Nondestructive measurement of the grid ratio using a single image

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The antiscatter grid is an essential part of modern radiographic systems. Since the introduction of the antiscatter grid, however, there have been few methods proposed for acceptance testing and verification of manufacturer-supplied grid specifications. The grid ratio (r) is an important parameter describing the antiscatter grid because it affects many other grid quality metrics, such as the contrast improvement ratio (K), primary transmission (T_p), and scatter transmission (T_s). Also, the grid ratio in large part determines the primary clinical use of the grid. To this end, the authors present a technique for the nondestructive measurement of the grid ratio of antiscatter grids. They derived an equation that can be used to calculate the grid ratio from a single off-focus flat field image by exploiting the relationship between grid cutoff and off-focus distance. The calculation can be performed by hand or with included analysis software. They calculated the grid ratios of several different grids throughout the institution, and afterward they destructively measured the grid ratio of a nominal $r8$ grid previously evaluated with the method. They also studied the sensitivity of the method to technical factors and choice of parameters. With one exception, the results for the grids found in the institution were in agreement with the manufacturer's specifications and international standards. The nondestructive evaluation of the $r8$ grid indicated a ratio of 7.3, while the destructive measurement indicated a ratio of 7.53 ± 0.28 . Repeated evaluations of the same grid yielded consistent results. The technique provides the medical physicist with a new tool for quantitative evaluation of the grid ratio, an important grid performance criterion. The method is robust and repeatable when appropriate choices of technical factors and other parameters are made. © 2009 American Association of Physicists in Medicine.

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I. INTRODUCTION

The antiscatter grid is an essential part of modern radiographic systems. Since Bucky introduced the first antiscatter grid in 1913,¹ however, there have been few methods proposed for the acceptance testing and verification of manufacturer-supplied grid specifications. Acceptance testing is used to benchmark the performance of new equipment and compare its performance against the manufacturer's specifications. Methods and criteria for acceptance testing of radiographic imaging systems have been proposed,² and performance criteria for antiscatter grids have been defined.³ However, recommendations regarding acceptance testing of antiscatter grids are completely absent,² and recommendations for routine quality control are limited to tests concerning alignment and artifacts.^{4,5}

When considering the purchase of a radiographic system, the choice of antiscatter grid is often limited to the inclusion or exclusion of certain "midrange" grids that provide marginal image quality over a range of source-to-image distances (SIDs) from 100 to 180 cm. Because of these limited choices, extensive characterization of the antiscatter grid in these situations may not be warranted, and international standards require that only certain performance characteristics are specified on the label of a grid.³ These characteristics include grid ratio (r), strip frequency (N), and focusing distance (f_0). Additional characteristics, such as contrast im-

provement ratio (K), primary transmission (T_p), and grid selectivity (Σ),^{3,6} are only required to be included in accompanying documents, which are often not provided by the OEM. The grid ratio affects all of the aforementioned characteristics^{7,8} and is independent of x-ray spectrum, patient thickness, field size, and other influences. However, we are not aware of the existence of any methods for nondestructive measurement of the grid ratio for acceptance testing. Evaluating the grid ratio is important because high-ratio grids are expensive and difficult to manufacture. Alternatively, the use of a higher ratio grid in applications, where a lower ratio grid was specified, can result in poor image quality and artifacts due to grid cutoff from misalignment, for example, in bedside imaging.

II. MATERIALS AND METHODS

In this work, we adapted grid performance characteristics first proposed by Boldingh in the late 1950s (Refs. 9 and 10) to the nondestructive measurement of the grid ratio (r). Boldingh calculated near and far focusing limits for grids on the basis of an acceptable limit of 50% primary radiation loss at a distance of 15 cm from the centerline of the grid.⁹ However, Boldingh's derivation assumed vertical septa, which is an oversimplification when calculating primary radiation loss (i.e., grid cutoff) at any location other than the centerline of the grid. In fact, the greater the distance from the centerline

FIG. 1. C is the off-axis distance from the centerline of the grid to a point on the flat field image with noticeable grid cutoff. f_1 or f_2 is the distance at which the off-focus image is acquired. Finally, h is the height of the grid septa and D is the width of the interspace.

