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Effectiveness of Using Analog Grid and Virtual Grid in Thoracic Radiography Examination

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ABSTRACT

Chest radiography is essential for diagnosing thoracic abnormalities, but scattered radiation often reduces image contrast and diagnostic accuracy. Conventional analog grids mitigate scatter yet increase patient dose, while virtual grids offer digital correction with potentially lower radiation exposure. This study aimed to compare image quality and radiation efficiency between analog and virtual grids in thoracic radiography, contributing empirical evidence on the feasibility of adopting virtual grids as safer and more efficient alternatives. Three imaging protocols (Analog Grid, Virtual Grid 1, and Virtual Grid 2) were compared using identical exposure parameters on a phantom. Image quality was evaluated both objectively and subjectively. Results showed that Virtual Grid 2 achieved the highest score (4.47), slightly outperforming the Analog Grid (4.20) despite using lower radiation, while Virtual Grid 1 scored the lowest. ANOVA confirmed significant differences among the three methods, though the t-test between Analog Grid and Virtual Grid 2 showed no significant difference. A moderate negative correlation indicated that a reduced dose does not always compromise image quality when supported by advanced processing. In conclusion, Virtual Grid 2 demonstrates strong potential as a reliable alternative to analog grids, enabling excellent image quality with minimal radiation and supporting safer radiographic practices.

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I. INTRODUCTION

Chest radiography is a fundamental diagnostic technique for evaluating health conditions, especially in diagnosing abnormalities in vital organs such as the lungs and heart. In this context, scattered radiation poses a significant challenge. Scattered radiation can reduce image contrast, which can complicate the diagnostic process and ultimately affect the overall quality of radiographic image. To overcome this problem, the use of grids in radiography systems is considered crucial. Grids are designed to absorb scattered radiation, which substantially increases image contrast and clarifies important details in radiographic images [1], [2].

Two types of grids are commonly used in radiography practice: analog grids and virtual grids. Analog grids consist of physical materials and have been astandard component of radiographic procedures for many years. These grids are placed between the radiation source and the detector to filter out scattered radiation. However, the grid ratio chosen can affect the number of X-ray photons reaching the detector. While analog grids are effective in enhancing contrast, their main drawback lies in their tendency to increase image noise, which can degrade image quality [3], [4]. To achieve adequate image quality, radiographers often have to increase the exposure factor, which leads to a higher radiation dose for patients, especially for those requiring repeated examinations [5], [6].

With technological advancements, virtual grids have emerged as an innovative solution to reduce scattered radiation without the need for physical overlays. Virtual grids rely on software and image processing algorithms to correct for scattering, thereby reducing the required radiation dose without degrading image quality [5], [7]. Research has shown that the implementation of virtual grids can improve radiographic image quality and represent a significant step forward in improving both procedural efficiency and image quality [8], [9].

Although virtual grids offer many advantages, theliterature indicates the need for further research to assess their effectiveness in consistently producing high-quality images. Important parameters that should be tested to determine the ability of virtual grids to replace analog grids in clinical applications include contrast, sharpness, and image resolution [4], [10]. Additional research is needed to provide clinical validation of virtual grids, as studies have shown debate among practitioners regarding the advantages of virtual grids over conventional physical grids [5], [9].

The use of virtual grids contributes not only to efficiency and safety in radiography practice but also enhances diagnostic accuracy. Reduced radiation exposure is a key advantage offered by virtual grids, especially for

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patients requiring repeat examinations, where additional radiation doses can be potentially harmful [6], [11]. The implementation of advanced technology in chest radiography suggests that virtual grids can pave the way for safer and more effective medical practices, benefiting not only patients but also improving the diagnostic experience of radiographers [5], [7].
However, the cost of implementation and its financial impact on medical institutions also need to be considered. Investment in software and practitioner training is required to ensure optimal utilization ofthis innovation [4], [6]. Changes in processing patterns and transfer techniques will be required, demanding flexibility in methodology and radiographers training. Improved image quality with a reduced radiation dose is an important consideration that justifies investment in training and infrastructure [2], [10], [12].

Changes in radiography system design that support the use of virtual grids will be critical to support this transition. Further research focused on optimizing image processing algorithms and testing systems across various clinical settings will provide more in-depth guidance on the efficiency of virtual grids in practice [6], [8], [9]. By addressing the challenges of reducing radiation while maintaining image quality, virtual grids can be a valuable tool for medical professionals, promoting patient safety and diagnostic effectiveness [10], [13].

