Investigation of the line-pair pattern method for evaluating mammographic focal spot performance

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The latest American College of Radiology (ACR) Mammography Quality Control Manual contains a new method for evaluating focal spot performance, which this paper refers to as the ''line-pair pattern test.'' The ACR describes a variety of methods for performing this test, and does not advocate one method over another. The authors of this paper conducted an investigation to compare the optional ways for performing the test. Resolution measurements were obtained using a prototype line-pair resolution phantom imaged with a GE DMR mammography unit. Measurements were made with the line-pair pattern 4.5 cm above the breast support platforms in both conventional (contact) and magnification geometries. Both 4.5 cm of air and Lucite were tested as attenuators between the line-pair pattern and the breast support platform. Image receptors that were employed included film alone, screen-film, and screen-film that was not allowed to wait the recommended 15 min before exposure. kVp was varied as was the orientation of the line-pair pattern relative to the chest wall. For the air attenuator case, the screen degraded the measured resolution by 1–3 lp/mm when compared to the direct film. The Lucite attenuator reduced the resolution by an additional 1 lp/mm. Increasing kVp improved the resolution slightly for the conventional mode, but decreased it slightly for the magnification mode. Based upon the results of this study, recommendations are made for improving the test protocol. For a test of focal spot performance, one should use the no-attenuation with direct film detector setup. For a measure of the resolution of the entire imaging chain, one should use the Lucite attenuator with screen-film detector setup. [S0094-2405(97)01001-8]

Key words: mammographic resolution, focal spot, quality control

I. INTRODUCTION

The latest edition of the American College of Radiology (ACR) Mammography Quality Control (QC) Manual[1] contains a description of a new method for routine evaluation of focal spot performance in mammographic units. This method determines ''limiting resolution'' in units of line pair per millimeter (lp/mm) rather than effective focal spot size in millimeters, which is determined with the other (slit camera) method described in the manual. The ACR refers to the new method as a ''high-contrast resolution pattern'' method and recommends that either a bar pattern, star pattern or wedge pattern be employed as the test tool. Since most implementations of this method involve bar or line-pair patterns, we will refer to it as the ''line-pair'' method in this paper. The ACR recommends that both the line-pair and slit camera methods be employed for acceptance testing of new mammography units, and the line-pair method alone be used for routine (e.g., annual) QC tests. If a system fails the routine QC test, the ACR suggests performing a more detailed investigation using the slit camera method. Although the motivation for recommending the new focal spot test is not discussed in the manual, it is obvious that the ACR desires a test that is easier to perform and more directly related to the spatial resolution observed in clinical images.

The ACR recommends that a high-resolution bar pattern be employed for the line-pair test, specifically, one extending to about 20 lp/mm. This pattern is placed 4.5 cm above the breast support plate, centered laterally and positioned within 1 cm of the chest wall edge of the imaging receptor. The pattern is imaged with the bars both parallel and perpendicular to the anode–cathode axis of the x-ray tube. The ACR describes several optional setups for performing the line-pair resolution test. These include: (1) either no material (except air) or a 4.5-cm-thick homogeneous attenuator (e.g., Lucite) being placed between the pattern and the breast support plate, and (2) either screen-film or direct film (e.g., a ready pack) being employed as the detector.

The purpose of our study was to compare the results for a variety of the possible attenuator–detector combinations. Other studies on the effects of intensity distribution, position, kVp/mA and screen-film contact on mammographic focal spot measurements have been reported in the literature,[2–4] but none have specifically analyzed the line-pair pattern methods recommended by the ACR.

II. MATERIALS AND METHODS

The test tool we employed was a prototype manufactured by Computerized Imaging Reference Systems (CIRS, Inc., Norfolk, VA). It has a solid Lucite base with a slider/pattern holder on the top surface. The slider can either be positioned directly above the Lucite base to achieve the 4.5-cm-thick homogeneous attenuator condition, or be extended out from the base (i.e., cantilevered) to achieve the ''no attenuator'' condition, with the pattern held securely 4.5 cm above the breast support plate. The line-pair pattern itself is made of gold and contains individual segments having resolutions of 5, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 and 20 lp/mm. The length of the pattern from the 5 lp/mm end to the 20 lp/mm end is 1.8 cm. The pattern is encased in a thin plastic piece that fits within a recessed well in the slider, permitting the pattern to be positioned either with the bars parallel or perpendicular to the x-ray tube anode–cathode axis.

