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Material characteristics test for electromedical prototype using radiographic image analysis

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Abstract: *The research conducted is the development of a phantom used for testing materials commonly used for electromedical prototypes. The research method used is Research and Development (RnD). Phantoms are made from acrylic and use Nylon, Iron, Stainless Steel, Galvanized, Aluminum, and Acrylic materials, as well as Medium Density Fiberboard (MDF). The phantom is then tested with a radiography system and exposed to voltage variations of 60 kV, 70 kV, and 80 kV. The best image results are when using a voltage of 80 kV. The results obtained, the image can distinguish materials with high and low absorption coefficients. Materials with high absorption coefficients such as Iron, Stainless Steel, Galvanized and Aluminum are good when used for electromedical prototypes that require movement in their working methods.*

Keywords: radiographic image; material analysis; material absorption coefficient

INTRODUCTION

The development of electromedical technology has begun to be widely implemented in Indonesia in line with the acceleration of the use of domestic medical devices. The development of medical devices, in terms of type and quantity, is widely pursued by the medical device industry. The Indonesian government encourages health facilities to purchase domestic medical devices. The government facilitates the medical device industry to improve the products and quality of medical devices (Muhamarwan, 2024). One of the regulations to protect the domestic medical device market is that the procurement must use domestic products with a Domestic Component Level (TKDN) of at least 25%. (Farmalkes, 2023). With this regulation, the medical device industry is required to maintain the quality of the medical device materials produced (Waluyo, 2024).

The medical device independence program encourages domestic industry players and researchers to innovate further. Various innovative products and research on health technology have been developed. Some products have even met the requirements and have been included in the health e-catalogue. Researchers are also conducting basic research using mechatronics technology for medical device applications (Artanto et al., 2023; Noviyanto et

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al., 2021; Siswoyo & Pranowo, 2022). Domestic medical device product innovation needs to be supported by the quality of the materials used.

Radiological techniques have developed into a non-destructive testing method that is widely used in material quality testing (Lopez et al., 2018). Digital X-ray radiography has been used for testing various applications in industry such as aluminium weld joint evaluation (Saravanan et al., 2014), non-destructive testing for pearl oysters (Susilo et al., 2018), electronics quality test (Azin et al., 2018; Michalska, 2021), and metal testing (Wardhani, 2019). In addition, it is also widely used in medical applications.

Other researchers have also conducted studies to characterize X-ray absorption in materials with the aim of testing the quality of materials, including measuring the quality of imaging systems (Louk & Suparta, 2014), measuring the quality of computer radiographic images with image processing (Ningtias et al., 2016), image processing to improve the quality of X-ray images with the filtering method (Wilianti & Agoes, 2019), and optimization of radiographic exposure factors for oyster shell testing (Susilo et al., 2018).

The imaging method with radiology is done by taking images inside the body or material using x-rays that can penetrate thick materials (Hussain et al., 2022). X-rays have special properties that make these rays useful for disease diagnosis. X-rays are electromagnetic waves that have a very short wavelength and are able to penetrate solid materials or masses with very high penetrating power such as bones and teeth because of their high energy. The digital x-ray radiography system has the advantage that its energy can be adjusted and its images can be recorded and stored on computer. In digital radiography, analog radiographic images are converted into digital images and then stored on a computer (Wilianti & Agoes, 2019).

The use of X-ray radiography in industry and medicine must be equipped with quality control procedures to ensure safety for operators. Quality control in radiology practice must be carried out frequently (Martin, 2007). This aims to ensure stable equipment performance, good image quality, low radiation dose, patient safety is maintained and operators work in a safe environment (López, 2018). There are three main aspects of quality control in radiography, namely instrument performance, radiation dose, and image quality (Setyowati et al., 2016).

The quality of radiographic images is influenced by several factors, starting from the acquisition process and the equipment used and how the image is displayed. The specifications of the equipment used in digital image data management vary depending on the application and needs of each facility. However, for all applications, the equipment used must provide image quality and availability that meets the needs of both clinical and product quality control (Krupinski et al., 2007).