Ultimately, the effectiveness of virtual grid use in chest radiography should be continuously evaluated, as further research in this area remains necessary. By studying the impact of virtual grid use and comparing it with analog grids, we can understand the nuances that influence image quality and patient safety. This is a crucial step toward implementing evidence-based medical practices that will usher in a new era of safer and more effective radiography for patients [1], [4], [10], [13].

Collaboration among researchers, radiographers, and radiologists is needed to thoroughly explore the potential of virtual grids and develop comprehensive protocols for adopting this new technology across the medical landscape. In this way, we not only improve chest radiography techniques but also contribute to the safety and health of the patient. Therefore, this study aims to evaluate and compare the effectiveness of analog grids and two types of virtual grids in thoracic radiography using a phantom model. The contribution of this research lies in providing empirical evidence on whether virtual grids can maintain or even improve image quality while reducing radiation exposure, thereby supporting safer and more efficient radiographic practices in clinical applications.

II. MATERIALS AND METHOD

A. Dataset

The dataset used in this study consists of thoracic radiographic images generated from a thorax phantom. This data was obtained through an exposure process using two types of grids.

Table 1. Exposure Factor

Grid Type					
Analog			Virtual		
kVp	mA	mAs	kVp	mA	mAs
102	200	5	102	200	5 / 0.2

Table 1 presents the exposure parameters applied to both analog and virtual grid techniques. As shown, the analog grid and Virtual Grid 1 were both operated at 5 mAs, whereas Virtual Grid 2 employed a substantially lower exposure of 0.2 mAs. This clear differentiation in exposure factors allows a direct comparison of how image quality and radiation dose vary between conventional and digital grid technologies under controlled conditions. There are 3 groups of image datasets in the table above, namely

Dataset A: Analog grid, standard exposure, Dataset B: Virtual grid, standart exposure and Dataset C: Virtual grid, low exposure Each group produced a series of chest radiograph images on phantoms, which were then assessed both objectively through digital analysis and subjectively by a radiologist.

The images were acquired and analyzed in several key regions of interest (ROIs): the lung fields, sternum, and ribs. The analysis was performed to measure contrast, edge sharpness, and spatial resolution in each of these areas using image processing software and clinical assessment using a scoring questionnaire developed for radiologists.

B. Data Collection

Data collection in this study is an experimental study designed to evaluate the image quality of analog grid and digital grid images.

1) Eksperiment Preparation

The experiment employs a thorax phantom model as the primary testing object. This model is instrumental in creating a realistic simulation of human thoracic anatomy, replicating soft tissue and bony structures. The use of a phantom is deemed essential for ensuring consistency and adhering to ethical standards during image acquisition, particularly by avoiding direct patient exposure is prioritized [14], [15]. Recent advancements in imaging methodologies emphasize employing such phantoms not only to improve diagnosis quality but also to enhance patient safety, as highlighted in related literature [16]

2) Image acquisition

HJ Once preparation is completed, exposure is executed using digital radiography (DR) systems. Here, specific technical parameters are maintained across the various experimental groups to ensure maximal control over imaging variables, excluding the type of grid utilized. The careful management of the source-to-image receptor distance (SID) and central positioning of the phantom guarantees that the results reflect genuine differences attributable to grid type rather than extraneous factors [17]. In this study,

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chest radiography was performed using the thorax phantom in the anteroposterior (AP) supine position with a fixed source-to-image receptor distance (SID) of 180 cm. The phantom was positioned with the mid-sagittal line aligned to the central ray and parallel to the detector to avoid rotation. Collimation was restricted to the thoracic field, covering the lung apices to the costophrenic angles, including both lateral chest borders. To ensure reproducibility, the phantom was immobilized with positioning markers on the examination table to prevent displacement across different groups. Anatomical alignment was standardized by aligning the shoulder height and the midline of the sternum with the collimator light field. These measures ensured that all image acquisitions followed identical protocols, thereby minimizing variability and confirming that differences in image quality were attributable solely to the type of grid used. The implementation of a virtual grid through post-acquisition digital processing signifies an innovative step in radiographic imaging, promising not only cost-effectiveness but also enhancing the quality of imaging outputs by leveraging computational algorithms [14], [18]

