An automatic and accurate x-ray tube focal spot/grid alignment system for mobile radiography: System description and alignment accuracy^{a)}

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Purpose: A mobile radiography automatic grid alignment system (AGAS) has been developed by modifying a commercially available mobile unit. The objectives of this article are to describe the modifications and operation and to report on the accuracy with which the focal spot is aligned to the grid and the time required to achieve the alignment.

Methods: The modifications include an optical target arm attached to the grid tunnel, a video camera attached to the collimator, a motion control system with six degrees of freedom to position the collimator and x-ray tube, and a computer to control the system. The video camera and computer determine the grid position, and then the motion control system drives the x-ray focal spot to the center of the grid focal axis. The accuracy of the alignment of the focal spot with the grid and the time required to achieve alignment were measured both in laboratory tests and in clinical use.

Results: For a typical exam, the modified unit automatically aligns the focal spot with the grid in less than 10 s, with an accuracy of better than 4 mm. The results of the speed and accuracy tests in clinical use were similar to the results in laboratory tests. Comparison patient chest images are presented—one obtained with a standard mobile radiographic unit without a grid and the other obtained with the modified unit and a 15:1 grid. The 15:1 grid images demonstrate a marked improvement in image quality compared to the nongrid images with no increase in patient dose.

Conclusions: The mobile radiography AGAS produces images of significantly improved quality compared to nongrid images with alignment times of less than 10 s and no increase in patient dose. © 2010 American Association of Physicists in Medicine. [DOI: [10.1118/1.3518085](https://doi.org/10.1118/1.3518085)]

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I. INTRODUCTION

Scattered radiation has long been known to reduce the subject contrast of radiographs. In radiography, antiscatter grids are routinely used to reduce scatter and improve image contrast. Two exceptions exist: Radiography of thin subjects, such as extremities and infants, and mobile radiography. Antiscatter grids are not used for extremities and infants because thin subjects produce little scatter. In mobile radiography, grids are often not used because of the difficulty in aligning the x-ray tube focal spot with the grid and because of artifacts and poor image contrast that can result when the focal spot and grid are misaligned.

The advent of digital imaging has introduced the possibility of increasing image contrast through image processing. Several researchers have developed algorithms to reduce the effect of scatter in clinical images.^{1–7} While linear techniques such as scatter deconvolution^{1–6} can improve the contrast of an image, the image contrast-to-noise ratio (CNR) cannot be improved because of the inability to remove the quantum noise inherent in the scatter signal. Nonlinear techniques such as Bayesian image estimation⁷ can increase the CNR but require *a priori* knowledge of the scatter-free image. It has long been known that the use of an antiscatter grid does increase the CNR at constant patient exposure in moderate

and high-scatter situations, but can lower the CNR in low-scatter situations.^{8–11}

In fixed radiographic equipment, the image receptor and the x-ray tube are mechanically linked and designed to ensure that the x-ray focal spot is aligned with the grid focal axis and image receptor. This is not the case in mobile radiography. The image receptor is placed between the mattress and the patient, and the x-ray tube is manually positioned over the patient. The task of centering the tube over the image receptor with the correct source-image distance (SID) and the central ray orthogonal to the grid is left to the technologist. Visually aligning the focal spot and image receptor with the accuracy required to use a grid is difficult and time consuming, and the level of accuracy achieved is less than with fixed equipment.

If the x-ray source is located on the grid focal axis but is not centered over the grid (on-axis misalignment), the alignment between the radiation field and the image receptor is affected, but the grid transmission is not reduced nor are image artifacts produced. When the x-ray source is centered over a level grid but the SID is incorrectly set (off-focus misalignment), the transmission of the grid to primary x rays is unchanged at the center of the grid but will be degraded toward the sides of the grid that are parallel to the grid focal axis. When the SID is correctly set but the x-ray source is to

the side of the grid focal axis (lateral misalignment), the grid transmission is uniformly degraded, increasing image noise and reducing contrast. Off level or tilt misalignment occurs when the focal spot is directly over the center of the grid and is the correct distance from the center, but the grid is tilted. For small tilt angles, the effect of off level misalignment on the grid primary transmission is essentially the same as lateral misalignment. For large tilt angles, the effect of off level misalignment is equivalent to a combination of lateral and off-focus misalignment. When lateral and off-focus misalignment are both present, grid transmission varies asymmetrically across the image. In chest radiography, this artifact could change the apparent relative lucency of the lungs and possibly mimic pathology. As a result, grids are not commonly used in chest mobile radiography. The effects of grid misalignment are more pronounced as grid ratio increases, and so high ratio (12:1–15:1) grids are seldom used in mobile radiography. When a grid is used in mobile radiography, it usually has a low ratio (6:1–10:1), is usually not accurately aligned, and the full benefit of employing a grid is not realized.