Measurement using radiological techniques also faces various challenges. One of the main challenges is the optimization of the radiation dose used, considering that excessive radiation exposure can have negative impacts on health, especially for operators. In addition, the precision in interpreting imaging results is highly dependent on the quality of the images obtained and the capabilities of the imaging technology used. Image quality can be affected by several factors, including the resolution of the device, the type of radiation used, and the presence of artifacts in the image.

Thus, there is a need to develop a method for measuring objects using radiology that not only provides accurate results but also prioritizes user safety. This study aims to explore and optimize the radiological measurement method so that it can be widely applied in various fields, both medical and industrial. In this study, a quality inspection of materials that are widely used in electromedical technology will be carried out. So that it can be used as a reference for the efficiency of electromedical equipment production and the safety of material structures.

METHOD

This research is a type of Research and Development research to produce a product in the form of an X-ray radiography phantom using materials that are often used in making electromedical prototypes. This phantom will be used as an object for material quality inspection. The phantom will then be photographed with several kV variations to produce a radiological image. The stages carried out in this study adapt the ADDIE development model which consists of the stages of Analysis, Design, Development, Implementation and Evaluation (Ningtias et al., 2016).

The ADDIE model was chosen as the development framework because it has a systematic and structured approach that is appropriate to the phantom creation process. The ADDIE model allows for formative evaluation at each stage. So that the product design can be improved or adjusted before the final implementation stage so that it is appropriate in this study.

The research stages are carried out with the following steps:

1. Analysis

In the analysis stage, materials are analyzed to determine radiation absorption and scattering characteristics that are appropriate for radiological equipment. The materials used to make phantoms must be chemically and physically stable, and have affordable costs. In addition, the manufacture of phantoms must consider ease of use and easy to reproduce. Physical parameters such as absorption and image dimensions are important aspects for understanding the characteristics of materials in radiological images. For this application, various materials with certain thicknesses are used, such as Nylon, Iron, Stainless Steel, Galvanized, Aluminium, and Acrylic, as well as Medium Density Fibreboard (MDF). Nylon, Acrylic, and MDF are selected as low-density materials, while Iron, Galvanized, Alumunium and Stainless Steel are selected to illustrate high-density materials. The phantom is expected to produce images with varying densities. The results of this analysis are used to design the phantom in the next phase.

2. Design

Based on the material characteristics identified in the analysis, the phantom was designed with an acrylic base featuring eight holes to accommodate the selected materials. Small circles on the phantom are used for the materials used. There are three different types of circle diameters for dimension measurement. The finalized design is shown in Figure 1. The manufactured phantom was then subjected to X-ray testing, as outlined in the Development stage.

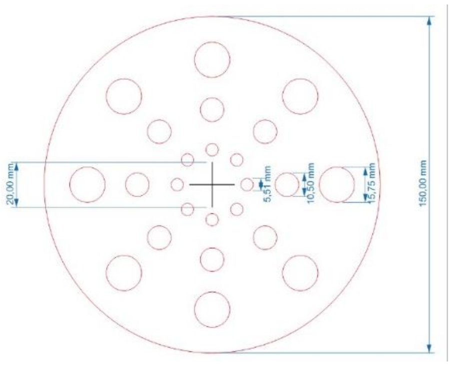


Figure 1. Radiographic Phantom Design with acrylic base and eight material slots, each with a different diameter for measuring material dimensions.

3. Development

Following the finalization of the design, the phantom was fabricated using the selected materials. The materials were cut to the specified diameters (as shown in Figure 1) using a Computer Numerical Control (CNC) machine for precision. The cut pieces were then assembled and affixed to the acrylic base. Subsequently, the fabricated phantom was radiographed using X-ray energy variations of 60 kV, 70 kV, and 80 kV to evaluate its performance under different exposure conditions.