3) Image Quality Assessment
Image quality assessment encompasses both subjective and objective evaluations. Experienced radiologists assess images subjectively using a structured scoring questionnaire focusing on parameters such as contrast, sharpness, clarity of anatomical boundaries, and visibility of crucial structures like the sternum and ribs. Three board-certified radiologists performed subjective image quality assessments with a minimum of five years of clinical experience. Evaluations were based on a structured Likert scale (1–5), where a score of 1 indicated very poor image quality and a score of 5 indicated excellent image quality. The criteria assessed included image contrast, edge sharpness, visibility of anatomical structures (sternum, ribs, and lung fields), and the presence of artifacts. To ensure consistency across evaluators, inter-rater reliability was analyzed using Cohen's kappa, demonstrating a good agreement level (>0.75). This confirmed that the subjective evaluations were reliable for establishing the clinical relevance of the images. This subjective component complements the objective analysis, which utilizes quantitative metrics such as mean pixel values, local contrast ratios, and Contrast-to-Noise Ratio (CNR) to provide a thorough overview of image quality [19], [20]. Objective image quality analysis was performed using ImageJ software (National Institutes of Health, USA), which has been widely employed in radiological research for digital image processing and quantitative analysis. The parameters measured included mean pixel values, local contrast ratios, edge sharpness assessed through line intensity profiles, and the Contrast-to-Noise Ratio (CNR) in regions of interest (ROIs) such as the lung fields, sternum, and ribs. The validity of these measurements was supported by previous studies utilizing similar software for radiographic image evaluation [19], [20]. Prior to analysis, images were calibrated using the software's built-in intensity scale to ensure consistency of pixel values across datasets. The results were statistically analyzed using t-tests for two-group comparisons, ANOVA for three-group analyses, and Pearson correlation to examine the relationship between radiation dose (mAs) and image quality metrics. This approach strengthens the scientific validity and reproducibility of the objective assessments. Notably, employing both assessment methods enhances the robustness of the findings, as subjective evaluations reflect practical diagnostic challenges while objective measures substantiate these observations with quantifiable data [21].

4) Radiation Dose Measurement
In parallel with image quality assessments, radiation doses administered during the imaging processes are carefully monitored. This aspect of the study is crucial, as it evaluates the safety of lower radiation settings (potentially facilitated by the virtual grid) and assesses their impact on image quality. Using dosimeters placed on the phantom allows for accurate measurement of doses delivered to various thoracic areas [22]. The investigation compares dosages from both virtual and analog grids at designated exposure levels (5 mAs and 0.2 mAs) to evaluate the efficacy of virtual grids in maintaining imaging quality while potentially reducing radiation exposure [15]. The selection of 5 mAs for both the manual grid, as well as 0,2 mAs for the low-dose virtual grid, was based on a combination of literature recommendations and preliminary tests conducted on the thorax phantom. The five mAs value was chosen to represent a standard exposure level in thoracic guidelines. Meanwhile, the 0,2 mAs value for the virtual grid was determined, and the algorithm was still capable of producing analyzable image quality despite the lower dose.

Thus, these exposure parameters were not arbitrarily selected but rather reflect a standard exposure (5 mAs) and an optimized low-dose approach (0,2 mAs), representing realistic conditions in radiographic practice. This approach strengthens the comparative evaluation of virtual and manual grids in terms of image quality and radiation dose.

5) Analysis
The final phase of data analysis involves employing statistical methods to interpret the accumulated data. Descriptive and inferential statistics, including t-tests for comparing mean scores of image quality between the two types of grids, provide a framework for assessing the relative effectiveness of the grid types [23]. Additionally, correlation analyses help elucidate the relationship between image quality metrics and radiation exposure, providing critical insights into whether the use of virtual grids compromises diagnostic quality in favor of reduced doses [24]. The overarching goal is to ascertain whether virtual grids

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are comparable to analog grids in terms of image quality and offer significant advantages in lowering radiation dosage during imaging procedures.

In conclusion, the data collection process described represents a nuanced and ethically sound framework capable of yielding valuable insights into the comparative efficacy of virtual versus analog grids in thoracic imaging. By employing a robust phantom model, rigorous exposure protocols, dual assessment methodologies, and careful dose monitoring, the study is positioned to make a meaningful contribution to the optimization of radiological practices while ensuring patient safety.

