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GENERAL AND APPLIED PHYSICS

The Application of Pyroelectric Sensors in the Measurementof X-Ray Intensity and Ultrasonic Transducer Output Power: a Review

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Abstract
The biological effects of the signals produced by X-ray and ultrasound equipment strongly depend on their intensity. Some articles were published addressing the use of pyroelectric sensors to measure the intensity of X-rays and ultrasonic transducer output power. The objective of this work was to carry out a literature review addressing the use of pyroelectric sensors to measure the intensity of X-rays and the acoustic power generated by ultrasound transducers. For the development of the review, a methodology with the guidelines of the Preferred Items for Systematic Review Reports and Meta-analysis (PRISMA) was used. After the searches, 11 papers were selected for analysis, 8 referring to X-ray and 3 to ultrasound. In most research, the response of the pyroelectric sensor was linear with the intensity of the radiation.

Keywords Pyroelectric · Sensors · Detectors · Diagnostic · Therapy · Ultrasound

1 Introduction

Monitoring the power or intensity of the signal produced by medical diagnostic and therapy equipment is important because if the signal level is not adequate, the patient's health can be harmed. Some of these equipment are X-ray or ultrasound emitters, and it is necessary to monitor the intensity of this emission in order to meet the necessary requirements for calibration and its protocols, and to guarantee the safety of procedures with patients.

Pyroelectric sensors have many applications, which include monitoring X-ray and ultrasound emissions in many different frequency ranges and intensities, including diagnostic and therapy equipment. These sensors have remarkable characteristics in their applications for measuring the intensity of electromagnetic radiation and acoustic signals, because they are sensitive to a large spectral range, from infrared to γ radiation, including electrons [1].

1.1 X-ray

About 2400 years ago, the Greek philosopher Theophrastus mentioned that a stone, called lyncurium (in Latin) had the property of attracting straw and pieces of wood. This was probably the first report on pyroelectricity.

The first in-depth theory of pyroelectricity was published by William Thomson (Lord Kelvin) in 1878.

Pyroelectricity is the property of some materials that presents an electric polarization when a temperature variation is applied uniformly.

Pyroelectric detectors have some relevant characteristics such as the following:

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- They respond to temperature variation;
- They have very short response times, as they do not need to reach thermal equilibrium;
- They respond almost instantaneously (10^{-7} s) to any variation in the radiation energy fluency rate;
- They are sensitive to a wide spectrum of radiation, from infrared to γ radiation, including electrons [1].

Ta in 1938 [2], for the first time, identified the actions of radiation using pyroelectric detectors, which was still done in the period between the two world wars and deserves to be highlighted in its precursory aspect.

The use of ferroelectric materials for remote thermometry and non-ionizing radiation dosimetry, such as infrared, gained ground in the research of Cooper in 1962 [3] and Ludlow in 1967 [4].

In 1964, Hester [5] used ferroelectric materials to measure ionizing radiation, γ Gamma ray pulses, using lead titanate and barium titanate zirconate sensors, the latter also studied by Kremenchugkii and Strakovskaya in 1976 [6].

In 1984, Paula et al. [7] implemented an instrument whose main component was a piezo-pyroelectric lead zirconate titanate (PZT) sensor to measure the intensity of the radiation produced by an X-ray equipment (Model MG150, Muller) with a tungsten target that could be operated in the 50–90 kV range. The total beam filtration was 2 mm Al. The irradiated area on the sensor was 1 cm^2. The beam was chopped with a lead sectored disk. The instrument presented a linear response with the radiation intensity.

Carvalho et al. in 1992 [8], described two thermal methods to measure the energy fluency of a brief exposure of diagnostic X-rays: the pyroelectric and the photoacoustic. In the pyroelectric, the electrical signal produced is due to the temperature variation that occurs when an X-ray pulse is totally absorbed by a pyroelectric sensor. The photoacoustic method is based on the expansion of the gas existing in a closed chamber, due to the absorption of X-rays by a lead disc, located inside the chamber. The increase in gas pressure is transmitted, through a 1 mm duct, to a highly sensitive microphone. To measure the energy fluency of a radiation pulse, there is no need to use a chopper or a lock-in amplifier, resulting in robust and low-cost instruments.

