	1.39	6.14	8.08
34	1.61	7.10	9.42

Table 5. Comparison between dose readings by Barracuda® and the system notebook screen for a series of exposures at mammography kVp range (22 to about 34 kV).

Barracuda® [mGy]	Developed System [mGy]
2.32	2.44
2.80	2.75
2.87	2.86
3.27	3.42
3.62	3.56
3.73	3.56
3.85	4.12
4.36	4.39
4.74	4.40
5.26	5.23
5.30	5.93
5.72	5.37
6.15	6.21
6.95	6.63
7.09	7.33
8.09	7.89
9.56	9.56

Note: values at right column: average of 6 measurements, discarding the highest and the lowest values (see corresponding graph at Figure 13).

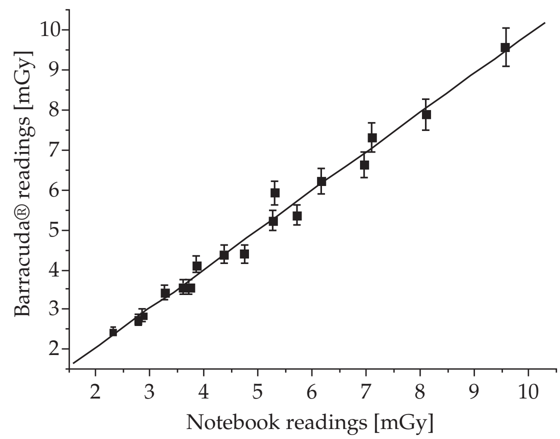

Figure 13. Graph showing the comparisons in dose between the readings by the system notebook and the Barracuda's® display.

Reproducibility

The device calibration was performed by comparing the results with data obtained by a calibrated Barracuda® (mentioned in the previous section) after exposures in the Contour2000 mammography equipment also previously mentioned. Thus, all the exposures were made simultaneously to the current developed system and the Barracuda® sensor. Table 6 shows the values obtained by both systems during several exposures at same kVp value. Additionally, Table 7 shows the results for time exposure measurements provided by the system described in this paper in comparison to those read at Barracuda's® display, with the relative difference in percentage.

Table 6. Comparison between the kVp read by Barracuda® measurement instrument and the values read at the sensor circuit output (given in V) in order to evaluate the system reproducibility. Values at left column correspond to the reading at Barracuda® panel; values at right column correspond to the average and standard deviation of readings made by the software input stage (from 6 measurements, discarding the highest and the lowest values).

kVp Barracuda®	System sensor circuit output [V]
22.10	0.38 ± 0,01
23.03	0.48 ± 0.00
24.71	0.70 ± 0.05
26.30	0.85 ± 0.01
28.12	1.10 ± 0.01
32.43	1.77 ± 0.02

Note: values above were obtained at 140 mA and 0.2 s of exposure time.

Table 7. Comparisons between the actual X-rays exposure time (read by Barracuda®) and the value provided by our system, with the percentage relative difference. Also here data provided by the system software correspond to the average value (and the respective standard deviation) according to the same procedure used for displaying Table 6 (from 6 measurements discarding the highest and the lowest values).

kVp	Exposure time at Barracuda's display [s]	Exposure time displayed by the developed system [s]	Relative difference [%]
22.1	0.302	0.31 ± 0.00	2.5
23.0	0.302	0.31 ± 0.00	2.5
24.5	0.302	0.31 ± 0.00	2.5
26.8	0.303	0.31 ± 0.00	2.3
28.8	0.300	0.31 ± 0.00	3.3
30.6	0.300	0.31 ± 0.01	3.3
32.3	0.300	0.31 ± 0.00	3.3
33.9	0.300	0.31 ± 0.01	3.3

Discussion

The results obtained in the tests were checked with some calibrated instruments designed to measure individually parameters as kVp, electrical current (direct measurement with adequate probes and voltage dividers in the generator high voltage circuit), exposure time, HVL (conventional method – Trout *et al.*, 1960) and dose. They were verified in good agreement with the individual results from those instruments, hence confirming the efficacy of the sensor used in this work for purposes of analyzing the X-ray tube beam.

We think one advantage of the proposed methodology is the possibility of recording and storage of a lot of information. The possibility of storage of the sensor output signal in order to perform the signal post-treatment by computer is also an advantage relative to other available devices, since it could be analyzed later. Besides, the information storage is always an important request for quality assurance programs, since it allows knowing better the equipment performance during its useful life.

During the procedures, the operator is required only for fitting the support device under the tube and proceeding the exposures. Then, the system allows determining automatically the different parameters under investigation, at any moment, since these data are already recorded into the notebook memory.