Several researchers have investigated the means of aligning the focal spot and grid in mobile radiography.^{12–17} MacMahon¹² and Niklason *et al.*¹³ developed mechanical attachments that couple the grid to a mobile radiographic unit and require a trial and error process on the part of the technologist to align the focal spot and grid. MacMahon *et al.*^{14–16} subsequently developed a laser device that requires the user to align a laser, also by trial and error, to a mark in the collimator light field and a reflector mounted on the corner of the grid. O'Donovan *et al.*¹⁷ developed a system involving an electronic level on the grid housing, a second level on the source housing, an alignment target attached to the source, and cross-hairs in the alignment light field. The user employed a tape measure to ensure the proper SID and the collimator light to position the tube housing until the shadow of the cross-hair fell on a mark on the grid housing. The user would then rotate the source housing until the two levels indicate that the central ray was normal to the grid housing in one direction.

These systems required extra and tedious effort on the part of the technologist to align the focal spot and grid, and, as a result, never gained widespread clinical acceptance. In the present paper, we describe the modifications to a commercially available mobile radiographic unit that permits the automatic alignment of the x-ray tube focal spot to the grid (and image receptor). The automatic grid alignment system (AGAS) simplifies the task of aligning the x-ray source to the grid (and image receptor) by automating the processes of position measurement and tube movement. Described are measurements of the accuracy of the focal spot to grid alignment obtained with the mobile radiography AGAS. Also presented are a clinical chest image taken conventionally without a grid and an image of the same patient taken at the same kVp and mAs (and patient dose) with a high ratio grid aligned with the mobile radiography AGAS.

FIG. 1. The AMX-4+ modified with the AGA system. The modifications shown are (a) camera and LED lamp array housing mounted in front of the collimator, (b) grid tunnel mounted on the cassette bin door, (c) alignment button mounted on the side of the collimator, (d) optical target arm mounted on the top of the horizontal extension arm, and (e) housing for vertical drive motor.

Table of Abbreviations

AGAS	= Automatic grid alignment system
CNR	= Contrast-to-noise ratio
CPU	= Central processing unit
ICU	= Intensive care unit
IEEE-1394	= Communication bus standard commonly called "Firewire"
MCS	= Motion control system
MCU	= Microcontroller unit
RMS	= Root mean square
RS-485	= Industry standard noise resistant multinode serial communication bus
SID	= Source-to-image distance

II. MATERIALS AND METHODS

II.A. Mobile radiographic unit, grid tunnel, and target arm

The mobile radiography AGAS consists of a modified GE AMX-4+ (GE Healthcare, Waukesha, WI) mobile radiographic unit (see Fig. 1) and a custom built grid tunnel with an optical target arm (see Fig. 2). The grid tunnel has an aluminum frame and carbon fiber covers and can be equipped with a variety of standard antiscatter grids. The grids are inserted with the grid lines running parallel to the short sides of the tunnel. The tunnel can accommodate standard 35 cm × 43 cm computed radiography (CR) cassettes and is built with rounded edges and handles to make it easier to slide under the patient. A removable target arm is attached to either side of the grid tunnel, and an optical target is mounted on the end of the arm. The arm is long enough to

FIG. 2. The custom grid tunnel with the target arm attached to the left dock. The arm may be attached to either the left or right dock by the technologist as desired.

extend out from under a large patient so the optical target is visible from the x-ray collimator housing when the x-ray tube is placed over the patient. The optical target consists of four markers made of retroreflective material.