4. Implementation

In this phase, the fabricated phantom was utilized to analyze key radiological parameters, including the radiation absorption coefficient, image contrast, and dimensional sharpness. The radiographic images acquired during the development phase were analyzed using ImageJ software. The analysis focused on measuring line profiles and optical density, which are crucial for quantifying how each material absorbs and scatters radiation.

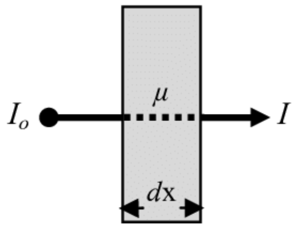


Figure 2. Illustration of x-ray intensity before and after penetrating a material, showing changes due to absorption and scattering.

The fundamental principle underlying this analysis is the attenuation of X-ray intensity upon penetrating a material. As illustrated in Figure 2, the transmitted intensity (I_2) is lower than the initial intensity (I_1). This decrease occurs due to interactions between the X-ray radiation and the atoms of the material, with different materials producing distinct transmission intensities (Mohammad & Ali, 2022). The relationship between the initial intensity (I_1), the transmission intensity (I_2) and the linear attenuation coefficient (μ) of the material is defined by the Lambert-Beer law, as expressed in Equation 1 (Oshina & Spigulis, 2021; Weiskerger et al., 2018).

$$I_2 = I_1 e^{-\mu t} \tag{1}$$

In this study, the attenuation properties of materials with different absorption coefficients were compared through quantitative analysis of the radiographic image intensities.

5. Evaluation

The quantitative data obtained from the implementation phase were subsequently evaluated to characterize the phantom's performance and the radiological properties of the constituent materials. This evaluation, performed using ImageJ software, consisted of a qualitative visual analysis and a quantitative contrast analysis based on line profile measurements.

Visual Analysis

A systematic qualitative assessment was conducted on all acquired radiographic images. This involved a visual inspection for artifacts, noise, and the structural integrity of the phantom. Using ImageJ's brightness/contrast adjustment tool (the 'B&C' function), the display range was manipulated to subjectively evaluate the visibility and differentiation of each material insert against the acrylic background at various window/level settings. This step provided an initial overview of image quality and the presence of any obvious imaging non-uniformities.

Contrast analysis

A rectangular selection tool was used to draw a line profile across the edge of each material insert in the phantom image. ImageJ's "Plot Profile" function was then employed to generate a graph of pixel intensity (optical density) versus distance. The results and a comprehensive discussion of these findings are presented in the Results and Discussion section.

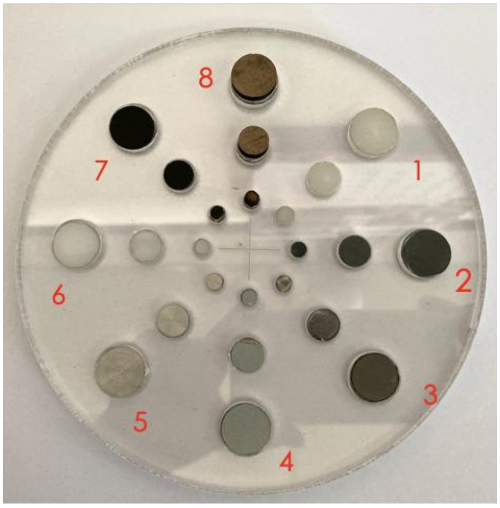
RESULTS AND DISCUSSION

In radiological measurements, each material has different radiation absorption characteristics based on its composition, density, and thickness. The absorption of radiation by this material will affect the quality of the image result, such as brightness and contrast, which then play a role in the clarity of objects in the image.

In radiological measurements, the absorption of radiation is a fundamental property that varies significantly with a material's atomic number, density, and thickness. This differential absorption is the cornerstone of image formation in radiography, as it directly influences the signal that reaches the detector, thereby determining the resultant image's brightness, contrast, and ultimately, the clarity of the objects within it (Liu et al., 2023). The following sections detail the implementation of our phantom-based testing and the evaluation of the results.

