Investigation into the optimal linear time-invariant lag correction for radar artifact removal

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(Received 16 July 2010; revised 10 March 2011; accepted for publication 16 March 2011; published 27 April 2011)

Purpose: Detector lag, or residual signal, in amorphous silicon (a-Si) flat-panel (FP) detectors can cause significant shading artifacts in cone-beam computed tomography (CBCT) reconstructions. To date, most correction models have assumed a linear, time-invariant (LTI) model and lag is corrected by deconvolution with an impulse response function (IRF). However, there are many ways to determine the IRF. The purpose of this work is to better understand detector lag in the Varian 4030CB FP and to identify the IRF measurement technique that best removes the CBCT shading artifact.

Methods: We investigated the linearity of lag in a Varian 4030CB a-Si FP operating in dynamic gain mode at 15 frames per second by examining the rising step-response function (RSRF) followed by the falling step-response function (FSRF) at ten incident exposures (0.5%–84% of a-Si FP saturation exposure). We implemented a multiexponential ($N=4$) LTI model for lag correction and investigated the effects of various techniques for determining the IRF such as RSRF versus FSRF, exposure intensity, length of exposure, and spatial position. The resulting IRFs were applied to (1) the step-response projection data and (2) CBCT acquisitions of a large pelvic phantom and acrylic head phantom. For projection data, 1st and 50th frame lags were measured pre- and postcorrection. For the CBCT reconstructions, four pairs of ROIs were defined and the maximum and mean errors within each pair were calculated for the different exposures and step-response edge techniques.

Results: A nonlinearity greater than 50% was observed in the FSRF data. A model calibrated with RSRF data resulted in overcorrection of FSRF data. Conversely, models calibrated with FSRF data applied to RSRF data resulted in undercorrection of the RSRF. Similar effects were seen when LTI models were applied to data collected at different incident exposures. Some spatial variation in lag was observed in the step-response data. For CBCT reconstructions, an average error range of 3–21 HU was observed when using IRFs from different techniques. For our phantoms and FP, the lowest average error occurred for the FSRF-based techniques at exposures of 1.6 or 3.4% a-Si FP saturation, depending on the phantom used.

Conclusions: The choice of step-response edge (RSRF versus FSRF) and exposure intensity for IRF calibration could leave large residual lag in the step-response data. For the CBCT reconstructions, IRFs derived from FSRF data at low exposure intensities (1.6 and 3.4%) best removed the CBCT shading artifact. Which IRF to use for lag correction could be selected based on the object size.

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Key words: x-ray detector, flat-panel, lag, a-Si, radar artifact

I. INTRODUCTION

Cone-beam computed tomography (CBCT) is a popular application for amorphous silicon (a-Si) flat-panel (FP) detectors. It has been shown that a-Si FPs exhibit detector lag that affects the CBCT reconstructions.^{1–5} Detector lag is defined as signal present in frames following the frame in which it was generated. In projections, lag causes temporal blurring and reduces temporal resolution. In CT reconstructions, detector lag can lead to a range of image artifacts, such as streaking, azimuthal blurring,^{1,2} skin-line artifacts of several hundred HU,³ or shading artifacts. Specifically for a pelvic

phantom scan, detector lag has been reported to cause shading artifacts of up to 20–35 HU.^{4,5} The main contributor to detector lag in FP x-ray detectors is believed to be charge trapping in the a-Si. Defect states known as traps fill with charge during photodiode illumination and then release the charge at a later time. For parts of the panel that have been highly irradiated, the a-Si and scintillator sensitivity will increase with exposure and exhibit a larger gain than other parts of the same a-Si FP that saw less irradiation. In addition to creating residual signal, charge traps can make accurate and stable dose measurements or calibrations hard to achieve if no equilibrium is reached during panel irradiation.⁶

Several different approaches have been taken for lag compensation and the methods can be categorized as either software or hardware methods.

For software lag compensation methods, a suitable model of the lag decay is fit to the a-Si FP data, such as a multiexponential⁷ signal or a power function.⁸ An attractive feature of the multiexponential model for lag decay is that the trapping and releasing of charge from traps are also described by exponential functions.⁹ Typically, the a-Si FP is modeled as a linear, time-invariant (LTI) system, which is described by an impulse response function (IRF). The correction is a temporal deconvolution of the detector output with the modeled IRF.¹⁰

There are many ways to measure an IRF of the a-Si FP. Previous authors have directly measured it by irradiating for a single frame.¹ A response can also be measured to much longer periods of irradiation, as shown in Fig. 1. The rising step-response function (RSRF) looks at the a-Si FP response to the application of x-rays, while the falling step-response function (FSRF) is the response after a long irradiation has stopped. For an LTI system, the IRF is directly related to the step responses through differentiation. Another point to consider is the length of the IRF. Strategies have been reported where authors limit the IRF to a few frames, tens of frames, or let it be infinite in length.^{3,7,10} Our strategy will follow the latter since it is our experience that the long time constants associated with charge trapping cause the artifacts that are the focus of this study.

Several hardware approaches exist that make no LTI assumptions for the a-Si FP. One simple approach to reduce lag is to insert empty frames (x-rays turned off) to flush the lag signal out of the detector during acquisition.² However, the introduction of extra empty frames increases scan time for CBCT. Furthermore, traps at deeper energy levels in the band gap will not have emptied and may still contribute to the detector output. Another method is to use LEDs to illuminate the a-Si and saturate the traps between detector readout

and x-ray illumination.¹¹ Thus, lag is actually increased in the panel, but it is made into a completely uniform offset. A similar trap saturation approach operates the photodiodes in a forward bias mode.^{12,13} One drawback of these methods is that they do not have the ability to correct for temporal effects in the scintillator. Furthermore, additional hardware changes are needed, frame rates could be limited, and dark currents may increase. Finally, their effect on removing severe lag artifacts in CT reconstructions still requires investigation.