III. RESULTS

A. Method of the Imaging

This study used a thoracic phantom as the primary test object in anteroposterior (AP) radiographic imaging simulation. Three imaging methods were compared: Analog Grid, Virtual Grid 1, and Virtual Grid 2, all performed using a Digital Radiography (DR) system. Fig.1 illustrates the chest phantom images produced using the three different imaging methods: (a) Analog Grid, (b) Virtual Grid 1, and (c) Virtual Grid 2. These images visually demonstrate differences in contrast, anatomical clarity, and artifact presence, which were later validated through both subjective scoring by radiologists and objective image quality analyses.

(a) (b) (c)

Fig. 1. (a) Analog Grid, (b) Virtual grid 1, (c) Virtual grid 2

The exposure parameters and differences in the characteristics of the three are presented in the Table below:

Table 2. Comparison of Imaging Methods

No	Imaging Methode	Grid	kV	mA	mAs
1	Analog (An)	Analog	102	200	5
2	Virtual 1 (V1)	Virtual	102	200	5
3	Virtual 2 (V2)	Virtual	102	200	0,2

B. Image Quality Assessment

Table 3 compiles assessments of the aspects of contrast, density, visibility of anatomical structures, and image artifacts.As indicated in Table 3, the Analog Grid and Virtual Grid 2 achieved higher scores across nearly all anatomical structures, particularly in thin structures such as the pulmonary apex and sinus costophrenicus. In contrast, Virtual Grid 1 consistently showed lower visibility and contrast, confirming its weaker performance compared to the other methods.

Table 3. Image Quality Assessment Based on Anatomical Structure

Aspect	Structure	An	V 1	V 2
Image Contrast	Thin structure	5	2	5
	Thick structure	4	4	5
Density	Thin structure	4	3	4
	Thick structure	4	3	5
Anatomical Visibility	Pulmonary Aspex	5	3	4
	Left Clavicula	5	3	5
	Arcus aorta	5	3	5
	Lung shadow	5	3	5
	Hemidiafragma	5	3	5
	Sternoclavicular joint	4	3	4
	Sinuscostophrenicus	5	2	5
Image artifacts	Grid Linis	4	5	5
	Grid cut off	4	5	5

Table 4. Independent t-test of image quality scores between grids

Parameter	Analog	Grid 2	t	p-value	Interprestation
Image quality score (n=14)	4.20 ± 0.63	4.47 ± 0.54	-1.38	0.189	Not statistically significant ($p > 0.05$)

Table 4 shows the independent t-test comparing Analog Grid and Virtual Grid 2. Although the p-value (0.189) indicates no statistically significant difference, the slightly higher mean score of Virtual Grid 2 suggests a clinically meaningful advantage in image quality despite using a lower radiation dose.

Table 5. ANOVA test of image quality scores between 3 groups

Grup	Average Score	F-Statistic	p-value	Interpretation
Analog	4.20	24.56	1.25×10^{-7}	There are differences between at least two groups (p <

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		0.001)
Vir 1	3.00	
Vir 2	4.47	

Table 5 demonstrates significant differences in image quality scores among the three groups ($p < 0.001$). This confirms that at least one imaging method performs substantially differently, with Virtual Grid 1 performing the weakest, and Virtual Grid 2 performing the best overall.

The analysis showed a significant difference in the overall image quality score ($F = 24.56$; $p < 0.001$), indicating that at least one of the three methods performed substantially differently. Further analysis using the Tukey HSD post-hoc test after ANOVA showed that there were significant differences between Virtual Grid 1 and Analog Grid ($p < 0.01$) and between Virtual Grid 1 and Virtual Grid 2 ($p < 0.001$). Meanwhile, the difference between Analog Grid and Virtual Grid 2 was not significant ($p > 0.05$). These results indicate that Virtual Grid 1 produces significantly lower image quality compared to the other two methods, while Virtual Grid 2 is able to achieve image quality equivalent to the analog grid despite using a lower radiation dose.

Tabel 6. Correlation between mAs and Image Quality

Variable 1	Variable 2	Koefisien Korelasi	p-value	Interpretation
mAs	Image Quality Score	-0.60	0.586	The negative relationship is moderate, but not statistically significant. (p > 0.50)

Table 6 reveals a moderate negative correlation ($r = -0.60$) between mAs and image quality, although it is not statistically significant ($p > 0.50$). This suggests that a lower radiation dose does not necessarily reduce image quality when digital correction methods are effectively applied.