II.B. Mobile radiographic unit modifications

Figure 3 is a schematic diagram of the AGAS modifications that were incorporated into the AMX-4+ unit. The host central processing unit (CPU) was a Pentium-based (Intel Corporation, Santa Clara, CA) embedded computer running the Windows XP Embedded operating system (Microsoft Corporation, Redmond, WA) and custom written software. The video camera was a Fire-i OEM B/W Board Camera (Unibrain SA, Athens, Greece). As shown in Fig. 1, the camera was mounted in front of the collimator housing and is surrounded by an array of high intensity light emitting diodes (LEDs) (Super Bright LEDs, Inc., St. Louis, MO).

The tube support mechanism was modified by adding a motion control system (MCS), composed of a motor, gear box, and position encoder for each of six degrees of freedom—three for positioning the x-ray tube focal spot (rotation of the column, elevation of the arm, and extension

of the arm), two for directing the x-ray beam central axis (roll about the long axis of the arm and pitch about the anode-cathode axis of the tube), and one for collimator rotation. Each of the six motions has a motor/encoder pair serviced by a motion control printed circuit board (PCB) with a microcontroller unit (MCU) and motor drive and signal circuitry. Each MCU services the motor drive, electromagnetic brake and clutch (if present), and position encoder, and communicates with the host CPU via an RS-485 bus running a proprietary protocol.

The video camera is connected to the host CPU by an IEEE 1394 bus (commonly known as a Firewire bus). The LED array surrounding the camera is controlled by a microcontroller that is connected to the host CPU via the RS-485 communication bus. Employing custom written software, the host CPU interprets position data read from the video camera and subsequently directs the motion control system to drive the x-ray tube housing and collimator to the correct position and orientation.

The user interface consists of colored status LEDs on the collimator/video camera housing, an alphanumeric display on the x-ray console for more detailed information, and a detachable deadman hand switch on the side of the collimator. When the status LEDs indicate AGAS is ready, the user removes the hand switch from its mount on the collimator and depresses the switch, and the computer starts the alignment process and energizes the MCS. If the operator releases the switch at any time before the system is aligned, the alignment is aborted and the motors stop. Thus, the alignment is completely under user control. A second safety feature is that the dead man switch has two positions and two microswitches. Both have to be closed to initiate the alignment process and energize the MCS.

The modifications did not affect the manual operation of the AMX-4+. That is, the modified unit can be used without AGAS to image patients in the same manner as an unmodified AMX-4+.

II.C. System operation

The system is operated as follows:

- (1) The technologist places an image receptor into the grid tunnel and places the grid tunnel partially under the patient.
- (2) The x-ray tube is then manually positioned over the patient.
- (3) The technologist removes the target arm from its mount on the tube support arm and attaches the target arm to the grid tunnel. He/she then slides the grid tunnel fully under the patient.
- (4) The technologist verifies that the video camera is pointed roughly at the optical target and that all target markers are visible and then pushes the alignment button.
- (5) The computer determines the location of the focal spot relative to the optical target, directs the MCS to move the x-ray tube to its proper position, and then takes a second position measurement to verify the alignment.

FIG. 3. Schematic showing major electrical subsystems and components of the AGA system. All components shown are added except the three components in the AMX-4+ box.

FIG. 4. Images of the optical target captured from the video camera: (a) Background image (LED array off), (b) foreground image (LED array on), and (c) background-corrected image. Note that a ball of crumpled aluminum foil used as a distracter for these pictures is visible near the center of (a) and (b) but not in (c).

- (6) If the system is aligned, a green LED on the collimator is illuminated, indicating that the system is ready for x rays. Otherwise, the computer repeats step (5) until the system is aligned.

Note that step (5) takes 7 s or less, depending on the amount of movement required. When step (5) is repeated, the movement required is small and it is rarely repeated more than once. Thus, the automatic part of the alignment process generally takes less than 10 s. A video of the mobile radiography AGAS in simulated clinical use is available through the supplementary material archive.¹⁸