For an x-ray image intensifier system with cesium iodide (CsI) scintillator, the temporal modulation transfer function (MTF), which is the normalized magnitude of the Fourier transform of the temporal IRF, has been observed to be dependent on the exposure level.^{14,15} Furthermore, differences between using the RSRF or FSRF measurements were observed, and appropriate corrections to detective quantum efficiency (DQE) measurements made to account for the nonlinearities of detector lag. For a-Si FPs, Mail *et al.*³ and Yang *et al.*⁷ stated that an IRF derived from the RSRF more accurately reflects the conditions when the FP is being irradiated, and thus should give better results than from using the FSRF, although comparisons were not given. This work will focus on finding the software LTI method for an a-Si FP that best removes the severe shading artifacts in CBCT. Specifically, the sensitivity of IRF calibrations to different measurement techniques will be investigated. Next, IRFs that span the range of possibilities from different measurement techniques will be used to correct the CBCT projection data, and the resulting reconstructions will be evaluated for shading artifact removal.

This work will focus only on LTI corrections for several reasons. First, all lag corrections for CT and CBCT reconstructions so far published are LTI corrections, while nonlinear corrections for projection data have only been suggested¹ or only shown on step-response data.⁹ Second, while the a-Si FP may not be perfectly described by a linear system, LTI systems are much better understood than nonlinear systems and an LTI description may be good enough to remove the radar artifact. Finally, to properly understand the performance improvement of a potential nonlinear, time-variant correction, and make a fair comparison to existing LTI corrections, it is extremely important to understand the performance capabilities of LTI corrections.

The paper is organized as follows. Section II gives background on the lag artifacts and charge traps in a-Si. Section III describes the step-response measurements used to investigate the FP and derive the IRFs. It also describes the CBCT data sets used to compare the different corrections. Finally, Sec. IV presents the results of those experiments, and Sec. V discusses the results and differences from previous work.

II. BACKGROUND AND THEORY

II.A. Lag artifacts

Ideally, under constant irradiation, one would expect the spatially averaged response of an a-Si FP to be constant over time. However, under experimental conditions, a 4% exponential rise in the RSRF can be seen in Fig. 1. The spatially

FIG. 1. The normalized measured and ideal responses of the Varian 4030CB a-Si FP to 600 frames of x-ray exposure. (125 kVp, 32 mA, 17 ms, 15 fps). A 4% signal increase is seen in the measured RSRF. After the x-rays are turned off, a FSRF with 2.5% first frame lag that slowly decays away is observed. Note the break in the y-axis.

averaged FSRF, which ideally should be zero after x-ray turn-off, can be seen in Fig. 1 to be greater than 0.1% for hundreds of detector frames.

Long-term lag greater than 0.1%, as seen in Fig. 1 from x-ray turn-off to frame 1100, is substantial because it could easily equal the signal behind a large object. As an example, for 36 cm of water and a mean x-ray energy of 75 keV, the output radiation from the object is also approximately 0.1% of the incident radiation.

The effect on CBCT reconstructions of the nonideal FP temporal response seen in Fig. 1 can be simulated. Figure 2(a) shows the lag-free reconstruction from simulated projection data (625 projections) of a uniform 42 cm $\times$ 26 cm pelvic phantom. Signal levels meant to mimic realistic exposure levels were used. The unattenuated x-ray exposure was set at 84% of the FP saturation and a monoenergetic x-ray spectrum was simulated. The attenuation coefficients used for calculating the line integrals were scaled such that the lowest signal values on the FP were in the range of 0.1%–0.3% of the FP saturation, which matches what it seen in practice for a physical phantom of the same size. For the reconstruction with simulated lag in Fig. 2(b), an IRF was determined from the FSRF data in Fig. 1, which was taken at 52% of detector saturation. The measured 1st and 50th frame lags in the 52% FSRF data are 2.9 and 0.49%, respectively. The mean signal difference between the two indicated ROIs is 45 HU. In Fig. 2(c), the largest differences (brightest pixels) between the sinograms with and without lag occur at collected points outside the object. For a third-generation CT acquisition system, time corresponds directly to gantry projection angle [vertical direction in Fig. 2(c)] and this causes the temporal blurring of detector lag to result in a vertical

blurring in the sinogram. Those detector cells that transition from full x-ray exposure to object shadow see the greatest effect of the vertical blurring and determine spatially where the severe shading artifact occurs. The detector elements that cause the artifact in Fig. 2(b) are located in the sections labeled 1 in Fig. 2(c). The radius of the well-defined brighter region is determined by the width of section 2 in Fig. 2(c), which is comprised of detector elements that are always blocked by object shadow.

Figure 2(d) shows the resulting lag artifact for real data from a CBCT reconstruction for a 42 cm $\times$ 26 cm pelvic phantom where the shading artifact is 51 HU in contrast between the two indicated ROIs. The image was reconstructed from 625 projections with a 1 mm² pixel size for the 2D axial slices, 5 mm slice thickness, and narrow collimators in the z direction to minimize scatter.

Previous works^{3,5} have identified this skin-line or radar artifact for elliptical and off-center objects, and this is the CBCT artifact that this work is concerned with. The artifact is not due to the dynamic gain mode of the detector because the detector pixels switch to the high-gain mode within several millimeters of the object boundary, which is evident as a faint line just inside the object boundary in Fig. 2(d). Furthermore, the artifact can be reproduced in fixed gain modes as well. A reconstruction of a smaller pelvic phantom (30 cm $\times$ 22 cm) collected with the detector in dynamic gain mode is shown in Fig. 3(a). Figure 3(b) shows the reconstruction from data collected in a 4 pF fixed gain mode. The artifact does not appear the same as scatter or beam-hardening artifacts in CBCT reconstructions,^{16–19} and has been observed for centered geometries.³ Finally, since the artifact appears to be reproduced in the simulation, which did not

FIG. 2. Reconstructions of a simulated, uniform pelvic phantom (42 $\times$ 26 cm) with (a) no lag and (b) simulated detector lag. The mean signal difference between the two marked ROIs is 45 HU. (c) Sinogram with no lag subtracted from the sinogram with lag. A vertical blurring is seen at the edges of the object (indicated with arrows) in the difference sinogram. Detector elements in section 1 experience a large dynamic range while those in section 2 are always in object shadow. (d) CT reconstruction of a pelvic phantom showing the radar artifact. Scanned at 125 kVp, 80 mA, 30 ms on a Varian 4030CB table-top system. Reconstructed with filtered backprojection with a voxel size of 1 mm² $\times$ 5 mm. Between the specified ROIs there is a mean difference of 51 HU. Window, level = 200, 0 HU.