All tests were performed on a General Electric (Milwaukee, WI) model DMR mammography x-ray unit in our clinic. This unit has nominal focal spot sizes of 0.1 and 0.3 mm. It was operated only in the molybdenum target, molybdenum filter mode for this study. Using 0.5° and 1.0° star patterns within a GE supplied holder that positions the patterns along the appropriate reference axes of the mammography unit, we measured the large and small focal spot dimensions to be 0.42 mm×0.33 mm and 0.09 mm×0.06 mm, respectively, where the first dimension represents the width and the second, the length of the focal spot.

The screen-film detector was Kodak (Rochester, NY) Min-R/Min-R E. To ensure that the same imaging geometry (specifically focus-to-film distance) was employed for both the screen-film and direct film detector situations in our study, we chose not to use a ‘‘ready pack’’ as the direct film detector. Instead, we used an identical screen-film cassette, but blocked virtually all screen light by placing a totally black film between the screen and the Min-R film that was used as the detector. The latter film was placed emulsion side up (facing the x-ray tube) to further reduce any effects of the screen light. The ‘‘totally black film’’ was obtained by developing a Min-R E film that we purposely exposed to direct light. Its measured optical density was 4.39; hence its visible light transmission was about 0.004%.

To begin the study, we placed the line-pair pattern directly on top of a screen-film cassette that was placed on the breast support plate and made an exposure (the technique was 26 kVp, 5 mAs, 0.5 mm aluminum additional filtration). The developed film provided us with the limiting resolution of the screen-film system by itself (no effect of the focal spot).

We then proceeded to perform the line-pair pattern test under a variety of possible conditions described in the ACR manual. For conventional (contact) geometry (0.3 mm focal spot, line-pair pattern 4.5 cm above the cassette holder/breast support plate), these included tests with no attenuator (air) between the pattern and breast support plate and both direct film and screen-film as the detectors, and tests with 4.5 cm of Lucite between the pattern and the breast support plate with a screen-film as the detector. For the latter test, the Bucky (grid) cassette holder was employed; whereas, for the tests with no attenuator, the gridless magnification cassette holder was employed. For 1.8× magnification geometry, the line-pair pattern was placed 4.5 cm above the magnification stand/breast support platform, and tests were performed using the no-attenuator with direct film combination and using the Lucite with screen-film combination. The gridless cassette holder was employed for all magnification techniques. Tests using the Lucite with direct film combination were not performed for either the contact or the magnification geometry cases because of the excessive exposure times that would have been required. Finally, for the no-attenuator with screen-film cases, we found it necessary to add a 0.1 mm aluminum filter to the beam in order to achieve the desired film optical density at minimal x-ray system mAs. This additional filtration was taped to the collimator to minimize the influence of the resulting x-ray scatter.

The same screen-film cassette was employed for all screen-film detector images, and each time the film was loaded, we waited at least 15 min before making the exposure in order to permit any entrapped air between the film and screen to escape.

The majority of the exposures were made at 26 kVp which is a typical x-ray tube potential used for imaging an average breast in our clinic. The ACR recommends the use of such a tube potential for the test. The mAs was adjusted to obtain films with background optical densities (in the region just outside the image of the line-pair pattern) in the 1.2–1.6 o.d. range suggested in the ACR manual.

Several additional comparison images were also obtained at tube potentials of 22 and 30 kVp to determine the influence of kVp on the measured resolution. Also a limited study was performed in which radiographs were produced without waiting 15 min between loading the film in the cassette and making the exposure to examine what effect this might have on the measured resolution.

In performing the tests, measurements were made with the bars of the line-pair pattern both parallel and perpendicular to the anode–cathode axis of the x-ray tube. In most cases, when the bars were perpendicular to the anode–cathode axis, the bar pattern was oriented such that the 20 lp/mm end was closest to the chest wall. To determine the influence of pattern position on spatial resolution, a limited series of tests were also performed in which, instead, the 5 lp/mm end was closest to the chest wall.