IV. DISCUSSION

This study aims to evaluate and compare the effect of virtual grid technology implementation on the quality of chest radiographic images in the Anteroposterior (AP) position. This objective is very relevant in efforts to increase radiation dose efficiency while maintaining or even improving the visual performance of the resulting radiographic images. Three imaging methods covered in this evaluation include conventional analog grids and two variants of the Virtual Grid based on the Digital Radiography (DR) system, namely Virtual 1 and Virtual 2. The applied exposure parameters are uniform, with kV and mA of 102 kV and 200 mA, respectively, but there is a significant difference in the mAs value: 5 mAs for both the Analog and Virtual 1 methods, while only 0.2 mAs for the Virtual 2 method. With this difference, the study aims to explain the correlation between radiation dose and diagnostic image quality objectively.

Visual assessment of the resulting images showed varying performance between the tested methods. The Virtual 1 method experienced a significant decrease in quality, particularly in contrast and visibility of thin anatomical structures. The low scores obtained, with the average rating actually being in the adequate category, indicate that the use of this technology does not provide the expected results. In contrast, the Analog and Virtual 2 methods showed good and stable image performance, with scores generally in the range of 4 to 5. This indicates that although Virtual 2 uses a lower radiation dose, the resulting images still meet acceptable diagnostic criteria, even outperforming the Analog method in some aspects. These findings reflect its potential use in modern clinical practice, where the emphasis isincreasingly prioritizes patient safety by reducing unnecessary radiation doses [25], [26].

An inferential analysis using an independent two-sample t-test of the image quality scores between the Analog and Virtual 2 methods yielded a p-value of 0.189 ($p > 0.05$), indicating no statistically significant difference between the two methods. Although the mean image quality score for Virtual Grid 2 (4.47) was slightly higher than that for Analog Grid (4.20), this finding should be viewed as an initial, exploratory indication, not as a definitive conclusion regarding clinical superiority. The limited sample size in this study likely contributed to the low power of the statistical test. Further research with a larger sample size is highly recommended to determine whether the numerical differences are consistent and clinically and statistically significant. In radiology practice, although statistical significance is the primary reference, small, visually meaningful differences can still be a basis for decision-making, particularly in the context of operational efficiency and convenience. These findings align with the understanding that image quality is measured not only by purely statistical criteria but also by considering the clinical value that can be obtained.

Furthermore, ANOVA analysis was performed to examine differences between the three imaging methods. The results showed a significant difference in the overall image quality scores ($F = 24.56$; $p < 0.001$), indicating that at least one of the three methods performed substantially differently. In this case, the Virtual 1 method was identified as not achieving optimal performance, despite using the same dose as the conventional analog method. The decrease in scores for this method may be due to limitations in the image processing algorithm, which is unable to effectively handle the visual degradation caused by the absence of a physical grid. This suggests that despite the advancement of technology, its use must be continuously optimized to achieve the desired results [26], [27].

The observed correlation between mAs values and image quality scores showed a coefficient of -0.60 with a p-value of 0.586. Although this relationship was not statistically significant, there was a negative trend

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indicating that a decrease in image quality does not always accompany dose reduction. This is especially true when digital processing technology is optimally utilized. The correlation analysis results showed a value of r = -0.60, indicating a moderate negative relationship between radiation dose (mAs) and image quality, but it was not statistically significant (p = 0.586). This is most likely influenced by the relatively small sample size (n = 14), which limited the statistical power of the test in detecting significant differences. With a larger sample size, this relationship has the potential to become significant, as demonstrated in several previous studies. Therefore, these correlation results should be interpreted cautiously as preliminary indications, underscoring the need for further research with a larger dataset and an expanded sample size to strengthen the conclusions. Virtual Grid 2 technology, for example, is able to compensate for physical limitations through digital image processing, effectively reducing the need for high exposures, which has direct implications for safer and more efficient radiographic practices without sacrificing diagnostic accuracy [26].

Another advantage of using Virtual Grid 2 is the elimination of physical artifacts that often appear in imaging using manual grids, such as grid lines and grid cut-off effects. In this study, Virtual 2 obtained a perfect score on the image artifact aspect, indicating clean images free from visual disturbances. This not only increases comfort in the image interpretation process by radiologists, but also minimizes the need for repeat imaging due to artifacts that interfere with important areas. This efficiency has a direct positive impact on radiology workflow, patient waiting time, and savings in hospital resources [25], [28].