FIG. 3. 1 $\times$ 1 $\times$ 5 mm reconstructions of a pelvic phantom (30 cm $\times$ 22 cm) collected with the detector in (a) dynamic gain and (b) low gain (4 pF) mode. Window, level = 250, 0 HU.

include scatter, beam-hardening, dynamic gain switching, offset geometry, or normalization phantoms, detector lag is the most likely cause.

II.B. Charge traps

Charge traps in a-Si are responsible for what is seen in both Figs. 1 and 2(d). Amorphous silicon has a larger band gap energy than crystalline silicon (1.7 versus 1.1 eV), but because of the disappearance of long range crystalline order and the introduction of many dangling bonds inside the material, a well defined band edge does not exist.²⁰ In fact, exponential tails spread into the band gap, creating a large population of trap states in the material and reducing the overall electron mobility. The amount of charge that is deposited into and from the trap states during a given frame depends on several parameters, including the trap density, illumination intensity, and the current state of the traps (i.e., the previous irradiation history of the panel).⁹

For the RSRF projection data in Fig. 1, some of the charge that would have been collected by the readout process instead fills empty traps. As traps fill, a higher percentage of generated charge is collected in later frames, along with an increasing amount of leaked charge. An increasing output signal (for a constant input) will continue until the trapping and detrapping rates become equal. In CBCT, all pixels being exposed to x-rays will also see a gradual increase in gain, but pixels that see a large and sudden drop in signal have the large detrapping currents that create the artifact seen in Fig. 2(d).

II.C. Hsieh LTI algorithm for lag correction

In his work, Hsieh *et al.*¹⁰ represents the temporal IRF for afterglow as a multiexponential signal, where the time constants and coefficients are known *a priori* for the underlying continuous process. For operating on frame-integrated data that comes from an a-Si FP detector, it is useful to have a discrete-time version, since the detector output is inherently discrete. A discrete-time version can be easily derived, starting from the multiexponential IRF

$$h(k) = b_0\delta(k) + \sum_{n=1}^N b_n e^{-a_n k}, \quad (1)$$

where k is the discrete-time variable for x-ray frames and N is the number of exponential terms in the IRF, typically between two and four.^{3,7,21} $\delta(k)$ is the impulse function of magnitude one, and $b_0\delta(k)$ represents the portion of the input signal that is unaffected by lag. The coefficients b_n will be referred to as the lag coefficients and the exponential rates a_n will be referred to as the lag rates. Given $h(k)$, the actual FP output is

$$y(k) = x(k) * h(k). \quad (2)$$

The ideal output of the FP with no charge trapping and a lag-free measure of exposure on the FP is $x(k)$, what we wish to determine. The units of $y(k)$ and $x(k)$ are detector counts, and

the units of $h(k)$ are (detector counts with lag/detector counts without lag).

The recursive deconvolution algorithm for this IRF model is

$$x(k) = x_k = \frac{y(k) - \sum_{n=1}^N b_n S_{n,k} e^{-a_n}}{\sum_{n=0}^N b_n}, \quad (3)$$

$$S_{n,k+1} = x_k + S_{n,k} e^{-a_n}. \quad (4)$$

$S_{n,k}$ is a state variable that contains the contribution from previous inputs. Hsieh's recursive algorithm is a computationally efficient way to implement the LTI correction. Only the current frame and the $S_{n,k}$ term need to be stored in memory to perform the deconvolution.

The sum of all b_n in the denominator of Eq. (3) will be forced to equal 1.0 so that $h(0)$ equals 1.0. The b_n could be scaled to other values, but that will only result in an overall scaling of the estimated signal $x(k)$.

II.D. Exponential model fitting

In this work, the IRF will be determined from rising or falling step responses. By fitting the measured FSRF or RSRF to their parameterized models, the lag rates and coefficients can be easily obtained. The measured FSRF is related to the parameters in Eq. (1) and can be written for a specific exposure x as

$$FSRF_{\text{unnormalized}}(k) = \sum_{n=1}^N x \frac{b_n}{1 - e^{-a_n}} e^{-a_n k} u(k), \quad (5)$$

where $u(k)$ is the discrete unit step function. Normalizing the FSRF by the exposure x gives

$$FSRF(k) = \sum_{n=1}^N \frac{b_n}{1 - e^{-a_n}} e^{-a_n k} u(k). \quad (6)$$

The FSRF can be described as a simple multiexponential by defining $\tilde{b}_n = b_n / (1 - e^{-a_n})$, which gives

$$FSRF(k) = \sum_{n=1}^N \tilde{b}_n e^{-a_n k} u(k). \quad (7)$$

Similarly, the measured RSRF(k) is related to Eq. (1), where

$$RSRF(k) = \left(1 - \sum_{n=1}^N \tilde{b}_n e^{-a_n k} \right) u(k). \quad (8)$$

For practical purposes, the falling step function used as input to determine the measured FSRF in Eq. (7) is approximated as a long square wave of irradiation, as in Fig. 1. To properly account for a finite-length step-function in Eq. (7), the response of an exposure of N_f frames in length is

$$FSRF_{N_f}(k) = \sum_{n=1}^N w_n \tilde{b}_n e^{-a_n k} u(k). \quad (9)$$

Here w_n is the summation of the exponential that falls within the exposure length, normalized by the total summation of the exponential

$$w_n = \frac{e^{-a_n} - e^{-a_n N_f}}{e^{-a_n}}. \quad (10)$$

The N_f subscript will typically be dropped since it refers to all collected FSRF data in this paper.

Fitting the N exponentials in Eqs. (8) and (9) is a nonlinear problem and a Gauss–Newton nonlinear least squares method can be used.