of the grid, the more error that is introduced by this simplification. Given that we attempted to exploit primary radiation loss as a tool to calculate r , we present here a derivation that considers the angled septa in a focused grid. We used the limiting angle α_0 (Ref. 8) at the focus distance f_0 (Fig. 1) to derive an equation that was used to calculate r from a single flat field image acquired at an off-focus distance f_1 . Figure 1 shows the acceptance angle α_0 at the grid focal distance f_0 . At an off-focal distance, $f_2 > f_0$, the acceptance angle becomes α_2 , where $\alpha_2 < \alpha_0$. Both α_2 and α_0 can be expressed in terms of f_0 and f_2 ,

$$\alpha_0 = \arctan\left[\frac{C}{f_0}\right], \quad \alpha_2 = \arctan\left[\frac{C}{f_2}\right], \quad (1)$$

where C is the distance from the centerline of the grid. For the case of $f_2 > f_0$, the ratio of the height of the septa to the septal shadow, h/δ_2 , can be expressed in terms of α_2 and α_0 ,

$$\frac{h}{\delta_2} = \frac{\sin(90 - \alpha_0)}{\sin(\alpha_0 - \alpha_2)}. \quad (2)$$

Substituting Eq. (1), this quantity can be simplified using properties of trigonometry to

$$\frac{h}{\delta_2} = \frac{\sqrt{C^2 + f_2^2}}{C\left(\frac{f_2}{f_0} - 1\right)}. \quad (3)$$

The amount of primary radiation loss δ_2 can be expressed as

$$\delta_2 = D - D\left(\frac{U_C}{U_0}\right), \quad (4)$$

where U_0 is the mean For Processing¹¹ pixel value measured in an ROI at the grid centerline and U_C is the mean For Processing pixel value measured in an ROI at a distance C from the grid centerline. Substituting Eq. (4) into Eq. (3), the result can be reduced to

$$r = \frac{1}{C} \left[1 - \frac{U_C}{U_0} \right] \frac{\sqrt{C^2 + f_2^2}}{\left(\frac{f_2}{f_0} - 1\right)}. \quad (5)$$

An additional term is introduced to correct for the decrease in the primary radiation at C due to the inverse-square law,

$$r = \frac{1}{C} \left[1 - \frac{U_C}{U_0} \left(\frac{C^2 + f_2^2}{f_2^2} \right) \right] \frac{\sqrt{C^2 + f_2^2}}{\left(\frac{f_2}{f_0} - 1\right)}. \quad (6)$$

Similarly, for the case where $f_1 < f_0$, the acceptance angle is $\alpha_1 < \alpha_0$. The derivation is nearly identical and results in the relationship

$$r = \frac{1}{C} \left[1 - \frac{U_C}{U_0} \left(\frac{C^2 + f_1^2}{f_1^2} \right) \right] \frac{\sqrt{C^2 + f_1^2}}{\left(1 - \frac{f_1}{f_0}\right)}. \quad (7)$$

The special case of the parallel or infinite focus grid follows similarly and results in the following relationship when a flat field image is obtained at a source-to-grid distance (SGD) f ,

$$r = \frac{C}{f} \left[1 - \frac{U_C}{U_0} \left(\frac{C^2 + f^2}{f^2} \right) \right]. \quad (8)$$

Equations (6)–(8) can be used to calculate r using a single off-focus flat field image provided that the mean raw pixel values U_0 and U_C are obtained from For Processing data that exhibit a linear relationship to incident exposure. Image receptors with a nonlinear characteristic function may also be used provided that the characteristic function is known or measured and used to transform the data into linear exposure space. Also, any DC offset present in the For Processing images must be subtracted or r will be underestimated.

We measured r on a selection of grids obtained throughout our imaging departments. These grids had nominal r ranging from 8 to 16 and focus distances ranging from 100 to 180 cm. Table I details the grids subjected to nondestructive measurement of r .

Equations (6)–(8) will produce a result for any grid imaged regardless of user selection of f_1 , f_2 , C , and kVp. We determined the sensitivity of our method to the selection of f_1 , f_2 , kVp, and C in order to identify the set of parameters that yields the most accurate repeatable results. We imaged a single grid while varying the aforementioned parameters and studied the effect on the calculated r .

II.A. Sensitivity of the method to f_1 , f_2 , and kVp

Two focused grids (grids 2 and 3, Table I) were tested in combination with a GE Definium 8000 (GE Medical Systems, Waukesha, WI) digital radiography system to determine the sensitivity of this method to changes in f_1 , f_2 , kVp, C , tube current, focal spot size, and x-ray source centering. The Definium 8000 provides For Processing images for every acquisition. The pixel values in these For Processing images are characterized by a linear response to incident detector exposure with no DC offset. U_C and U_0 were measured from these images. Technique factors, including

TABLE I. Characteristics of the antiscatter grids tested. All grids had Pb septa.