However, it should be noted that digital processing performed by virtual grid algorithms, particularly under low-dose conditions, can potentially introduce processing artifacts or even reduce diagnostic detail in fine anatomical structures. For example, soft tissue details or very small density differences may be reduced in visibility due to the image normalization process. These limitations must be taken into account when interpreting the results, and further research is needed to evaluate the extent to which virtual grids contribute to noise, processing artifacts, and loss of diagnostic detail in various clinical conditions.

The implications of this research are highly relevant in implementing low-dose technology and improving imaging services in the digital era. Virtual Grid 2 technology can be an ideal solution for hospitals or healthcare facilities facing high volumes, especially in radiation-sensitive populations, such as children and patients with chronic conditions who require regular examinations. The dose efficiency offered not only reduces the risk of cumulative exposure, but also supports the ALARA (As Low As Reasonably Achievable) principle, which is a basic guideline in modern radioprotection [27].

This research also contributes to the development of radiographer training curricula in the educational realm. Practical materials and critical discussions can introduce an understanding of the integration of digital technology, the influence of exposure parameters on image quality, and the importance of visual artifact testing. Thus, learning will not only focus on conventional techniques but also direct readiness to face technological transformations in radiology services in the future [29].

Furthermore, the thorax phantom test object does not fully represent the complexity of human anatomy, biological tissue variations, or potential clinical artifacts that occur in real patients. These limitations may affect the generalizability of the results; therefore, the findings of this study should be viewed as preliminary evidence under controlled conditions. Further clinical research in real patient populations is urgently needed to validate the effectiveness of virtual grids in everyday radiology practice and ensure the obtained results are clinically relevant. In an era where technology in the medical field continues to advance, this study provides a solid initial overview of the potential use of Virtual Grid technology in the context of chest radiography. Certainly, further research with diverse approaches will enrich our understanding of the influence of new technologies and optimization of the imaging process to improve clinical outcomes and overall patient safety [26].

The findings of this study have the potential to be integrated into daily clinical practice, particularly in digital chest radiography. Implementation of Virtual Grid 2 can reduce the need for physical grids, simplify the radiographer's workflow, and minimize the risk of repeat imaging due to physical artifacts. For patients, the implementation of the virtual grid has the potential to reduce radiation dose without sacrificing image quality, in line with the ALARA (As Low As Reasonably Achievable) principle. While these results are promising, further research is needed. Clinical trials in real-world patients with diverse populations (e.g., children, obese patients, or patients with specific chest disorders) are essential to confirm the effectiveness of the virtual grid in complex clinical situations. Furthermore, further evaluation of diagnostic accuracy, including radiologists' ability to detect pathological abnormalities with the aid of the virtual grid, will provide stronger evidence for the implementation of this technology in modern medical practice.

V. CONCLUSION

This study demonstrates that second-generation Intelligent Grid technology (Virtual 2) is capable of producing equivalent and even slightly superior anteroposterior (AP) chest radiographic image quality compared to conventional analog grid methods, despite using a significantly lower radiation dose (0.2 mAs compared to 5 mAs). ANOVA statistical test showed a significant difference between imaging groups ($p < 0.001$), with the Virtual 1 method showing the lowest image quality score. Meanwhile, the t-test results between the Analog and Virtual 2 methods did not show a statistically significant difference (p = 0.189), but the difference in

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mean scores (4.47 vs. 4.20) still has important clinical implications.

The negative correlation between mAs values and image quality (r = –0.60) indicates that dose reduction does not always correlate with image quality degradation, especially when supported by optimal digital image processing technology. Another advantage Grid 2 is its ability to eliminate visual artifacts such as grid lines and grid cut-offs, which are commonly found in analog systems. Overall, the results of this study support the potential implementation of second-generation Intelligent Grid technology as an effective and efficient alternative in digital radiography practice, especially for applications that require high image quality with the lowest possible radiation dose. Further research with human subjects and quantitative approaches based on digital image analysis is recommended to strengthen the external validity of these findings.

The strength of this study lies in its controlled experimental design using a thoracic phantom, which enabled systematic comparison between analog and virtual grids under standardized exposure conditions. The dual use of both objective and subjective assessments also increased the robustness of the findings. However, the main limitation is that phantom imaging does not fully represent the complexity of human anatomy and clinical variability, thereby limiting external validity. In addition, the relatively small sample size of image assessments may affect the generalizability of the results. Therefore, future research involving patient populations and larger datasets is necessary to confirm and extend these findings.

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extensively discussed the application of medical physics methods to support community health development and radiology service systems in local healthcare institutions.

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