Also in 1992, Carvalho and Mascarenhas [9] compared the characteristics of a photoacoustic and a pyroelectric instrument to measuring the intensity of X-rays, in the diagnostic range from 50 to 90 kVp. The instruments were also used to measure the energy fluency of an X-ray pulse.

In 1997, Carvalho and Alter [10] proposed a pyroelectric detector implemented with a ceramic of a PZT disk (model PKI 502, Piezo Kinetics Inc.), 15 mm diameter and 1 mm thick. A Philips MG-323 constant potential generator was used. The tube potential was varied in the range of 50 to 150 kVp (equivalent photon energy between 29 and 45 keV) with currents in the range of 25 to 150 mA. This equipment could provide pulses with exposure times of 0.1 to 6 s. The response of the pyroelectric detector is linear with the intensity (energy fluence rate) in the photon energy range of 29 to 45 keV, and exposure times of 0.1 to 6 s. The minimum intensity that the system can measure is 71 mW/m^2, considering a signal to noise ratio of 5.

Carvalho et al. in 2004 [11] and 2005 [12], described detector systems that measured X-ray intensity in the mammography range (X-ray equipment tube voltage in the range of 22 to 36 kVp and equivalent photon energy from 11 to 15 keV). The system consists of a lithium niobate sensor and a highly sensitive current-to-voltage converter. In the paper published in 2004, a 10-mm-diameter and 1-mm-thick lithium niobate sensor manufactured by Inrad International (USA) was used. In the paper published in 2005, lithium niobate and lithium tantalate sensors were used. The main component of the current-to-voltage converter was the OPA 111 operational amplifier. The instrument's response was linear with the intensity of radiation produced by a mammography equipment whose tube voltage could be varied in the range of 22 to 36 kVp. The experimental results showed that there was negligible variation in the piezoelectric constant d_{33} and in the pyroelectric coefficient even after the sensors had received high doses of radiation ($3.6\times10^{-2}Ckg^{-1}$ air). The instrument has features that make it capable of monitoring radiation from mammography devices. It also has the potential to allow measurement of the X-ray energy imparted to patients who have undergone mammography screening.

Pontes [13] and Pontes et al. [14] implemented a pyroelectric instrument to measure the energy fluence rate of X-ray energy in the orthovoltage range of 120 to 300 kV (corresponding to the effective photon energy between 34.7 and 178.2 keV). Its response was non-linear with radiation intensity. The minimum energy fluence rate that this equipment could measure was 0.95 W/m^2 considering a minimum signal-to-noise ratio of 5. The instrument's precision is better than 3%.

Sakamoto et al. [15] used a ferroelectric composite material consisting of modified lead titanate (PZ34) and polyether-ether-ketone (PEEK) polymer matrix to measure the intensity of X radiation in the orthovoltage range. An X-ray equipment (Siemens Stabilipan II) was used, in which the tube potential can be varied in the range of 120 to 300 kVp. The instrument directly measured the X-radiation intensity in the orthovoltage range. The pyroelectric sensor response was non-linear in the range of 120 to 180 kVp and linear in the range of 180 to 300 kVp. The results showed that there was no degradation of the material after the irradiation of the sensor. The d_{33} pyroelectric coefficient remained unchanged after the sensor received a high exposure (0.2 C/kg) of radiation.

1.2 Ultrasound

In 2007, Zeqiri et al. [16] described a new method to monitor the output power of signals produced by medical ultrasound equipment using the pyroelectric properties of a transducer implemented with a thin PVDF (polyvinylidene fluoride) membrane and a backing consisting of a thick layer of polyurethane rubber that attenuates extremely the ultrasound. The variations in pyroelectric voltage generated by the on–off switching of the transducer are related to the acoustic power produced by the ultrasound transducer. An experimental evaluation of the new measurement technique was carried out, covering the frequency range from 1 to 5 MHz and output power of up to 1 W.

In 2008, Zeqiri and Barrie [17] described a new method to determine the acoustic power generated by physiotherapy ultrasound transducers. It uses the pyroelectric effect generated within a thin layer of PVDF that is backed by a thick layer of polyurethane. When the transducer is switched, the ultrasound energy is absorbed over a short distance into the backing material, leading to a rapid increase in temperature near the membrane-absorber interface. This heating leads to the generation of electrical charge through the electrodes of the PVDF pyroelectric sensor, and an electrical signal is generated whose characteristics are related to the power level of the ultrasound provided by the transducer. The experimental results showed that the device responds to the power of the ultrasound at frequencies of 1 and 3 MHz.