ID	Manufacturer	N (cm^{-1})	d (μm)	f_0 (cm)	Interspace material	r	
						Nominal	Measured
Grid 1	Mitaya ^a	40	50	100	Al	8	7.3
Grid 2	Mitaya	70	40	180	Al	13	13.0
Grid 3	Mitaya	70	40	100	Al	13	12.8
Grid 4 ^b	Siemens ^c	83.3	20	105	Fiber	16	14.5
Grid 5	Mitaya	70	40	130	Al	10	9.0
Grid 6	Siemens	83.3	20	115	Fiber	16	14.3
Grid 7	Mitaya	70	40	100	Al	12	12.3
Grid 8	Smit-Röntgen ^d	36	36	140	Fiber	12.4	12.3

^aMitaya Manufacturing Co., Ltd., Tokyo, Japan.^bSepta in this grid run diagonally at a 17° angle.^cSiemens Medical Solutions, Malvern, PA.^dSmit-Röntgen, Eindhoven, The Netherlands.

milliamperes-second product and kVp, were adjusted to maintain a constant detected exposure indicator value on the Definium system within the recommended range in technical mode for all flat field images obtained.

II.B. Sensitivity of the method to alignment and centering

The focal spot of the x-ray tube must be aligned with the centerline of the grid to avoid lateral decentering, which would introduce error into our nondestructive measurements. It is a simple matter to verify x-ray source alignment on the resulting For Processing image on the basis of the location of the maximum pixel value. Grid lines should run parallel to the anode-cathode axis to eliminate uncertainties due to the anode heel effect, and the second ROI measurement U_C should be made at a distance C from the center in a direction perpendicular to the anode-cathode axis and grid lines.

II.C. Verification of the method

Although we made many nondestructive measurements of grid ratios, we could not be absolutely certain that our method was providing accurate results without destructively measuring r . To this end, we destructively measured r for an r 8 focused (100 cm) aluminum-interspaced grid (grid 1, Table I) after performing our nondestructive evaluation. This grid had been previously removed from clinical service because of damage at the corners of the grid. The grid covers were removed, and the grid was divided into 16 equal sections and disassembled. Samples of the aluminum-interspaced material were taken from each section of the grid. Any lead remaining on the interspace material was chemically removed with a 2:1 solution of distilled white vinegar and hydrogen peroxide.¹² Multiple individuals measured r in each of the 16 sections using high-precision calipers, and these measurements were used to calculate the actual r of this grid.

III. RESULTS AND DISCUSSION

The results of our nondestructive measurement of r for the clinical grids evaluated in this study are presented in the last column of Table I. With one exception, the grids evaluated were characterized by ratios close to the manufacturer's specifications. The largest deviation from the nominal r was grid 6, with nominal r 16 and measured r 14.3. This is outside the $\pm 10\%$ standard required by the International Electrotechnical Commission (IEC).³ Further evaluation of this grid demonstrated that the discrepancy in r was likely due to the centerline of the grid being displaced approximately 5 cm. This was confirmed with a grid centering test tool. All other grids were within the $\pm 10\%$ standard required by IEC.

III.A. Sensitivity to f_1 , f_2 , and kVp

The sensitivity of our technique to kVp selection is shown in Fig. 2(a). We believe that penetration of the grid septa and an increase in extrafocal radiation contributed to measurement inaccuracy at higher kVp. Owing to the steep incidence angle, the photon path length through a 20 μm wide and 1.6 mm tall Pb septum (r 16) will be no less than 300 μm in an off-focus image acquired at 40 kVp. The 20 μm wide septum is the thinnest we evaluated and is the thinnest septum likely to be found in antiscatter grids currently in clinical use. For this limiting case, the septal penetration at 40 kVp is far less than 1%, but rises sharply to 12% at 80 kVp. Thicker septa, usually found in lower r grids, will allow less septal penetration. Also, it has been shown that extrafocal radiation increases with kVp (Refs. 13–15) and decreases sharply below 60 kVp.¹⁴ We therefore recommend the use of the lowest available kVp setting for the measurement of r . A 40 kVp setting is available on most radiographic systems. However, extrafocal radiation can still comprise as much as 5% of the total x-ray energy fluence at 40 kVp.¹⁵ A 5% underestimate of r would not be expected, but extrafocal radiation may have a small impact on the calculated r , even at 40 kVp.

FIG. 2. Examples of variation in calculated grid ratio with changes in f or kVp. (a) Calculated r with changes in kVp for grid 3 imaged at an 85 in. SGD. (b) Calculated r versus f_1 for grid 2 measured at 40 kVp. (c) Calculated r versus f_2 for grid 3 measured at 40 kVp.