Three medical physicists (the authors of this paper) reviewed the images of the bar patterns with 7× and 30× magnifying lenses, and the resolutions were determined by consensus as follows. Each physicist examined the images independently and decided upon a resolution using the ACR criterion that the lines be distinctly visible throughout at least half the bar length. In most cases the first analyses were made with the 7× magnifier, which was easier to use. The physicists then discussed their assessments, and if there were differences, the images were reexamined with the 7× and 30× magnifiers. The results were discussed further and a resolution was decided upon that was agreeable to all. The maximum difference between the assessments of the individual readers was 1 lp/mm, and it was felt that our decision by consensus was as effective and valid as the ACR method of averaging the individual readings.

III. RESULTS

The radiograph produced with the pattern placed directly on top of the screen-film cassette displayed 20 lp/mm resolution. The resolutions measured in the contact mode (0.3

TABLE I. Measured resolution for contact geometry using nominal 0.3 mm focal spot and 26 kVp (a plus sign implies bars very clearly discerned and limiting resolution is greater by about 0.5 lp/mm or more).

Attenuator	None (air)	None (air)	Lucite
Detector	Direct film	Screen-film	Screen-film
Use of grid	No	No	Yes
mAs	160	4 (with 0.1 mm additional Al attenuation)	160
Limiting resolution with bars parallel to anode–cathode axis	20 lp/mm	17 lp/mm	16 lp/mm
Limiting resolution with bars perpendicular to the anode–cathode axis (20 lp/mm segment within 1 cm from the chest wall)	20+ lp/mm	18 lp/mm	18 lp/mm
Limiting resolution with bars perpendicular to the anode–cathode axis (5 lp/mm segment within 1 cm from the chest wall)	20+ lp/mm	18+ lp/mm	

TABLE II. Measured resolution for 1.8 times magnification geometry using nominal 0.1 mm focal spot and 26 kVp (a plus sign implies bars very clearly discerned and limiting resolution is greater by about 0.5 lp/mm or more).

Attenuator	None (air)	None (air)	Lucite
Detector	Direct film	Screen-film	Screen-film
Use of grid	No	No	No
mAs	200	7 (with 0.1 mm additional Al attenuation)	160
Limiting resolution with bars parallel to the anode–cathode axis	20+ lp/mm	20+ lp/mm	19 lp/mm
Limiting resolution with bars perpendicular to the anode–cathode axis (20 lp/mm segment within 1 cm from chest wall)	15 lp/mm	14 lp/mm	13 lp/mm
Limiting resolution with bars perpendicular to anode–cathode axis (5 lp/mm segment within 1 cm from chest wall)		16 lp/mm	

mm focal spot) at 26 kVp are listed in Table I and those measured in the 1.8× magnification mode (0.1 mm focal spot) are listed in Table II. The mAs factors are also included in the tables. In general, the spatial resolution is best for the no-attenuator direct-film detector *test method*. The resolution degrades by 1–3 lp/mm when screen-film is used as the detector. An additional degradation of about 0.5–1 lp/mm occurs when Lucite is employed as the attenuator between the line-pair pattern and the detector. Waiting 1–2 min instead of 15 min to permit entrapped air between the film and screen to escape resulted in reduced resolution by as much as 3 lp/mm.

The measured spatial resolutions at different kVp's are listed in Table III(a) for the contact geometry and Table III(b) for the 1.8× magnification geometry. In general, we observed that the spatial resolution improved as the kVp increased for the contact geometry, but it displayed the exact opposite trend for the magnification geometry.