II.D. Software

As noted above, the host CPU is a Pentium-based single board embedded computer running Windows XP. The software is stored on a solid-state Flash drive in a read-only configuration; this prevents the operating system from being corrupted when the system is shut down. When the AMX-4+ is turned on, the Windows operating system and AGAS application loads in approximately 45 s. During this time, the AMX-4+ can be moved to the patient's bedside. When the software is loaded, the status LEDs and alphanumeric display indicate that AGAS is ready for use. When the hand switch button is depressed, the AGAS software application acquires two images of the optical target, one with the LED lamp array turned off and one with the array turned on. The software then subtracts the images to generate a background-corrected image; in this image the optical targets have extremely high contrast relative to the background. Examples of the foreground, background, and difference images are shown in Fig. 4. The software processes the background-corrected image to determine the focal spot position relative to the grid. The ideal position for the focal spot is determined and the software directs the motors to move the focal spot to this position, to aim the central axis of the x-ray beam at the center of the grid, and to align the radiation field with the image receptor. The data acquisition and processing generally take less than 0.25 s, and, as noted above, the motion generally takes 7 s or less. After the motion is completed, a second set of images of the optical target is

FIG. 5. Camera calibration jig. The camera is positioned a known distance above a grid of dots spaced by 1 cm. The larger central dot identifies the center of the reference plane.

acquired and processed. If the alignment is not acceptable, then the focal spot position is fine-tuned; this process may be repeated up to five times. The software labels an alignment as acceptable if the on-axis misalignment is less than 10 mm, the off-focus misalignment is less than 5 mm, and the lateral misalignment is less than 3 mm. For most alignment attempts, the focal spot is moved close to the desired location on the first try and rarely does it take more than one fine-tuning to achieve an acceptable position.

The software includes several error checking steps to ensure that the calculation of the focal spot position is valid. There must be exactly four objects in the image with the size, shape, and brightness of the fiducial markers, these must be within approximately 1 pixel of the correct position, and the desired focal spot position must be no more than 30 cm from the present focal spot position. These test conditions will not be met if any of the targets is fully or partially blocked from the camera by sheets, lines, or other objects, if an object appears in the image that mimics a fiducial marker, or if the system is sufficiently misaligned at the start. If any of the test conditions is not met, the images are reacquired and reprocessed. If several such failures occur in a row, the procedure is aborted and an error message displayed.

If at any point the user releases the alignment button, the motors are stopped and the alignment process is aborted. This is a safety feature to protect both personnel and medical equipment.

II.E. Calibration procedure

II.E.1. Camera calibration

The first data processing step in the position measurement uses the background-corrected image to calculate the grid position and orientation relative to the camera. This involves comparing the predicted positions of the optical targets in the

FIG. 6. Radiographic alignment jig. The upper and lower plates contain radio-opaque objects; the positions of these objects in the acquired image are analyzed to determine the location of the focal spot.

image to the actual measured positions. To calculate the predicted positions, the software calculates the positions of the targets in the three-dimensional frame of reference of the camera and then projects these positions from the camera onto a reference plane. To be able to compare the predicted positions to the measured positions, each pixel in the camera image is mapped onto a point in the reference plane.

The camera calibration determines this mapping. This calibration is done before the camera is mounted on the collimator. The camera is positioned a known distance from a 1 cm calibration grid of small black dots and a single larger central dot (Fig. 5). The plane of the calibration grid defines the reference plane. An image is taken of the grid; this image is processed to determine the centroids of each of the dots. Each centroid is assigned a Cartesian coordinate equal to the coordinates of the corresponding dot relative to the large central dot. A two-dimensional quadratic function of pixel location is fitted to these coordinates; this function was chosen to provide a first-order correction for optical field curvature. From this fitted function, the reference plane x - y position is determined for every pixel in the camera image.

II.E.2. Geometry calibration

The data processing also requires comparing the measured position and orientation of the target array relative to the camera to the position and orientation of the target array when the system is aligned. A second calibration procedure, the geometry calibration, determines the relative position of the target array when the system is aligned and is done using a radiographic alignment jig (Fig. 6). The jig consists of two parallel sheets of Lucite mounted a fixed distance from each other. Radio-opaque fiducial markers are built into the sheets. The grid tunnel can be mounted to the bottom of the lower sheet. The position of the x-ray tube focal spot relative to the grid tunnel is determined by placing a CR cassette (Fujifilm Corporation, Tokyo, Japan) into the grid tunnel and taking a radiograph. The cassette is then processed and analyzed to determine the locations of the upper and lower plate fiducial markers in the images and, in turn, the position of the focal spot relative to the grid tunnel.