At 40 kVp no detectable dependence on the focal spot size (1.2 mm/0.6 mm) or tube current was seen. This was an expected result. There was, however, a dependence on the selection of f_1 or f_2 . Figures 2(b) and 2(c) illustrate this dependence for grids 2 and 3. Figure 2 illustrates the dependence on f_1 for a 180 cm grid as the x-ray source is moved closer to the grid [Fig. 2(b)] and the dependence on f_2 for a 100 cm grid as the x-ray source is moved away from the grid [Fig. 2(c)]. In both cases, measured grid ratios were calculated with a choice of C such that U_C/U_0 was equal to 0.3 unless U_C/U_0 was greater than 0.3 across the entire image, in which case the measurement was made at the edge of the image receptor. If the off-focus distance was too small, the results were erratic owing to noise, grid focus imperfections, and grid nonuniformities [Figs. 2(b) and 2(c)]—the effects of which became greater as C decreased. The required f_1 or f_2 depended on r —lower ratios required a greater off-focus distance than higher ratios. Our results showed that the off-focus distance should be adjusted such that $0.1 < U_C/U_0 < 0.2$ at the edge of the image receptor. If this rule was observed, the results were consistent and repeatable.

III.B. Sensitivity to selection of C

For high-quality grids, there was a weak dependence on C , the off-axis distance from the grid centerline where the U_C measurement was made (Fig. 3). As C was varied across the flat field image obtained at $f_2=203$ cm using grid 3, results were consistent within the following approximate range: $0.2 < U_C/U_0 < 0.7$. An ROI measurement at too small a value of C (close to the centerline of the grid) resulted in an inaccurate estimate of r . Similarly, an ROI measurement at too large a value of C (complete grid cutoff) may include a large fraction of extrafocal radiation compared to focal primary radiation, and resulted in an inaccurate measurement. We found that measurement of U_C at a distance C , where $U_C/U_0=0.3$ yielded consistent repeatable results. Lower quality grids may exhibit more fluctuation in the calculated r as C is varied than depicted in Fig. 3 owing to slight variations in f_0 or r across the grid. Rectangular image receptors,

such as computed radiography (CR) plates, should be oriented with the long access perpendicular to the grid lines to ensure enough cutoff is captured.

We have included a Windows executable file¹⁶ that, when the user imports a flat field image in a valid format that meets the criteria listed in this paper, will output r for each half of the grid, as well as graphs similar to those in Fig. 3. A fitting routine is used to calculate an average r for each half of the grid within the U_C/U_0 range recommended in the previous paragraph. The routine uses a smoothing spline with a smoothing parameter close to 1 to reduce the effects of grid nonuniformities or slight grid focus inconsistencies within the U_C/U_0 range. Pixel values must be in linear exposure space, but a field is provided to input a known DC offset, which is subtracted from the image. Analysis of the output can provide insight into overall grid quality and uniformity.

III.C. Comparison to a destructive test

Grid 1 was imaged and evaluated using our nondestructive technique. At $f_2=203$ cm, our technique resulted in a calculated r of 7.3 for this grid. The grid was then disassembled as described previously, and the width (D) and height (h) of the aluminum-interspaced strips were measured. The destructive grid measurement yielded an actual r of 7.53 ± 0.28 . The actual r , as measured destructively, agreed well with the r calculated using the technique described in this paper. Both measurements indicate that the actual r is less than the nominal $r8$ specified by the manufacturer.

III.D. Caveats

Several caveats concerning our method should be mentioned. The first involves integrated grids in fixed-SID systems, for example, dedicated chest radiography systems. In this case, the acquisition of an off-focus image of the grid would be impossible. We suggest working with the service engineer to either measure r before the grid is installed or to

FIG. 3. Analysis of an off-focus flat field image made at $f_2=203$ cm with grid 3. (a) Change in the calculated r as a function of C . (b) U_C/U_0 versus C in the off-focus flat field image.

remove the grid and measure r at acceptance testing. A variable-SID digital radiography system or a CR plate can be used for the measurement.

The second caveat is reciprocating grids. We are uncertain of the impact of reciprocation on measured grid ratio, so we recommend that reciprocation be disabled during the measurement of r or that the grid be removed from the Bucky to perform the measurement.