Zeqiri et al. in 2011 [18], described the progress made in the technique of measuring the power of the ultrasound signal that they reported in previous studies. In this work, they describe a pyroelectric sensor built with a PVDF pyroelectric membrane and a thick backing of polyurethane rubber material. The studies carried out showed the relevance of the properties of the pyroelectric membrane and the backing in the sensor response. With the aid of a 3.5-MHz NPL Pulsed Checksource focused transducer, the high sensitivity of the technique was demonstrated. Using the method, it was possible to implement instruments that can measure the ultrasound power, at mW levels, generated by medical diagnostic equipment.

It is important to mention that in the works by Zeqire et al. the measurements of power generated by ultrasound transducers were performed with pyroelectric sensors, therefore based on the pyroelectric effect.

1.3 Objectives

The main objective of this research was to carry out a literature review on the application of pyroelectric sensors to measure the intensity of X-ray and the output power of medical ultrasound transducers. Information was extracted on the applications of pyroelectric sensors, their characteristics, among other specificities, that include their use within the aforementioned areas.

1.4 Text structure

The next section will address the methodology used in this research. Afterwards, the results will be presented, followed by the discussion section. And finally, the conclusion.

2 Methods

2.1 Search strategy

For the development of this review, the methodology was used through the guidelines of the Preferred Items for Systematic Review Reports and Meta-analysis (PRISMA) [19, 20]. The search took place through terms related to the use of pyroelectric sensors in detecting the radiation level of equipment with applications in medical therapy and diagnostics. The search in the databases used the keywords with their general terms, and search by title and abstract.

The terms used were the following: (detectors AND pyroelectric AND diagnostic) OR (sensors AND pyroelectric AND diagnostic) OR (sensors AND pyroelectric AND therapy) OR (detectors AND pyroelectric AND therapy).

The databases searched were PubMed, IEEE Xplore, Web of Science, and Scopus. Studies that contained books, systematic reviews, posters, abstracts, comments, and conferences were excluded. Articles in the English language were considered. The filter by title and abstract were used. In order to search for additional articles that met the eligibility criteria, works from other sources were searched.

2.2 Inclusion and exclusion criteria

The chosen inclusion criteria were the following: contains the use of pyroelectric sensors to measure the intensities of X-ray and ultrasound produced by medical equipment.

The Mendeley program was used as a tool to manage references and eliminate duplicates.

The exclusion criteria were the following: the non-use of sensors in the health area and use of sensors to measure biological/physiological signals, in the measurement of some environmental magnitude, among other sensor applications that do not meet the inclusion criteria.

The analyzes by titles and abstracts were evaluated regarding the inclusion and exclusion criteria by the authors A.H.M. Costa, C.P. Silva, and E.A. Santos. The readings of the remaining articles, in full, were carried out by the authors A.A. Carvalho, A.H.M. Costa, C.P. Silva, and E.A. Santos.

3 Results

3.1 Study selection

The search criteria identified 172 works, with 6 articles found in other sources. Duplicate articles were removed, leaving 107 for analysis by titles and abstracts. All authors agreed with the exclusion and inclusion of articles. In Fig. 1, the article selection process and the reasons for exclusion in the full-text analysis step are presented.

After selection, 42 articles remained to be analyzed in full.

3.2 Analysis of studies

After the searches, 11 articles met the inclusion criteria and were selected for analysis, 8 of which related to X-ray and 3 to ultrasound.

As for the period of publication, according to the data found, the oldest study dates from 1984 and the most recent was published in 2012. The most used pyroelectric sensors were PZT, cited by 4 studies, and PVDF, cited by 3 studies. Lithium niobate, lithium tantalate, iron-doped PZT, and composite PZ34-PEEK were also used as pyroelectric sensors (Table 1).

Pyroelectric sensors were used in 6 studies for measuring radiation intensity in diagnostic X-ray equipment (22 to 120 kVp) and in 2 studies in therapy X-ray equipment (120 to 300 kVp). They were used in 3 studies for determining the acoustic power generated by medical ultrasound transducers. The grid for extracting information from the selected articles was summarized in Table 1.