Implementation

To quantitatively assess these absorption characteristics, a custom phantom was developed. The phantom comprised a combination of materials commonly used in electromedical device prototyping, including metals (Aluminum, Iron, Stainless Steel, Galvanized Steel) and polymers/composites (Nylon, Acrylic, Medium Density Fiberboard (MDF)), as shown in Figure 3.



Materials used:
1. Nylon 5 mm
2. Iron 4 mm
3. Stainless stell mirror 4 mm
4. Galvanized 5 mm
5. Aluminium 5 mm
6. White acrylic 5 mm
7. Black acrylic 5 mm
8. MDF 9 mm

Figure 3. Phantom for material testing

Digital radiographic images were acquired using a standard digital radiography system, with exposures taken at tube voltages of 60 kV, 70 kV, and 80 kV. The images were saved in DICOM format to preserve data integrity before being converted to .jpg for subsequent analysis in ImageJ software. The resulting images are presented in Figure 4.

(a) (b) (c)

Figure 4. Phantom radiographic image results at tube voltage (a) 60 kV (b) 70 kV (c) 80 kV

The grayscale values from these images were extracted using ImageJ to create line profile plots, which provide a quantitative measure of radiation attenuation through changes in pixel intensity.

Evaluation

The evaluation of the phantom images was conducted through visual and quantitative contrast analysis to correlate image characteristics with material properties.

Visual Analysis

The linear attenuation coefficient (μ) quantifies a material's ability to absorb radiation energy. This coefficient is directly proportional to the material's density and effective atomic number (Langeveld, 2017). In radiographic imaging, this is visually represented by grayscale values; darker areas indicate low attenuation (more radiation reached the detector), while brighter areas indicate high attenuation (less radiation reached the detector) (Ludewig et al., 2023).

Our results (Figure 4) clearly demonstrate that digital radiography can effectively distinguish materials based on their attenuation coefficients. As supported by previous studies on material testing (Saravanan et al., 2014), polymeric materials like Nylon, Acrylic, and MDF appear darkest, confirming their low attenuation coefficients due to their low density and atomic number. Conversely, metals such as Iron, Stainless Steel, and Galvanized Steel appear brightest, indicating high attenuation coefficients, which aligns with their high density and atomic number (Jalal et al., 2021).

An interesting observation is the behavior of Aluminum. At lower energies (60 kV), its image is scarcely visible, but it becomes increasingly discernible at 70 kV and 80 kV. This phenomenon can be explained by the energy dependence of the attenuation coefficient. At lower kVp levels, the photoelectric effect dominates absorption, which is highly dependent on the atomic number (Z^3). As kVp increases, the Compton scatter becomes more dominant, which depends more on density than atomic number, making the contrast between low-Z and high-Z materials less pronounced but allowing mid-Z materials like aluminum to become more visible against the background (Als-Nielsen & McMorrow, 2011).

Contrast Analysis

For a detailed quantitative assessment, contrast analysis was performed on the 80 kV image, as it provided the best overall visualization of all materials. A line profile was plotted across all materials (Figure 5), measuring the grayscale value (pixel intensity) along a single line.