The final caveat is image receptor nonuniformity. Image receptor nonuniformities could influence the calculated r , as could differences in x-ray path length through the detector at large incidence angles. Also, gain calibrations are rarely, if ever, performed at 40 kVp. Acquiring a flat field image with nothing in the x-ray beam and dividing the off-focus grid image by the flat field image prior to performing the analysis will correct for these nonuniformities. This feature has been included in our executable program. However, errors caused by image receptor nonuniformities are likely to be very small and using a single image will, in the vast majority of cases, deliver accurate results. Also, nonuniformities such as shading on CR plate readers will not affect the calculated r because the shading will occur parallel to the grid lines if the cassette is oriented as recommended.

IV. CONCLUSIONS

Our technique provides the medical physicist with a new tool for quantitative evaluation of the grid ratio, an important

grid performance criterion. We have demonstrated that r can be measured nondestructively using a single flat field image acquired at an off-focus distance. With one exception, the grids evaluated with this method were characterized by ratios in agreement with manufacturers' specifications and IEC standards. The grid that did not meet IEC standards was found to be poorly constructed. In addition, we have included an executable program that allows the user to import an image that meets the requirements outlined in this paper and calculates the grid ratio and other analyses that allow for the evaluation of overall grid quality and uniformity.

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¹G. Bucky, "Über die ausschaltung der im objekt entstehenden sekundärstrahlen bei röntgenaufnahmen," *Verh. Dtsch. Rönt. Ges.* **9**, 30 (1913).

²"Specification, acceptance testing and quality control of diagnostic x-ray imaging equipment," *1991 AAPM Summer School Proceedings*, J. A. Seibert, G. T. Barnes, and R. Gould (American Institute of Physics, Santa Cruz, CA, 1991).

³International Electrotechnical Commission, *Diagnostic X-Ray Imaging Equipment—Characteristics of General Purpose and Mammographic Anti-scatter Grids* (IEC, Geneva, 2001).

- ⁴“Quality assurance for diagnostic imaging,” National Council on Radiation Protection and Measurements Report No 99 (NCRP, Bethesda, MD, 1988).
- ⁵“Quality control in diagnostic radiology,” American Association of Physicists in Medicine Report No. 74 (Medical Physics, Madison, WI, 2002).
- ⁶J. G. Bonenkamp and W. H. Boldingh, “Quality and choice of Potter Bucky grids: I. A new method for the unambiguous determination of the quality of a grid,” *Acta Radiol.* **51**, 479–489 (1959).
- ⁷J. G. Boenenkamp and W. H. Boldingh, “Quality and choice of Potter Bucky grids: II. Application of the criterion of quality to various types of grids,” *Annu. Rev. Phys. Chem.* **52**, 149–157 (1959).
- ⁸J. G. Bonenkamp and W. H. Boldingh, “Quality and choice of Potter Bucky grids: III. The choice of Bucky grid,” *Annu. Rev. Phys. Chem.* **52**, 241–253 (1959).
- ⁹W. H. Boldingh, “Grafische ermittlung der verluste an primärstrahlung infolge unrichtiger zentrierung und bewegung von streustrahlenblenden,” *Fortschr. Geb. Rontgenstr. Nuklearmed.* **89**, 233–238 (1958).
- ¹⁰W. H. Boldingh, “Quality and choice of Potter Bucky grids: Parts IV and V,” *Annu. Rev. Phys. Chem.* **55**, 225–235 (1962).
- ¹¹National Electrical Manufacturers Association, *Digital Imaging and Communications in Medicine (DICOM). Part 3: Information Object Definitions* (NEMA, Rosslyn, VA, 2008), <ftp://medical.nema.org/medical/dicom/2008/>.
- ¹²J. J. Palmer, *How to Brew: Everything You Need To Know To Brew Beer Right The First Time*, 3rd ed. (Brewers, Boulder, CO, 2006).
- ¹³R. Birch, “The spectrum and intensity of extra-focal (off-focus) radiation,” *Br. J. Radiol.* **49**, 951–955 (1976).
- ¹⁴S. R. Thomas, J. E. Freshcorn, K. B. Krugh, G. C. Henry, J. G. Kereiakes, and R. A. Kaufman, “Characteristics of extrafocal radiation and its potential significance in pediatric radiology,” *Radiology* **146**, 793–799 (1983).
- ¹⁵E. S. Ali and D. W. Rogers, “Quantifying the effect of off-focal radiation on the output of kilovoltage x-ray systems,” *Med. Phys.* **35**, 4149–4160 (2008).
- ¹⁶See EPAPS Document No. E-MPHYA6-36-031909 for supplementary executable file. For more information on EPAPS, see <http://www.aip.org/pubservs/epaps.html>.