To perform the geometry calibration, the grid tunnel equipped with the target arm is placed in the test jig. The

focal spot is moved into position over the jig, a radiograph is taken, and the focal spot position is determined by analyzing the radiograph. If the focal spot position is not correct, the tube position is adjusted and the process is repeated until the focal spot is located at the center of the grid's focal axis. A position measurement is then taken with the video camera mounted on the collimator. The AGAS application then stores this measurement in a calibration file; the goal of each clinical alignment procedure thereafter is to bring the focal spot back to this position. The target arm is then moved to the second dock on the grid tunnel, and a second position measurement is taken and stored.

II.F. Laboratory tests

The ability of an experienced registered radiological technologist to manually align the x-ray tube focal spot and grid was evaluated. The grid tunnel and target arm were placed on a table with a torso phantom positioned centrally on the grid tunnel. The technologist then manually aligned the focal spot by eye with the grid tunnel, without using a measuring tape or the alignment light. Once the technologist was finished, the computer used the video camera to determine the relative position of the x-ray tube housing and the grid tunnel, and calculated and recorded the alignment error. The tube housing was returned to its docked position by hand and the process is repeated 16 times. The technologist then used AGAS to align the x-ray tube focal spot and grid. As in the manual alignment case, the tube housing was returned to its docked position by hand and the process is repeated 16 times. For each automatic alignment test, the computer recorded the time it took to align the system as well as the alignment error for the three directions (lateral misalignment, off-focus misalignment, and on-axis misalignment). The latter refers to the distance from the center of the grid along the focal axis of the grid; this alignment error has no effect on the grid primary transmission or cutoff. The focal spot-grid alignment for these tests was calculated from the video images of the target arm.

Tests were subsequently performed to verify that the focal spot position measurement based on the video camera images closely correspond to the actual focal position measured using the radiographic alignment jig. This is a test of the software routines that determine the relative location of the focal spot and the grid from the optical measurements. For this test, the grid tunnel equipped with the optical target was placed in the alignment jig. The position of the focal spot was determined radiographically using the alignment jig and optically using the video camera; the radiographic measurement is the gold standard of the position measurements. These measurements were recorded, and the tube was then moved to a different position and orientation. This procedure was repeated for five focal spot positions.

The alignment jig measurements determine the focal spot position in the coordinate system of the alignment jig, while the camera measurements determine the focal spot position in the optical target coordinate system. The camera measurements are then transformed into the alignment jig coordinate

TABLE I. Results of laboratory test comparing manual and automatic alignment. The alignment error is calculated from the optical measurement of the relative positions of the collimator and the optical target.

Misalignment direction	RMS error of manual alignment (mm)	RMS error of automatic alignment (mm)
On-axis	30.3	3.8
Lateral	49.5	1.4
Off-focus	28.5	1.4

system, and the root mean squared difference between the camera measurements and the radiographic measurements is computed for each of the three alignment directions.

Subsequently, a series of position measurements was made with the radiographic alignment jig to evaluate the accuracy and repeatability of the automatic alignment process. The tube was moved well out of position by hand, and then AGAS automatically aligned the focal spot. Once the system was aligned, a radiograph was exposed and analyzed to determine the error of the focal spot position in each of the three misalignment directions. This process was repeated for a total of 16 position measurements.

II.G. Clinical evaluation

The system was put into limited clinical use at the University of Alabama at Birmingham (UAB) Hospital. For a few weeks, the system was used occasionally for adult ICU chest exams. UAB Hospital has a fleet of more than 15 AMX-4+ mobile radiographic units. The majority of the exams done with these units are chest radiographs of ICU patients. For the reasons mentioned above, UAB Hospital's mobile chest radiographic protocol does not employ a grid. With the AGAS unit, a 15:1 Mitaya (Mitaya Manufacturing, Tokyo, Japan), 60 lines/cm grid was employed. Technologists were directed to use the same radiographic technique (same kVp and mA s) with the AGAS unit that they would use with a standard AMX-4+ mobile radiographic unit. Many ICU patients receive a chest radiograph each day. The majority of the ICU chest exam requests were accommo-

FIG. 7. Accuracy of camera position measurements for different focal spot positions. The vertical axis is the difference between the focal spot positions determined by camera measurement and by radiographic measurement. The horizontal axis is the radiographic position measurement.