III. METHODS AND MATERIALS

Step-response measurements were made to investigate the lag characteristics of the Varian 4030CB a-Si FP and the variation in the derived IRFs. Next, CBCT projection data was collected and corrected with selected IRFs for lag artifact removal.

III.A. Step-response measurements

For the step-response measurements, the lengths of the rising and falling step functions were fixed. Traps with time constants ranging from a few milliseconds to several days exist. Those that have time constants of charge emission and uptake that are shorter than the time to acquire a single frame do not contribute significantly to the long-term lag responsible for the radar artifact. Conversely, traps that have time constants much longer than the typical scan time of the system under consideration can be corrected for by collecting frequent dark-field images and occasional gain calibrations. Moreover, the very long-term traps can be filled by warming up the panel with several flat-field images before use. The time constants of concern for our investigations are those between the duration of a single frame and the entire scan length. Our step-response measurements therefore consist of 600 RSRF frames followed by 600 FSRF frames, unless otherwise noted, since our CBCT acquisitions are on the order of 600 frames.

The step-response measurements at different exposures, RSRF and FSRF $_{N_f}$ in Eqs. (8) and (9), allow investigation into several aspects of detector lag, such as the necessary model order for lag characterization, charge trapping linearity, spatial variation, and frame-rate dependence. The step responses also allow investigation into the spatial, exposure, step-response edge (rising versus falling), and exposure length dependence of the IRF measurements and corrections. Similar to Yang *et al.*⁷ and Mail *et al.*,³ a single large ROI is spatially averaged (except where noted) in each step-response data set to characterize and to investigate the detector temporal response.

For IRFs and step responses, the residual first frame lag is often used as an error metric.¹ While the first frame lag depends on all of the exponential terms, the artifact observed in the CBCT reconstructions is more heavily dependent on exponential terms with longer time constants (i.e., greater than ten frames). The artifact is a blurring of previous, fully illuminated frames outside the object into frames with object shadow. Since the artifact is evident far from the edge in Fig. 2(d) and the effects from shorter time constants would have decayed away close to the object boundary, the lag with longer time constants must determine the artifact severity. As a measure of the longer time constant lag, the 50th frame lag [$t = 3.33$ s at 15 frames per second (fps)] is used. In our experience, comparing lags resulting from different measurement

or correction scenarios using either 50th or 100th (or higher) frames generate the same conclusions. The lag curves from different exposure intensities and the residual lags from different corrections never intersect in this study, and so a comparison at frame 50 provides the same rank ordering of residual lag as that measured in higher numbered lag frames.

Data for lag investigation was collected on a table-top system using a Varian 4030CB a-Si FP detector operating in dynamic gain mode. The detector operated at 15 fps, unless otherwise noted. The RSRF and FSRF data that was used to determine the IRF parameters was collected in a centered geometry, with no bow-tie filter, and no object in the x-ray beam.

The RSRF measurements were normalized by the output of a separate silicon photodiode attached to a ceramic GOS scintillator (Hamamatsu S8193) to form a normalization chamber. The silicon photodiode has no lag and the ceramic scintillator is extremely fast. Using the output of the normalization chamber, any variation in the measured RSRF due to the x-ray tube or generator can be removed. The output of the photodiode was amplified and digitized using a National Instruments A/D converter (USB-6008).

III.A.1. Multiexponential model order

From a performance standpoint, it is beneficial to use as few exponentials as possible, but enough exponentials to still capture the temporal behavior of the FP. The length of time needed to perform the correction is linearly proportional to the number of exponentials. Furthermore, more exponentials could lead to over-fitting of calibration data and actually lead to worse or more noise-sensitive results. To evaluate the optimal number of exponentials to use for the Varian 4030CB a-Si FP, the residual, which is calculated as the ℓ^2 -norm of the difference between the measured step-response data and an N -exponential model fit to the step-response data, was used to evaluate the fit quality. For plotting and comparison purposes, the residual errors were normalized such that for $N = 2$ the residual error is exactly one. N was varied from two to ten, and step-response data at different exposures were used.

III.A.2. Exposure dependence

To investigate the exposure linearity of the charge trapping mechanism in the Varian 4030CB FP, the RSRF and FSRF were measured for ten different incident exposure levels. The data was also normalized by the signal level in detector counts during exposure. The a-Si FP output signals as a percentage of the FP saturation level for the range of incident exposures used, along with the x-ray tube protocols, are listed in Table I. X-ray beam filtration of 0.5 mm Ti was used for all exposures, along with additional Cu filters, which were used to achieve the lowest exposure levels.

III.A.3. Frame-rate dependence

Step-response measurements were investigated at four frame rates (5, 10, 15, and 30 fps) by irradiating the Varian 4030CB in continuous fluoroscopy mode for 30 s at each frame rate. The protocol used was 70 kVp and 5 mA, and

TABLE I. Percent of a-Si FP saturation signal for different exposure intensities at 125 kVp with 0.5 mm Ti.

Exposure level	1 ^a	2 ^b	3	4	5	6	7	8	9	10
mA	10	10	10	10	10	16	25	32	40	50
ms	2	2	2	8	15	16	16	17	18	18
% a-Si FP saturation	0.5	1.6	3.4	8.5	15	25	38	52	68	84

^aUsed 1.75 mm Cu.^bUsed 0.5 mm Cu.

was chosen so that a signal level of 12% saturation exposure was present at 30 fps and 72% at 5 fps. Continuous fluoroscopy was chosen so that the same exposure was identically delivered for each frame-rate experiment, which should result in identical amounts of charge stored in the traps. Note the photodiode integration times change with frame rate, resulting in different FP signal levels during irradiation. The resulting RSRF data were plotted against frame number and time, and normalized appropriately so that the ending points of all plotted frame-rate data are 1.0. The resulting FSRF data were plotted in two different ways. First, the raw FSRF data were scaled by the incident exposure at 5 fps for all frame rates to visualize how lag absolutely changes and plotted versus frame number. Second, the unscaled FSRFs were multiplied by the frame rate, f , to determine $i_{\text{trap}}(t)$, the charge generated by the FP per unit time as

$$i_{\text{trap}}(t) = \text{FSRF}(t) \times f. \quad (11)$$

III.A.4. Spatial dependence

The uniformity of detector lag was investigated by collecting FSRF data with the gain corrections turned off. This was done in dynamic gain mode at a 3.4% exposure, which is below the threshold at which each pixel would switch to the low gain capacitor. The 2nd and 100th lag frames were visually compared and histograms of the frames were plotted to study the lag variability.