IV. DISCUSSION

All of the measured spatial resolutions listed in Tables I–III for the various setups exceed the minimum performance standards suggested by the ACR. For contact geometry, the minimum acceptable values are as follows: 13 lp/mm with the bars parallel to the anode–cathode axis and 11 lp/mm with the bars perpendicular to the anode–cathode axis. For magnification mode, the ACR states that the minimum resolution should be no lower than the values specified for contact geometry. It is interesting to note that for the GE DMR mammography unit in our facility, the resolution with the bars perpendicular to the anode–cathode axis is actually considerably worse in the magnification mode than in the contact geometry mode (see Tables I and II). The resolution is a function of focal spot shape, size, and central axis position and this property of lower resolution in the magnification mode may or may not be true for other manufacturer's mammography units.

Even though our measurements showed that the inherent resolution of the screen is slightly better than 20 lp/mm, the measured resolutions of the line-pair pattern in contact [magnification $(M)=1.1$] and magnification $(M=1.8)$ geometries were 1–3 lp/mm worse with the screen-film than with the direct film detector. The reason can be explained in terms of the overall MTF's of the imaging systems. The overall MTF is the product of the MTFs of the individual components (e.g., the MTFs of the focal spot, film, and screen). The geometric magnification factors associated with both the contact and magnification techniques result in degradation of the MTF of the focal spot and improvement in the effective MTF of the screen. When the latter improvement is not great enough to compensate for the focal spot MTF degradation, the limiting resolution is reduced to a lower spatial frequency, as we observed.

When performing the resolution measurements with a screen-film detector, it is very important to allow enough time for the entrapped air between the film and screen to escape. The ACR recommends waiting 15 min in their protocol for screen-film contact verification, but does not include this recommendation in the protocol for the focal spot

TABLE III. Resolution as a function of kVp for (a) contact geometry using a 0.3 mm focal spot and (b) 1.8 times magnification geometry using a 0.1 mm focal spot (a plus sign implies bars very clearly discerned and limiting resolution is greater by about 0.5 lp/mm or more).

(a) Attenuator	None (air)			Lucite	
Detector	Direct film			Screen-film	
Use of grid	No			Yes	
X-ray tube potential	22 kVp	26 kVp	30 kVp	26 kVp	30 kVp
Limiting resolution with bars parallel to the anode–cathode axis	18 lp/mm	20 lp/mm	20 lp/mm	16 lp/mm	17 lp/mm
Limiting resolution with bars perpendicular to the anode–cathode axis (20 lp/mm segment within 1 cm from chest wall)	20+ lp/mm	20+ lp/mm	20+ lp/mm	18 lp/mm	18 lp/mm

(b) Attenuator	None (air)		
Detector	Direct film		
Use of grid	No		
X-ray tube potential	22 kVp	26 kVp	30 kVp
Limiting resolution with bars parallel to the anode–cathode axis	20+ lp/mm	20+ lp/mm	20 lp/mm
Limiting resolution with bars perpendicular to anode–cathode axis (20 lp/mm segment within 1 cm from chest wall)	16 lp/mm	15 lp/mm	14 lp/mm

evaluation. Our tests revealed that too short a waiting time can reduce resolution by as much as 3 lp/mm. We believe that the ACR should include a reminder concerning the 15 min waiting time in their ''Precautions and Caveats'' statements for any tests dealing with spatial resolution, in particular the high contrast resolution test and the phantom image quality test.

When the Lucite attenuator is placed in the beam, the resulting increase in x-ray scatter at the detector causes a reduction in measured spatial resolution of about 1 lp/mm relative to the no-attenuator situation. (Compare columns 2 and 3 of Tables I and II.) This trend is expected since the scatter reduces the imaged contrast of the line-pair pattern. It is more difficult to analyze the images produced with the Lucite attenuator because of the reduced contrast; however, the imaging situation is closer to that for patients.

When examining images of the line-pair pattern, care must be taken to read from low line pairs to high line pairs so that spurious resolution is avoided. This effect is the same as that observed in the star pattern focal spot evaluation test. Resolution is apparent up to a certain lp/mm, after which it is lost, and then it seems to return with phase reversal (the black and white bars are reversed) at even higher lp/mm. The limiting resolution is the line pair of the segment that precedes the first one that cannot be resolved. The patterns that are employed for this test must contain fairly fine lp/mm increments; otherwise, the true limiting resolution may not be detected.