4 Discussion

According to the results obtained and considering the variety of information, it was possible to establish a theoretical dialogue comparable to the literature.

Carvalho et al. [8, 9] presented setups and equipment capable of interacting with the most varied ranges of energy. Innovative instruments were implemented using pyroelectric sensors made up of various types of materials such as PZT, PVDF, lithium tantalate, lithium niobate, iron-doped PZT, and PZ34-PEEK composite. The shielding of the conditioning circuits was an important milestone in the development of the equipment and contributed to the efficiency of the repeatability found in the capture of signals.

Another important aspect studied was the radiation intensity range, which over the years has been addressed by several authors, from non-ionizing radiation, such as infrared,

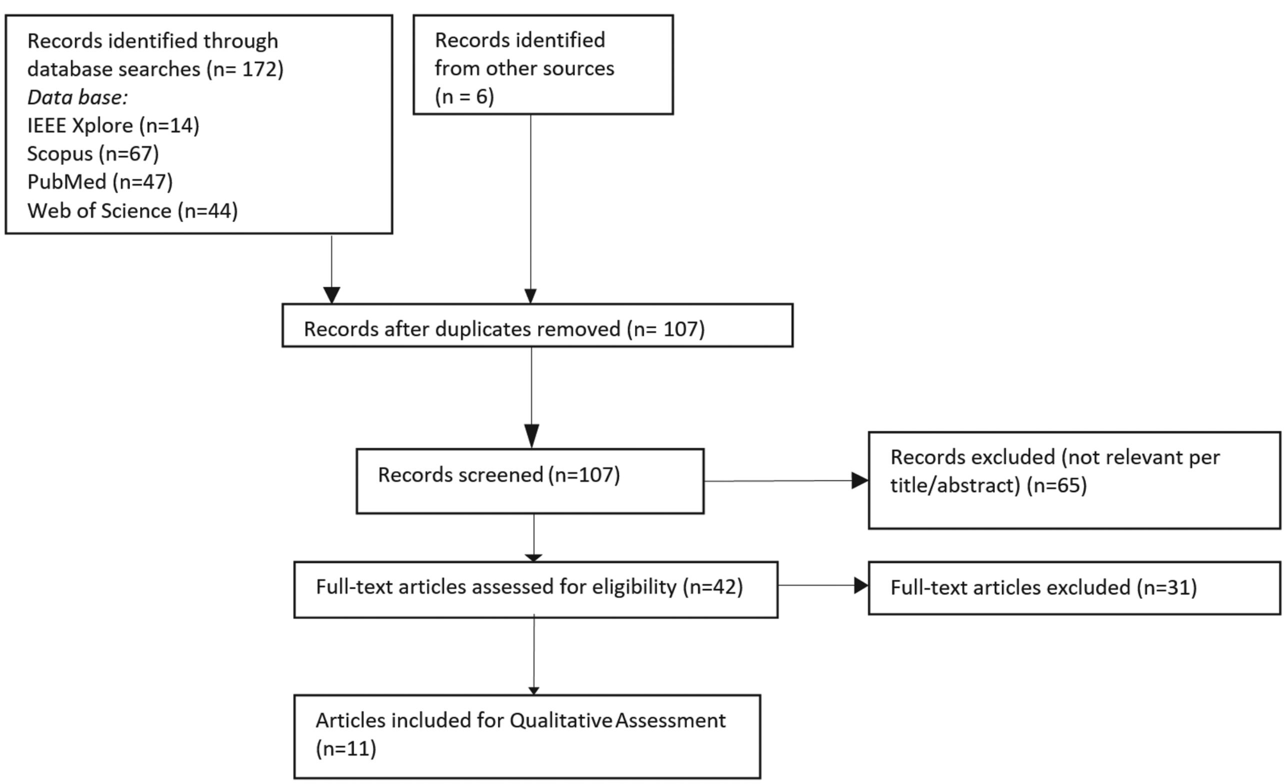

Fig. 1 Flowchart of the article selection process

Table 1 The grid for extracting information

Author	Year	Title	Objective	Diagnóstic/therapy	X-ray ultrasound	Range (kVp)	Sensor	Conclusion
M. H. de Paula, A. A. Carvalho, S. Mascarenhas, and R. L. Zimmerman	1984	A new radiation dosimeter using a pyroelectric detector	Implementation of a new type of radiation dosimeter for the diagnostic X-ray region using a pyroelectric detector	Diagnostic	X-ray	50 to 90	PZT	The pyroelectric instrument presented the following main characteristics: (a) linear response with radiation intensity in the medical diagnosis range; (b) inverse response with frequency on the chopping frequency from of 2 to 50 Hz; (c) it is simple to build, robust, and inexpensive
A. A. de Carvalho e S. Mascarenhas	1992	Piezo and pyroelectric radiation dosimetry	Compare the characteristics of the photoacoustic radiation dosimeter and the pyroelectric radiation dosimeter	Diagnostic	X-ray	50 to 90	PZT	The characteristics of a photoacoustic and a pyroelectric instrument in measuring the intensity of X-rays, in the diagnostic range from 50 to 90 kVp, were compared. The instruments were also used to measure the energy fluency of an X-ray pulse