III.A.5. IRF variability

IRFs were derived and compared from several different step-response techniques. First, the edge-technique dependence was investigated by using both the RSRF and FSRF to estimate the temporal IRF at a fixed exposure of 52% a-Si FP saturation and the resulting IRFs were compared after applying the Hsieh correction. Second, IRFs were also derived from RSRF and FSRF data at different exposures (Table I). Each of the IRFs were used to correct different exposure step-response data sets and the results compared to correcting data with IRFs derived from the same exposure level. Third, an IRF was derived for a small, central ROI (32 × 32 pixels) and then applied to the entire FP for a 38% FP saturation exposure to investigate the spatial nonuniformity of the IRF. Independent of the ROI size used to determine the IRF on the a-Si FP, Eqs. (3) and (4) are calculated at the individual pixel level. For analysis, the result of the correction was also broken into small ROIs of the same size to determine the spatial effectiveness of the correction.

Finally, to test the effect of step-response irradiation length (N_f) on the measured IRF, FSRF data generated from an x-ray exposure of one quarter (150 frames) the calibration length were acquired. The shortened FSRF₁₅₀ data were corrected with an IRF derived from a full-length calibration at the same exposure intensity.

III.B. CBCT measurements

CBCT data sets were acquired for two different phantoms: a large pelvic phantom (42 cm × 26 cm) and a uniform acrylic head phantom (20 cm × 16 cm). The large pelvic phantom is made up of a smaller pelvic phantom with an additional layer of attenuating material to simulate larger patients. A total of 625 projections were collected in a 2 × 2 binned pixel mode. The tube protocols were chosen to give high SNR. For the large pelvic phantom, a pulsed fluoroscopy protocol of 125 kVp, 80 mA, and 30 ms was used in an offset detector geometry (16 cm offset). For the uniform acrylic head phantom, a tube protocol of 125 kVp, 63 mA, and 18 ms was used. For all setups, a 10:1 antiscatter grid, an appropriately designed (i.e., centered or offset geometry) 8:1 Al bow-tie filter, and 0.5 mm Ti filter were also used. The x-ray beam was collimated to approximately 2 cm at the detector for data acquisition to reduce scatter effects. To further reduce the effects of beam-hardening and scatter, all data sets made use of circular normalization phantoms that were just larger than either the pelvic or head phantom.²² Filtered backprojection was used to reconstruct the data sets at a reconstruction pixel size of 1 mm² for the pelvic phantom and 0.5 mm² for the head phantom. The slices were averaged to a thickness of 5.0 mm to reduce noise.

The lag rates and coefficients estimated from both FSRF and RSRF data at ten different incident exposures (Table I) were used to correct the CBCT projection data. The variability in the residual lag artifact due to the IRF calibration method in the CT reconstructions was evaluated. For further comparison, the lag rates and coefficients were calibrated for small ROIs on the FP (32 × 32 pixels) to form an ROI-based calibration. The results of using this ROI-based calibration were compared to using a global calibration that used all of the detector data.

The error metric used in Mail *et al.*³ was a nonuniformity measure that examined the maximum difference in HU signal level among several ROIs. We define our error metric in a similar way. Four pairs of ROIs (10 × 10 pixels) that straddle the obvious lag artifact boundary in the uncorrected data sets are defined. The difference in the mean signals is calculated for each ROI pair and the average and maximum differences for each image are used as the error metrics. Since local regions are being compared, other factors potentially affecting image nonuniformity are minimized.

IV RESULTS

IV.A. Step-response measurements

IV.A.1. Multiexponential model order

The normalized residual error between the multiexponential fit and the step-response data is shown in Fig. 4 for two different x-ray tube settings (3.4 and 84% of FP saturation).

FIG. 4. Residual error in fitting multiexponential models of order N to measured step-response data for two different exposure intensities. Low exposure equals 3.4% and high exposure equals 84% of a-Si FP saturation.

It can be seen that the residual curves have a knee when the number of exponentials used is around three or four. This is the point where the reduction in error is quite small as N increases. For some points, the residual error increases for a larger N due to a failure of the nonlinear algorithm to properly find the global minimum. The low-exposure RSRF has a larger residual error due to noise from the x-ray source. In general, $N=4$ is an adequate choice for describing the RSRF, FSRF, and resulting IRFs.

IV.A.2. Exposure dependence

The rising and falling step responses for the nine highest exposure intensities are plotted in Fig. 5(a). The lowest exposure intensity of 0.5% is not shown because the data were much noisier due to the lower signal level. The raw FSRFs show an increase in the absolute amount of lag as the exposure on the FP increases. However, when the FSRFs are normalized by their respective exposures, as in Fig. 5(b), the FSRF signals decrease as a function of exposure. In fact, the FSRF decreases by more than a factor of two between the lowest and highest exposure intensities at 50 s. A similar exposure dependence is observed for the normalized RSRF data where the responses approach a value of one for larger exposure rates. For a linear system, the normalized plots should be identical. The RSRF part of the plots was filtered with a five-point moving average for noise reduction purposes.

IV.A.3. Frame-rate dependence

When plotted against frame number, the RSRF data from higher frame rates shows a larger deviation from the ideal (flat) temporal response [Fig. 6(a)]. When the same data are plotted against time [Fig. 6(b)], the RSRF data for each frame rate overlay each other almost perfectly. This suggests that the RSRF results from a continuous process inside the detector and is not dependent on the number of frame reads.

(a)

(b)

FIG. 5. (a) Raw (detector counts) and (b) normalized rising and falling step responses for several different exposure intensities. In (a), the measured lag increases as the exposure intensity increases. In (b), the measured data were normalized by the exposure intensity immediately before x-ray turn-off. As the exposure intensity increases, the relative amount of measured lag decreases.