TABLE II. Accuracy of camera measurements of the focal spot position.

Misalignment direction	RMS difference between radiographic and optical measurements (mm)
On-axis	2.8
Lateral	0.8
Off-focus	1.5

dated with a standard AMX-4+. On occasion, a request was accommodated with the AGAS unit. This allowed for the retrospective comparison of standard nongrid images with AGAS images of the same patients, with a delay of less than 1 day between images. All AGAS images were acquired with the patients supine or slightly elevated.

During the limited clinical use, the AGAS CPU was programmed to record for each alignment procedure the time required to align the system and the focal spot location as determined from camera measurements. The data from the ensemble of clinical measurements were analyzed to determine the root mean square (RMS) alignment error in each of the three misalignment directions and to determine the range and average of alignment times.

III. RESULTS

III.A. Laboratory tests

The results of the test comparing manual to automatic alignment error are presented in Table I. Using manual alignment, the technologist typically aligned the focal spot to the grid with a total error of about 60 mm. The largest errors were in the lateral direction; this is of particular concern because grid transmission is more sensitive to errors in this direction than the other two. In contrast, the automatic system aligned the focal spot to the grid consistently to within better than 5 mm and to within better than 1.5 mm in the lateral misalignment direction.

The difference between the radiographic and optical measurement techniques is presented in Fig. 7. The radiographically measured misalignment is plotted along the horizontal axis, while the misalignment determined using the camera is plotted along the vertical axis. The camera measurements agree with the radiographic measurements to within 3 mm over a range of positions of about 200 mm. In the critical lateral misalignment direction, the measurements all agree to

TABLE III. Results of laboratory test of automatic alignment. The alignment error is calculated from radiographic measurements of the focal spot position.

Misalignment direction	RMS alignment error (radiographic measurement) (mm)
On-axis	4.5
Lateral	1.9
Off-focus	1.4

TABLE IV. Accuracy of clinical alignment over 23 alignment procedures. The alignment error is calculated from optical measurements of the focal spot position.

Misalignment direction	RMS alignment error (optical measurement) (mm)
On-axis	3.6
Lateral	1.4
Off-focus	1.6

within 1.5 mm. A summary of the accuracy of the camera for all three directions is presented in Table II. The close agreement between radiographic and optical measurements demonstrates that the software calculates the focal spot position accurately to within 3 mm.

The radiographic measurements of the error after automatic alignment are summarized in Table III. The system reproducibly returns the focal spot to within 2 mm of its optimal location in the lateral and off-focus directions. Reproducibility in the on-axis direction is not as good, but as noted above, misalignment in this direction has no effect on the grid primary transmission. The time required to align the system automatically varied from 5.9 to 13.7 s, with an average time of 7.9 s.

III.B. Clinical evaluation

The results of the clinical alignment tests are summarized in Table IV. The clinical test differs from the laboratory test in that the focal spot position is determined using the video camera rather than radiographically. However, the correlation data of Fig. 7 and Table II demonstrate that the optical measurements are in close agreement with the radiographic measurements. The RMS clinical alignment error is comparable to that of the laboratory tests.

These results were obtained from measurements taken during 23 alignment procedures. The time required to align the system varied from 1.3 to 27.1 s, with an average of 9.3 s.

III.C. Clinical images

Figure 8 is a pair of clinical chest images; Fig. 8(a) was taken with no grid, and Fig. 8(b) was taken on the same patient 12–24 h earlier or later with a 15:1 grid aligned using the AGAS modified mobile radiographic unit. Both images were processed using the UAB Hospital's standard chest algorithm for CR images. Note that the technologist was directed to use the nongrid technique (kVp and mAs) for the grid image.

IV. DISCUSSION

The results presented demonstrate that the mobile radiographic AGAS can accurately and reproducibly align the focal spot with a grid. The positioning accuracy is within 2 mm RMS in the lateral and off-focus centering directions and within 5 mm RMS of the center of the grid in the on-axis direction. Misalignment in the lateral and off-focus direc-

(a)

(b)

FIG. 8. Clinical chest images of a patient acquired 12–24 h apart (a) without a grid and (b) with 15:1 grid aligned using AGAS.

tions result in decreased grid primary transmission and can give rise to grid artifacts; whereas if the x-ray tube focal spot lies on the grid focal axis and is not centered to the grid, the radiation field is shifted relative to the grid and image receptor, but there is no loss of grid primary transmission and grid misalignment artifacts are not present. In clinical practice, a 5 mm positioning error between the radiation field and the image receptor is within acceptable limits; this is 0.5% of SID, which is much better than the 2% required by FDA regulations for fixed equipment. The superior performance in the lateral and off-focus directions compared to the on-axis is by design; the software has tighter margins for acceptable alignment for lateral and off-focus misalignment than for on-axis misalignment.