A. A. Carvalho, S. Mascarenhas, M. H. de Paula, and J. R. Cameron	1992	Two thermal methods to measure the energy fluence of a brief exposure of diagnostic X-rays	Describe two thermal methods for measuring the energy fluence of a diagnostic X-ray exposure using a PZT pyroelectric sensor	Diagnostic	X-ray	50 to 90	PZT	The instruments described can measure the energy fluency of an X-ray pulse, an important parameter in some patient diagnostic procedures. The experiments were carried out with only one exposure time. Both instruments are robust and cost effective. The signal-to-noise ratio of the pyroelectric was 20 times greater than that of the photoacoustic instrument. Using any of the instruments and measuring the area of the radiation beam, the energy transferred to the patient can be determined
Aparecido A. de Carvalho and Albert J. Alter	1997	Measurement of X-ray intensity in the medical diagnostic angle by a ferroelectric detector	Describe a pyroelectric detector for measuring the energy fluence rate (intensity) of X-ray pulses	Diagnostic	X-ray	50 to140	PZT	The response of the pyroelectric detector is linear with the intensity (energy fluence rate) in the photon energy range of 29 to 45 keV, and exposure times of 0.1 to 6 s. The minimum intensity of the system can measure is 71 mW/m^2, considering a signal noise ratio of 5
A.A. de Carvalho, A.L. Brassalotti, M.H. de Paula and A.J. Alter	2004	Use of lithium niobate detector for measuring X-ray intensity in mammographic range	Implementation of a radiation dosimeter with a lithium niobate detector that can measure X-ray intensity in the mammographic range	Diagnostic	X-ray	22 to 36	Lithium niobate	A lithium niobate sensor and a current-to-voltage converter have been used successfully to measure X-ray intensity in the mammography range. The detector system showed a linear response in the photons equivalent energy range from 11 to 15 keV and with exposure times. From 0.6 to 2.3 s. Measurement accuracy was greater than 99%

Table 1 (continued)