Similarly, in Fig. 6(c), the raw FSRF data for each of the four frame rates have been identically scaled and plotted versus frame number. The higher frame rates have shorter integration times, which lead to smaller initial lag signals when viewed versus frame number. However, between frames 200 and 400, the lag signals from the different frame rates change their ordering such that the higher frame rates have a larger lag signal. In Fig. 6(d), the trap current, $i_{\text{trap}}(t)$, for each frame rate is plotted. The trap current is identical for each of the different rates, indicating that the charge that leaks out of the traps is independent of the number of reads and is only time dependent.

IV.A.4. Spatial dependence

For the 600th frame in an RSRF measurement at a 3.4% exposure with no gain correction, the circular shape of the x-ray beam intensity is evident [Fig. 7(a)]. For lag frame two with no gain correction, there is some lag variation visible

FIG. 6. The normalized RSRF data for each frame rate (5, 10, and 30 fps) plotted as a function of (a) frame number and (b) time. In (a), the RSRF decreases with increasing frame rate and in (b), the four data sets overlay each other. (c) The raw FSRF data for each frame rate scaled by the incident exposure at 5 fps and plotted versus frame number. (d) $i_{\text{trap}}(t)$ for the four frame rates. The charge per unit of time is constant across frame rates, indicating that the detrapping process is a continuous function of time.

across the panel [Fig. 7(b)], with the largest variations occurring near the edges of the FP. The nonuniformity in the gain-corrected 2nd and 100th lag frames is the inverse of the x-ray irradiation pattern [Figs. 7(c) and 7(d)]. For gain-corrected images, the width of the lag histograms decreases from 1.5% (with a mean value of 3.2%) in lag frame 2 to a width of around 1% in lag frames 50 and 100, which have mean values of 1.1 and 0.8% [Fig. 7(e)]. The histogram of the detector lag for lag frame two after gain correction is slightly wider than the histogram of the raw image because the x-ray intensity is very nonuniform across the FP. However, it is important to consider the lag images after gain correction because the gain correction step merges pixels from low and high dynamic ranges into a single scale for dynamic gain imaging.

IV.A.5. IRF variability

Figure 8 compares the results of using either the RSRF or FSRF for calibration of the IRF. One uncorrected and two

corrected calibration data sets are shown from an exposure level of 52% of FP saturation. The 1st and 50th frame lags for the uncorrected data are 2.9 and 0.49%. The correction done with the RSRF calibrated IRF shows a very flat corrected RSRF, but an overcorrected FSRF where the 1st and 50th frame residual lags become -0.54% and -0.25% . Conversely, the correction done with the FSRF calibrated IRF has a residual exponential rise to its corrected RSRF but a nearly ideal corrected FSRF. The 1st and 50th frame lags are greatly reduced to 0.24 and 0.017%.

An IRF was calibrated from 3.4% RSRF data and used to correct both 3.4 and 84% RSRFs [Fig. 9(a)]. The correction results in a nearly ideal (flat) 3.4% RSRF after correction, but an overcorrection of the 84% RSRF data. Similarly, the experiment was repeated for an IRF derived from the 3.4% FSRF data [Fig. 9(b)] and applied to both the small and large exposure data sets. For the corrected 3.4% FSRF data, the 1st and 50th frame lags are reduced from 3.6 and 1.0% to

FIG. 7. (a) The 600th frame in an RSRF measurement with no gain correction. (b) Raw lag frame two with no gain correction applied; the greatest lag variation occurs near the edges of the detector. Gain-corrected and normalized lag images for lag frames (c) 2 and (d) 100. (e) Histograms of pixel values for raw lag frame 2 and gain-corrected lag frames 2, 50, and 100. For all images, the object in the lower right corner is a c-Si photodiode used to normalize the x-ray source output. Exposure is 3.7% of saturation.

0.12 and 0.038%. Just as for the 84% RSRF data, the corrected 84% FSRF data show an overcorrection where the 1st and 50th frame lags are overcorrected from 2.3% and 0.42% to -1.1% and -0.54% . Using an IRF calibrated from a small exposure on larger exposure data highlights the exposure dependence of the FP.

Figure 10 shows the result of correcting step-response data at 38% FP saturation exposure using either the RSRF [Fig. 10(a)] or the FSRF [Fig. 10(b)] data from a central ROI. The responses of the central ROI, the average of all ROIs on the FP, and the ROI that is maximally deviant from the average ROI are shown for both uncorrected and corrected step-responses. The RSRF shows very little spatial variation, while considerably more is seen for the FSRF. For the average of all ROIs, the 1st and 50th frame lags are reduced from 4.0 and 0.62% to 0.66 and 0.1%. For the maximally deviant ROI, the 1st and 50th frame lags are reduced from 5.2 and 0.94% to 1.9 and 0.42%. At frame 50 ($t = 3.33$ s), the maximum residual lag is $4\times$ greater than the average residual lag.

FIG. 8. Uncorrected, RSRF corrected, and FSRF corrected data sets are shown. 1st and 50th frame lags for the uncorrected data are 2.9 and 0.49%. The correction done with the RSRF calibrated IRF shows a very flat corrected RSRF but a significantly overcorrected FSRF. The 1st and 50th frame lags become -0.54% and -0.25% . Conversely, the FSRF-based correction has a residual exponential rise in the corrected RSRF, but the 1st and 50th frame lags are much reduced to 0.24 and 0.017%.

In Figs. 8, 9(a), and 10(a), the corrected RSRFs have been scaled such that the sum of all b_n equals one in Eq. (3). Because of this, the corrected RSRFs are scaled such that they are smaller than the original, uncorrected RSRFs. By choosing the sum of b_n to be a smaller value, the corrected RSRFs could be scaled to larger values. However, the smaller scaling was chosen for plotting and comparison purposes.