The laboratory manual alignment test results validate the conventional wisdom that using a high ratio grid in bedside radiography does not usually improve image quality. The data in Table I show that the RMS lateral misalignment for manual alignment was ≈ 50 mm. For a 15:1 grid, this would result in a 70% reduction in the grid transmission, i.e., the grid primary transmission would decrease from $\approx 60\%$ to $\approx 18\%$. Grid misalignment does not significantly affect the

scatter transmission; approximately the same amount of scatter is transmitted by a grid and is incident on the image receptor whether the grid is aligned or misaligned. For a given x-ray beam, the result of employing a 15:1 grid laterally misaligned by 50 mm (compared to using no grid) would be a modest reduction in the scatter-to-primary ratio, a significant reduction in the imaged photon fluence, a marked increase in noise, and a degradation in the imaged contrast-to-noise ratio.

In contrast, the AGAS was able to consistently position the focal spot to within 2 mm of the grid focal axis in the lateral misalignment direction, with an associated loss of primary transmission of 3% or less. The resultant improvement in image quality is readily apparent in the 15:1 grid clinical images shown in Figs. 8(a) and 8(b).

The time required for AGAS to align the focal spot and grid was found to be slightly longer in the clinic than in the laboratory. This is attributed to the greater complexity of the clinical situation compared to the laboratory setting. It is more difficult to estimate the ideal tube position in the clinic than in the laboratory, so the initial misalignment in the clinic is greater and the tube must move a greater distance during the automatic alignment.

The clinical chest images show the marked contrast improvement possible with the AGAS. Line placement is clearer and easier to establish, and anatomy that is not visible in the nongrid images is easily seen in the AGAS images. Furthermore, this improvement was obtained without increasing patient dose. The use of nongrid techniques for grid images did not degrade the image quality when using CR cassettes due to their dynamic range and image processing.

The next generation of AGAS units will incorporate improvements to increase the range of clinical utility. The unit described here was unable to take upright radiographs; doing so would require rotating the tube housing around the axis of the horizontal extension arm by 90°, and the motor that rotates the tube housing around this axis does not have enough torque to rotate the x-ray tube through more than about $\pm 20^\circ$. Also, the geometry of the grid tunnel requires that the cassettes be crosswise; that is, with the long axis perpendicular to the craniocaudal axis of the patient. UAB's protocol for abdominal exams is to position the cassette lengthwise; that is, with the long axis of the cassette parallel to the patient's craniocaudal axis. This restricted the use of the AGAS unit to chest exams. The grid tunnel has been redesigned to accept cassettes in both the crosswise and lengthwise orientations.

The two calibration procedures that we describe should not generally need to be repeated once a system has been placed into clinical practice. The camera calibration should remain stable so long as the camera lens does not move relative to the camera. The geometry calibration should remain stable so long as the geometric relationship between the camera and the x-ray tube housing remains stable. However, if the collimator were replaced, the geometry calibration would need to be repeated.

We have demonstrated that AGAS can accurately align the x-ray tube focal spot with the focal axis of a 15:1 grid. This is a higher ratio than the 12:1 grid commonly used in

general radiography. The 15:1 grid was employed because it is the highest ratio grid in routine clinical use and also the most difficult to align. If good results are achievable with a 15:1 grid, then good results can also be expected with a 12:1 grid.

V. CONCLUSIONS

A mobile radiographic AGAS has been developed that is able to accurately align the x-ray tube focal spot to the center of a grid's focal axis. The system is easy to use and fast. The system typically aligns the focal spot and grid in less than 10 s. Furthermore, the demonstrated alignment accuracy is such that a high ratio (15:1) grid can be used. The clinical result is markedly improved images compared to nongrid images with no increase in patient dose.

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