Author	Year	Title	Objective	Diagnóstic/therapy	X-ray ultrasound	Range (kVp)	Sensor	Conclusion
M. H. de Paula, A.A. de Carvalho, A.L. Brassalotti, A.J. Alter, W. K. Sakamoto, J.A. Malmonge, A. de Almeida	2005	Microcontrolled pyroelectric instrument for measuring X-ray intensity in mammography	Implementation of a new instrument with a pyrolectric detector, a high-sensitivity current-to-voltage converter, a microcontroller and a digital display for measuring the X-ray intensity	Diagnostic	X-ray	22 to 36	Lithium niobate and lithium tantalate	The instrument's response is linear with the intensity of radiation produced by a mammography equipment whose tube voltage could be varied in the range of 22 to 36 kVp (corresponding to equivalent photons of energies of the beam between 11 and 15 keV). The experimental results showed that there was negligible variation in the piezoelectric constant d_{33} and in the pyroelectric coefficients even after the sensors had received high doses of radiation (3.6×10^{-2} Ckg^{-1} air). The instrument has features that make it capable of monitoring radiation from mammography devices. It also has the potential to allow measurement of the X-ray energy imparted to patients who have undergone mammography screening
W. Pontes, A. A. de Carvalho, W. K. Sakamoto, M. H. de Paula, M. A. A. Sanches, R. L. B. de Freitas, R. Borges, P. César and S. L. Piubéli	2010	PZT for measuring energy fluence rate of X-ray used in superficial cancer therapy	Implementation of a new, simple instrument with a PZT pyroelectric sensor that can measurer X-ray intensities in the orthovoltage range of 120 to 300 kV	Therapy	X-ray	120 to 300	Iron-doped PZT	The instrument directly measured the X-radiation intensity in the orthovoltage range. The pyroelectric sensor response was non-linear in the range of 120 to 180 kVp and linear in the range of 180 to 300 kVp. The results showed that there was no degradation of the material after the sensor after the irradiation of the sensor. The d_{33} pyroelectric coefficient remained unchanged after the sensor received a high exposure (0.2 C/kg) of radiation
W. K. Sakamoto, G. P. Estevam, A. A. de Carvalho, W. Pontes, M. H. de Paula	2012	Pyroelectric composite film for X-ray intensity detection	Implementation of an instrument with a pyroelectric composite for measuring X-ray intensities in the orthovoltage range	Therapy	X-ray	120 to 300	Composite PZ34-PEEK	A new instrument using a pyroelectric compound made with Pz34 ceramic and a PEEK polymer matrix was described as an alternative system to an expensive ionization chamber for dosimetry. The instrument measures X-rays intensity in the orthovoltage range directly and can accurately monitor the application of radiation therapy dose. The sensing element response was not linear with the radiation intensity between 120 to 180 kVp. A linear relationship can be observed from 180 to 300 kVp. Experimental results show that no degradation was observed in the composite material after irradiation

Table 1 (continued)

Author	Year	Title	Objective	Diagnóstic/therapy	X-ray ultrasound	Range (kVp)	Sensor	Conclusion
B. Zeqire, P. N. Gélat, J. Barrie, C. J. Bickley	2007	A novel pyroelectric method of determining ultrasonic transducer output power: device concept, modeling, and preliminary studies	Describes a new thermally based method of monitoring acoustic power generated by ultrasonic transducers	Therapy	Ultrasound	–	PVDF	A new technique for monitoring the output power of signals produced by medical ultrasound equipment using a pyroelectric sensor has been described. An experimental evaluation of the new measurement technique was carried out, covering the frequency range from 1 to 5 MHz and output power of up to 1 W
B. Zeqire, J. Barrie	2008	Evaluation of a novel solid-state method for determining the acoustic power generated by physiotherapy ultrasound transducers S	Evaluation of a thermal method for measuring the acoustic power generated by ultrasound transducers	Therapy	Ultrasound	–	PVDF	The experimental results showed that the device responds to the power of the ultrasound in the frequency range used in physical therapy
B. Zeqire, G. Zauhar, M. Hodnett, J. Barrie	2011	Progress in developing a thermal method for measuring the output power of medical ultrasound transducers that exploits the pyroelectric effect	Describe the progress in developing a new method for measuring the acoustic power generated by ultrasound transducers using pyroelectric sensors	Therapy	Ultrasound	–	PVDF	This article describes a new method that can determine ultrasound power. Using the method, it is possible to implement instruments that can measure the ultrasound power, at mW levels, generated by medical diagnostic equipment. Conceptual proof was also demonstrated, for a point detector configuration, of a pyroelectric sensor that responds to the ultrasound power

to γ-ray ionizing radiation, in particular, X radiation due to its usefulness in medical diagnoses and also in therapeutic treatment [21].

The use of pyroelectric sensors to detect ionizing radiation both in the diagnostic range, from 20 to 120 kVp, and in the therapy range, from 120 to 300 kVp, has proven the effectiveness of this method with the most diverse types of sensors, from ceramics (lead titanate zirconate (PZT)) to composites (titanate (PZ34) and poly (ether-ether-ketone) (PEEK)). The latter were capable of being subjected to tension and traction and even so, they did not show degradation after applications in the orthovoltage range [15].

Another important contribution over the years was the development of the signal conditioning circuit, which showed excellent response when using a current to voltage converter associated with operational amplifiers with high CMRR (common-mode rejection ratio), high input impedance, low output impedance, and excellent signal-to-noise ratio [22].