In Fig. 11, FSRF data generated from exposures of 10 s (150 frames) and 40 s (600 frames) at 25% of a-Si FP saturation are shown. The IRF was calibrated with FSRF₆₀₀ data and used to correct the same FSRF data, where a reduction in the 1st and 50th frame lags of 2.8 and 0.61% to 0.44 and 0.023% was observed. However, when the same IRF was used to correct FSRF₁₅₀ data an under-correction is seen. The 1st and 50th frame lags are only reduced from 2.6 and 0.45% to 0.52 and 0.082%. The IRF derived from the FSRF₆₀₀ data underestimates how much charge has gone into the traps.

In summary, varying the incident exposure and the step-response edge (rising versus falling) resulted in larger 50th frame residual lag errors greater or equal to 0.25% of the incident exposure in some cases. Furthermore, using an IRF from a small ROI resulted in an average 50th frame residual lag less than 0.25%, but a maximum 50th frame residual lag greater than that. Taking step-response data from different exposure lengths resulted in smaller errors of less than 0.1%.

IV.B. CBCT measurements

Figure 12 shows reconstructions of a large human pelvic phantom and head phantom taken on the Varian 4030CB table-top system. Figure 12(a) shows the uncorrected reconstruction with four pairs of ROIs defined. The maximum and

FIG. 9. Measured and corrected (a) RSRF and (b) FSRF data at a low and high exposures (3.4 and 84% of a-Si FP saturation). The IRFs used for data correction were calibrated from (a) 3.4% RSRF and (b) 3.4% FSRF data. The corrected 84% RSRF data are overcorrected, while the corrected 3.4% RSRF data is nearly flat. For the corrected 3.4% FSRF, 1st frame and 50th frame lag is reduced from 3.6 and 1.0% to 0.12 and 0.038%. For the corrected 84% FSRF, 1st and 50th frame lag is overcorrected from 2.3 and 0.42% to -1.1 and -0.54 %.

average errors for this reconstruction are 51 and 35 HU. Figure 12(b) shows the reconstructions with the smallest maximum (8 HU) and average (3 HU) ROI errors, which corresponds to correction with FSRF data taken at a 3.4% saturation exposure. Figure 12(c) shows the reconstruction with the largest maximum error (40 HU) that corresponds to correction with RSRF data taken at a 68% saturation exposure. Even with an average error of 3 HU in Fig. 12(b), a slight blurred ring artifact remains. Figures 13(a) and 13(b) summarize the maximum and average error results for all incident exposures for FSRF and RSRF calibrations. Table II gives the IRF parameters used to generate Fig. 12(b) as an example.

Figures 12(e)–(g) and 13(c)–(d) show similar results for the uniform acrylic head phantom. The maximum and average errors for the uncorrected head phantom reconstruction

FIG. 10. The uncorrected and corrected (a) RSRFs and (b) FSRFs for 32×32 pixel ROIs on the FP. The IRFs used for correction were derived from the (a) RSRF and (b) FSRF data of the central ROI. The corrected central ROI, the average corrected ROI, and the corrected ROI that is maximally deviant from the average are shown. For the average of all ROIs, the 1st and 50th frame lags are reduced from 4.0 and 0.62% to 0.66 and 0.1%. For the maximally deviant ROI, the 1st and 50th frame lags are reduced from 5.2 and 0.94% to 1.9 and 0.42%, which is $4\times$ greater than the average residual 50th frame lag.

are 24 and 19 HU. An IRF calibrated with the FSRF technique at a 1.6% saturation exposure provides the smallest average error of 2 HU and a maximum error of 5 HU. The largest maximum error (15 HU) occurs for the FSRF technique at 84%.

Figures 12(d) and 12(h) show reconstructions with ROI-based calibrations of the lag rates and coefficients for best case reconstructions for the pelvic and head phantom data. For the ROI-based pelvic phantom, the average and maximum errors are the same as for the global-based algorithm and for the head phantom the average and maximum errors are 3 and 4 HU. Overall, little difference in the radar artifact reduction is seen between the reconstructions from using either an ROI-based or global-based calibration of the lag rates and coefficients.

FIG. 11. Measured and corrected FSRF data for 10 and 40 s of x-ray exposure at 25% of a-Si FP saturation. IRF was calibrated with the measured 40 s FSRF data. For the corrected 40 s FSRF, 1st and 50th frame lags are reduced from 2.8 and 0.61% to 0.44 and 0.023%. For the corrected 10 s FSRF, 1st and 50th frame lags are reduced from 2.6 and 0.45% to 0.52 and 0.082%.

The difference image in Fig. 14(a) for the pelvic phantom between the reconstruction using the best LTI correction [Fig. 12(b)] and the uncorrected reconstruction [Fig. 12(a)] shows where the lag correction has altered the reconstruction. In the central part of the reconstruction, the difference is only a few HU except for the inside of the pelvic bone. Some subtle streaking is also evident in the difference image, which is due to quantization error when rounding the lag-corrected x-ray data to integer data types for the reconstruction pipeline. The largest differences occur at the boundary and outside the boundary of the circular interior of the phantom. Looking at the difference between the uncorrected and corrected detector sinograms in Fig. 14(b), it is observed that the lag correction altered by several hundred counts the detector elements outside the object's boundary and the detector elements that transition between full exposure and object shadow. Detector elements inside the object boundary are only altered by a few detector counts.

V. DISCUSSION AND CONCLUSIONS

Large exposure nonlinearity of charge trapping was observed in the Varian 4030CB. Overall, we found that the exposure level and step-response edge technique (rising versus falling) caused the greatest variation in the derived IRFs that led to residual 50th lag frame errors greater or equal to 0.25% in magnitude. When the IRFs were applied to CBCT projection data, the FSRF technique gave the best results at an exposure level of 3.4% for the pelvic phantom and 1.6% for the head phantom.