As the measurement tests were performed with the mammography unit previously mentioned, with a Mo target in the tube (and Mo filter), obviously the results are valid for this type of anode material. All the measurements were also performed by following a methodology which considers the practice measurement with the sensor placed as indicated in this work. Anyway, as the information obtained are based in relational results, that is, by the ratio between a filtered and a reference signal, additional filters only will produce a – proportional – decrease on both amplitudes, keeping the ratio between them.

This instrument is able to provide some advantages relatively to other commercial devices, as the penetrameters using radiographic films. For operating such instruments the user generally needs to know some techniques requested to the tests procedure, as well as to use an electronic device, such as a microdensitometer, in order to identify accurately the "match step" – or its equivalent (Ardran and Crooks, 1968). Nevertheless, the error range of a conventional penetrameter-type instrument can be as high as 25% (Vieira *et al.*, 1999), far from the requirements for mammography tubes. In this present proposal, the result can be provided directly by the software.

The determination of tube current is possible from the data recorded during the tests. This is also true even for systems displaying only the current-time (mAs) integrated control, very common in some mammography units, due to the knowledge of the radiographic system timer behavior (provided by the software by means the evaluation of the sensor output signal).

The possibility of viewing the sensor output signal is very important since such a signal has the same format of that applied by the high voltage generator to the tube electrodes. Thus, any problem in the generator voltage – which could not be detected or recognized in a first moment by image analysis – can be easily determined with this device. Development tests carried out in a hospital with a conventional X-ray equipment have casually shown this kind of problem with the generator, which had provided the correct voltage during half of the exposure time but, in the second half, the voltage amplitude decreased to about ½ of the original value. In practice, this means that the total radiation in such equipment was indeed about 25% to 30% less than that necessary to yield images with adequate contrast. And such problem could not be detected with accuracy by conventional methods of operational parameters measurements, mainly those using film for the evaluations.

The reproducibility of measurements was also verified as good, as shown the results presented in Tables 5 and 6 for example. These Tables have indicated consistency in the repeatability of measurements, even compared to results registered by the instrument used as reference. The same can be derived from analysis of results shown in previous Tables, mainly regarding the kVp measurements.

Furthermore, the signal acquisition device corresponds to a new and more practical methodology for measuring the half-value layer, since there are no need of using dosimeters, ionization chambers, neither the sequence of aluminum filters replacements, as needed in the conventional method (Trout *et al*., 1960; Vieira *et al*., 1999). Also the device with the aluminum wedge made more practical the HVL determination in any field location. This late characteristic, indeed, is an important difference when comparing this device to previous developed, including that proposed by Onusic *et al*. (2007), which is designed to measure the HVL from only one X-ray exposure by a device using a transducer with sensors based on photoluminescence of an anthracene scintillator. As with such a device, our system provides also the HVL measurement from only one exposure; however the simulation method implemented in the treatment software of our system provides additionally to identify the HVL values of interest in any field location from the procedures described in section 2. The replacement of the aluminum by copper could also allow determining the HVL for higher energies ranges. And, as the sensor is sensitive to the total amount of X-rays photons impinging it, the system can work also as a dosimeter.

In comparison to other types of instruments designed to evaluate mammography systems similarly to this one, the cost is another feature to be considered. As previously mentioned, costs of instruments like, for example, Barracuda® – used as reference during some of the tests – are usually unaffordable (about US$ 12,000) for many quality assurance programs in mammography units. On the other hand, the expectation on this system development cost should be less than half of that importance, which could allow its use by the most radiological centers.

Conclusions

The developed system is capable to evaluate the main operational parameters which are basis for the mammographic imaging. The possibility of obtaining a large amount of information during the measurement procedure, as well as the possibility of storage such information in a compact way is an important advantage compared to other instruments with similar purposes.

As one of the most important problems for effectiveness of mammography quality assurance programs in Brazil is the lack of accurate and efficient devices, the development of such kind of instrumentation at lower cost relatively to the imported ones should be of great interest. Some devices have been developed recently; however the main emphasis has been in terms of academic research and aiming usually the determination of one single parameter – commonly kVp, the most important operational factor affecting the X-ray beam quality. Therefore, from the point of view of the results and the technical composition, the proposed device can be considered suitable to the practice in operational parameters investigation for quality assurance programs in the routine of mammography units. Although at the present moment we cannot estimate exactly the final cost of a industrialized version of our prototype, we do believe that its cost-benefit ratio will be very encouraging so that most mammography facilities will interested of acquiring and using it.

Also, another reason for the conclusion above is that the simplicity of the output data provided by the developed software can make it of easy use in any program of mammography systems quality evaluation.

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