The importance and definition of the signal conditioning circuit depends on the tube voltage range of the equipment to be analyzed. Both in diagnosis and in therapy there is a need for analysis and shielding of the conditioning circuit as the tube voltage increased, this shielding of the conditioning circuit with lead and/or alloy was necessary, so that the readings obtained could be repeatable and accuracy after the signal acquisition setups are defined (Pontes et al. [14]).

As for the assembly of the cameras that were able to capture the radiation intensity in the different ranges, it also showed evolution. Initially, the apparatus had a large amount of iron, copper, and even aluminum to reduce the weight of the systems. Later, the use of acrylic was incorporated to avoid scattered radiation and only the contact terminals between sensors and the conditioning circuit were made of conductive material, usually copper [23].

Few articles were published addressing the use of pyroelectric sensors to measure the acoustic power generated by ultrasound transducers: only 3 published by the same research group. The studies have revealed that the device sensitivity varies with temperature, and that the physical properties of the PVDF membrane and backing strongly influence sensitivity.

5 Conclusion

This review was important to establish a historical context in the application of pyroelectric sensors in measuring the intensity of X-ray and the output power of medical ultrasound transducers. Equipment emitting X-ray and ultrasound require calibration to ensure safety in the procedures for therapy and diagnosis.

For the development of this review, the methodology used helped to organize the searches in the research platforms. After applying the inclusion and exclusion criteria, 11 papers were selected for this review, 8 related to X-ray, and 3 related to ultrasound.

All these papers described research that aimed to determine the intensity of X-ray or the output power of medical ultrasound transducers. The results found were of fundamental importance to know the profile of the studies that have been published over the last decades.

The implemented instruments can measure the radiation intensity in the mamographic, medical diagnostic, and in the orthovoltage ranges. In most researches, the response of the pyroelectric detector was linear with the intensity of the radiation.

The experimental results showed that there was no degradation of the ceramic and the pyroelectric composite after irradiation of the material. The pyroelectric coefficient and the d_{33} coefficient remained the same after the sensors were subjected to radiation.

The experimental results obtained by Zeqiri et al. showed that a pyroelectric sensor implemented with a thin PVDF membrane and a backing consisted of a thick layer of polyurethane rubber that attenuates extremely the ultrasound, responds to the acoustic power generated by ultrasound transducers in the frequency range used in physical therapy.

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Declarations

Ethics approval I understand that my manuscript and associated personal data will be shared with Research Square for the delivery of the author dashboard. The authors know and adhere to the ethical responsibilities when submitting the manuscript.

Consent for publication This manuscript has not been sent anywhere else.

Conflict of interest All authors declare that they have no conflict of interest.

References

1. A.S. Beddar, P.D. Higgins, Use of ferroelectric-crystal detectors for electron dosimetry. IEEE Trans. Ultrason. Ferroelectr. Freq. Control New York **37**(1), 26–29 (1990)
2. Y. Ta, Action of radiations on pyroelectric crystals. Compt. Rend. Paris **207**(1), 1042–1044 (1938)
3. J. Cooper, A Fast response pyroelectric thermal detector. J .Sci. Instrum. London **39**(23), 467–472 (1962)
4. J.H. Ludlow, W.H. Mitchell, E.H. Putley, N. Shaw, Infra-red radiation detection by the pyroelectric effect. J. Sci. Instrum. Bristol **44**(9), 694–696 (1967)