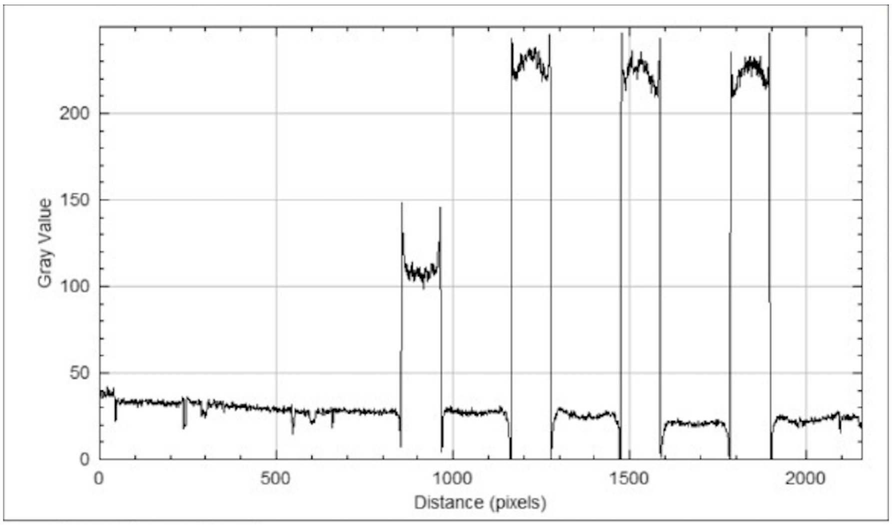


Figure 5. Radiographic image line profile of the phantom showing the difference in material density at 80 kV

The line profile data provides a clear, graphical representation of the differential attenuation, directly quantifying the visual observations from the radiographic images. This profile, which maps gray value against distance, shows that materials with low absorption coefficients (Nylon, Acrylic, MDF) exhibit grayscale values very similar to the base layer, making them difficult to distinguish from each other and the background. This indicates that their radiolucency is high, a property desirable for applications requiring minimal radiation interference, such as in custom immobilization devices or phantom components (Michalska, 2021).

In contrast, materials with high absorption coefficients (Aluminum, Iron, Stainless Steel, Galvanized) show distinct peaks with significantly higher grayscale values. The metallic materials, particularly, display line profiles with sharp, near-vertical changes in intensity at the edges, a key indicator of excellent spatial resolution (Agustito et al., 2025; Erlangga, Fitriyah, et al., 2024; Erlangga, Setyawan, et al., 2024; Mahsunah et al., 2024; Saputro et al., 2024). This high subject contrast is critical for identifying structural defects or precise component positioning in non-destructive testing (Krupinski et al., 2007). These properties make such metals ideal for constructing critical components in electromedical devices that require structural integrity, precise movement (e.g., in stirrer tools, robot arms, patient bed frames), and radiation shielding (Erlangga et al., 2025; Erlangga & Fitriyah, 2025; Fitriyah et al., 2025; Lubis et al., 2025; Trisniawati et al., 2025). The polymer-based materials, with their smoother line profiles and less defined edges, exhibit lower contrast (Erlangga et al., 2023; Johan et al., 2025; Setyawan et al., 2023). This lower attenuation is beneficial for applications where weight is a concern or electrical insulation is required. However, their mechanical strength and durability may be inferior to metals for load-bearing functions.

An important observation from the profile is the behavior of Aluminum, which presents a distinct, medium-sized peak. This confirms its position as a material with intermediate attenuation, clearly distinguishable from both the high-attenuation metals and the low-attenuation polymers at the 80 kV energy level. The steep slopes on the sides of the metal peaks confirm the system's ability to produce sharp edges, which is essential for accurate dimensional analysis and flaw detection.

The findings from this phantom study, supported by the quantitative line profile analysis, have direct implications for the domestic electromedical industry. The ability to nondestructively verify material composition and integrity using digital radiography supports quality control in local manufacturing (Nocum et al., 2021). By ensuring that materials like those tested here meet specifications, manufacturers can improve the reliability and safety of prototypes and final products, ultimately supporting Indonesia's medical device independence program. This analytical method provides a reliable framework for selecting appropriate materials based on their radiological properties, thereby enhancing production efficiency and ensuring the structural safety of electromedical devices.

CONCLUSION

From this research, it can be concluded that phantom images from various materials can distinguish materials and show good contrast on metallic materials such as iron, stainless steel, galvanized and aluminum. While lightweight materials such as nylon, acrylic, and MDF do not show good contrast. Voltage variations affect image quality, phantom radiographic images can show the best contrast when set at a voltage of 80 kV. Visual analysis shows that metallic materials have a higher density or absorption coefficient compared to lightweight materials.

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