The ACR protocol stipulates that the line-pair pattern be placed ''within 1 cm of the chest wall edge of the image receptor.''[1] These protocol directions are somewhat ambiguous for the case when the bars of the pattern are perpendicular to the anode–cathode axis, since one does not know which lp/mm segments of the pattern should be within the 1 cm distance. The effective focal spot size and the resultant spatial resolution varies rapidly along the anode–cathode direction. The distance between the lowest (5 lp/mm) and the highest (20 lp/mm) spatial resolution segments of our particular pattern was 1.8 cm. As seen in Table I, the results were about the same for contact geometry when the pattern was oriented with either the 5 or 20 lp/mm segment closest to the chest wall. However, for magnification geometry (Table II) there was a 2 lp/mm difference. To ensure consistent and comparable results, we believe that the ACR should recommend a specific design for the line-pair pattern (including dimensions) and should specify the position of a particular segment of the pattern. For example, they could specify that the 20 lp/mm segment be placed 0.5 cm from the chest wall edge of the image receptor, with lower resolution segments directed toward the nipple position. The ACR should also provide a more detailed description of where to place the pattern when performing the test in magnification mode. It is not clear whether the pattern or the projected image of the pattern should be within 1 cm of the chest wall edge of the detector. We placed the pattern within 1 cm of the top chest wall edge of the magnification stand when we performed our tests.

The x-ray tube potential (Table III) had a noticeable influence on the focal spot performance. For contact geometry, [Table III(a)] the resolution improved as the kVp increased. This was especially apparent when the bars of the pattern were oriented parallel to the anode–cathode axis. It is an expected result since the effective focusing of the electron beam in the x-ray tube is known to improve as the kVp is increased. For the magnification geometry, however, the resolution degraded as the kVp increased. This seemingly aberrant result can be explained by the fact that focal spot size is both a function of kVp and mA—the size decreases as the kVp increases and increases as the mA increases. On the GE DMR mammography unit, the mA changes as the kVp is varied. There is greater mA at high kVp and lower mA at low kVp. This change is much greater for the small focal spot than for the large (e.g., in going from 25 to 30 kVp on the large focal spot, there is a 14% increase in mA; whereas, the corresponding increase in mA for the small focal spot is 45%). For the small focal spot case, the mA is more important in determining focal spot size and resolution than the kVp. Accordingly, the lowest mA at 22 kVp in our tests results in the best resolution; whereas, the highest mA at 30 kVp results in the poorest resolution.

V. CONCLUSION

The new line-pair method for evaluating focal spot performance is convenient and easy to perform.

As shown in Tables I–III, the results of the line-pair resolution test depend upon the setup employed. Of the three possible setups, we prefer the one using no attenuator and direct film, because it does not require a 15 min waiting time between loading the cassette and making the exposure, and it results in a truly quick measure of focal spot performance. If, instead, one is interested in measuring the resolution of the entire imaging chain in a cliniclike situation, one should use the Lucite attenuator with screen-film detector setup. The third alternative—use of no attenuator with screen-film is not recommended.

In many instances, we were able to clearly discern the 20 lp/mm segment of the test pattern and expected to resolve greater line pairs. A pattern that ranges from 9 to 25 lp/mm in 1 lp/mm increments might be useful for more accurately determining the limiting resolution of a mammography system. Of course use of such a pattern is not absolutely necessary, as 20 lp/mm resolution should be more than adequate in most imaging situations.

The previous edition of the ACR manual[5] included the description of a focal spot test using a star pattern test tool. Because the spokes in the star pattern essentially produce a continuous rather than discrete spatial frequency scale, this test may yield a more accurate assessment of focal spot size than the line-pair resolution test. Furthermore, the star pattern test is easy to perform, especially when a star pattern positioner/holder is provided by the manufacturer. We hope that the ACR will endorse both the star pattern test with the focal spot test stand[5] and the star pattern test with manufacturer provided positioner/holder as additional acceptable focal spot evaluation methods in the next mammography QC manual. Finally, if the positioner/holder method is endorsed, the ACR should provide manufacturers with guidelines for the proper position of the star pattern (e.g., the projected center should be 4 cm from the chest wall).

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