5. D.L. Hester, D.D. Glower, L.J. Overton, Use of ferroelectrics for gamma-ray dosimetry. IEEE Trans. Nuc. Sci. New York **NS-11**(5), 145–154 (1964)
6. L.S. Kremenchugskii, R.Y. Strakovskaya, Using pyroelectric detectors for the dosimetry of pulsed g radiation. Instrum. Exp. Tech. New York **1**(3), 190–194 (1976)
7. M.H. Paula, A.A. Carvalho, S. Mascarenhas, R.L. Zimmerman, A new radiation dosimeter using a pyroelectric detector. Med. Phys. Maryland **11**(6), 866–868 (1984)
8. A.A. Carvalho, S. Mascarenhas, M.H. dePaula, J.R. Cameron, Two thermal methods to measure the energy fluence of a brief exposure of diagnostic x rays. Med. Phys. **19**(3), 575–578 (1992). https://doi.org/10.1118/1.596912
9. A.A. de Carvalho, S. Mascarenhas, Piezo and pyroelectric radiation dosimetry. IEEE Trans. Electr. Insul. **27**(4), 835–842 (1992). Disponível em: http://hdl.handle.net/11449/64254
10. A.A. De Carvalho, A.J. Alter, Measurement of x-ray intensity in the medical diagnostic range by a ferroelectric detector. IEEE Trans. Ultrason. Ferroelectr. Freq. Control **44**(6), 1198–1203 (1997). https://doi.org/10.1109/58.656620
11. A.A. de Carvalho, A.L. Brassalotti, M.H. de Paula, A.J. Alter, Use of lithium niobate detector for measuring X-ray intensity in mammographic range. Electr. Lett. Hertford IEE Inst. Elec. Eng. **40**(18), 1097–1098 (2004). Disponível em: <http://hdl.handle.net/11449/9653>
12. M.H. de Paula, A.A. de Carvalho, A.L. Brassalotti, A.J. Alter, W.K. Sakamoto, J.A. Malmonge, A. de Almeida, Microcontrolled pyro-electric instrument for measuring X-ray intensity in mammography. Med. Biol. Eng. Comput. **43**(6), 751–755 (2005). https://doi.org/10.1007/BF02430953
13. W. Pontes, Implementação de um sistema detector piroelétrico para medição de intensidade de radiação x na faixa de ortovoltagem. Dissertação (Mestrado)- Faculdade de Engenharia (Universidade Estadual Paulista- UNESP, Campus de Ilha Solteira, 2006)
14. W. Pontes, A.A. de Carvalho, W.K. Sakamoto, M.H. de Paula, M.A.A. Sanches, R.L.B. de Freitas, R.B.P. César, S.L. Poubeli, PZT for measuring energy fluence rate of X-ray used in superficial cancer therapy. Instrum. Sci. Technol. **38**(3), 210–219 (2010). https://doi.org/10.1080/10739141003707675
15. W.K. Sakamoto, G.P. Estevam, A.A. Carvalho, W. Pontes, P.M.H. De, Pyroelectric composite film for x-ray intensity detection. Mater. Res. Ibero Am. J. Mater. **15**, 198–203 (2012)
16. B. Zeqiri, P.N. G´elat, J. Barrie, C.J. Bickley, A novel pyroelectric method of determining ultrasonic transducer output power: deviceconcept, modeling, and preliminary studies. IEEE Trans. Ultrason. Ferroelectrics Freq. Control **54**(11), (2007)
17. B. Zeqiri, J. Barrie, Evaluation of a novel solid-state method for determining the acoustic power generated by physiotherapy ultrasound transducers. Ultrasound in Med. & Biol. **34**(9), 1513–1527 (2008)
18. B. Zeqiri, G. Zauhar, M. Hodnet, J. Barrie, Progress in developing a thermal method for measuring the output power of medical ultrasound transducers that exploits the pyroelectric effect. Ultrasonics **51**, 420–424 (2011)
19. A. Liberati, D.G. Altman, J. Tetzlaff, C. Mulrow, P.C. Gotzsche, J.P.A. Ioannidis, M. Clarke, P.J. Devereaux, J. Kleijnen, D. Moher, The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. J. Clin. Epidemiol. **62**(10), (2009)
20. D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med. **6**(7), (2009)
21. W.K. Sakamoto, R.T. Higuti, A.A. Carvalho, G.P. Estevam, W. Pontes, M.H. de Paula, Piezo and pyroelectric composite film for acoustic emission and x-ray radiation intensity detection, in *Piezoelectric Materials: Structure, Properties and Applications, vol.1*. ed. by W.G. Nelson (Nova Science Publishers, Inc., Hauppauge - NY, 2010), pp. 133–147
22. S. Franco, *Design with operational amplifiers and analog integrated circuits*, 2nd ed. (WCB-McGraw-Hill, USA, 1998), pp. 100–125
23. W. Pontes, Implementação de um sistema eletrônico para medir taxa de fluência de energia de radiação na faixa de radioterapia com sensor piroelétrico 2011 91 f Tese (doutorado), (Universidade Estadual Paulista Faculdade de Engenharia de Ilha Solteira 2011)