To apply these findings in practice for a given detector, the falling edge experiment could be repeated at different exposure intensities, and the resulting impulse responses used to correct CT data sets of uniform, elliptical objects of different sizes. The intensity that provides the minimum

FIG. 12. (a) The uncorrected reconstruction of the pelvic phantom with the ROI pairs denoted. Reconstructions with the (b) smallest average error and (c) largest maximum error, which correspond to IRFs derived from an FSRF at 3.4% and an RSRF at 1.6%. (d) Reconstruction using an ROI-based calibration. (e) Uncorrected reconstruction of a uniform acrylic head phantom. Reconstruction with the (f) smallest average error (FSRF at 1.6%) and (g) largest error (FSRF at 84%). (h) Reconstruction using an ROI-based calibration. Window, level = 200, 50 HU for the pelvic phantom and 100, 50 HU for the head phantom.

reconstruction error would be used to correct all future data for objects that are close in size. Since the large pelvic phantom and small head phantom had similar exposure intensity values, it would be expected that only two or three calibration sizes would need to be defined.

When the profile of the pelvic phantom in the x-ray projections is examined, the image intensity quickly transitions from the full exposure to several tenths of a percent. The 3.4% signal intensity occurs somewhere in the middle of the transition and may act as an average exposure value near the part of the detector that experiences the greatest dynamic range and artifact level. A correction calibrated at an even lower exposure provided the best correction of the smaller head phantom, but a similar argument may hold.

The FSRF technique may provide better results than the RSRF technique because the artifact investigated is inherently related to the FSRF. The artifact is generated in detector elements that transition from a high exposure to a low exposure, much like the FSRF measurements themselves.

FIG. 13. The maximum and average absolute errors between ROIs within a pair for the pelvic and head phantoms. The CBCT projection data were corrected with IRFs derived from different exposure intensities using either the FSRF data in (a) and (c) or the RSRF data in (b) and (d). For the RSRF data, the 0.5% exposure did not give a suitable fit for the multiexponential model.

An interesting outcome of this work is the comparison between the 32×32 pixel ROI-based calibration and the global calibration method. The spatial uniformity tests and the FSRF measurements showed some parts of the FP have much larger amounts of detector lag. However, for the CBCT reconstructions, little difference is observed in image quality between the ROI-based and global calibrations. This might be because the image nonuniformity due to lag is extremely small when compared to the high dynamic range

of CT data. Furthermore, the nonuniformity is low frequency and is more pronounced at the edge of the detector. For CBCT measurements, regions much smaller than the entire detector experience the radiation history that is the cause of the radar artifact. Looking at the smaller regions, detector lag may be uniform enough. While not improving the error metric used here, the ROI-based calibration may improve the noise properties in the final CBCT reconstructions, which will be the subject of a future investigation.

Siewerdsen and Jaffray¹ showed that lag as a percent of the incident signal increased for larger exposures. This is in direct contrast to what we have observed that lag as a percent of the irradiating signal decreases with larger exposures. Furthermore, the same work describes that lag is mostly a function of frame number, and only has a small dependence on time for first frame lag. Our results show that the lag is well described by a continuous-time function that can be frame-integrated to

TABLE II. IRF parameters from FSRF data at 3.4% exposure. a_n has units of frames⁻¹ and b_n has units of detector counts with lag/detector counts without lag.

a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4
0.0023	0.0150	0.0827	0.5786	1.611e-5	1.468e-4	9.190e-4	1.480e-2

FIG. 14. Difference images between the uncorrected pelvic phantom and the best LTI corrected data sets of (a) the CBCT reconstructions and (b) the raw x-ray detector sinograms. (b) Looks different than the simulation in because of the offset geometry acquisition. For the sinogram, projection angle and time increase in the downward direction. Window, level for (a) is 100, 0 HU and for (b) is 350, 200 detector counts.

determine lag at different frame rates for the Varian 4030CB FP. These differences could arise from several sources. First, the previous work measured the IRF directly, instead of either a RSRF or FSRF. Second, the detector hardware is different (panel manufacturer and scintillator type) and is operated at different frame rates. Wicczorek⁹ and Street²⁰ mention that lag is highly dependent on many manufacturing parameters that could have been quite different for the two a-Si panels.

Previous works used the RSRF to calibrate their LTI models of lag.^{3,10} In our results, some RSRF techniques performed nearly as well as the best FSRF techniques, but from different exposure levels. In general, RSRF measurements were harder to make and required the use of a separate silicon photodiode to remove noise from the x-ray source and generator. Overall though, both edge techniques exhibited an exposure dependence, which show an exposure nonlinearity for charge trapping. Theoretically the charge trapping in a-Si and the resultant lag signal should be illumination dependent. This nonlinear behavior highlights why different techniques for measuring the step response give different results, and it further highlights the limitations of using LTI model-based corrections. This may also explain the residual blurred ring artifact seen in Fig. 12(b).

This work identified the best results achievable with an LTI correction for removing the radar artifact, which is important to know when evaluating potential nonlinear solutions. Siewerdsen and Jaffray¹ notes that a lag correction algorithm should take into account the exposure nonlinearity of detector lag, which current techniques have not tried to do

for flat-panels. A nonlinear correction that takes into account the time variance (step-response edge dependence) of the charge trapping mechanism might remove residual artifact, eliminate the ambiguity of finding the best calibration procedure, and make the optimal lag correction independent of object size. This will be the subject of future work.

Similar to the argument for lag as the cause of the radar artifact in Sec. II A, the blurred ring artifact in Fig. 12(b) is most likely due to uncorrected lag artifact. The artifact resembles none of those previously observed for scatter and beam-hardening and is at the wrong location to be due to the bow-tie filter, dynamic gain switching, or normalization phantoms. The residual artifact occurs at the radar artifact boundary, which as seen in the sinogram difference image [Fig. 14(b)] can have a sharp transition between the always-blocked and the sometimes-blocked part of the detector.

Our results match those from investigations with an x-ray image intensifier system where the amount of lag was larger for RSRF based measurements than for FSRF experiments.¹⁴ In our case, RSRF-based IRFs often gave an overcorrection of the projection data as compared to the FSRF experiments. Furthermore, it was found that the FSRF matched most closely to small-signal approaches and thus provided the best description for use in DQE measurements.¹⁵ This is similar to our finding that the best overall artifact correction also used an FSRF technique. Since our work focused on a-Si FP detectors and not image intensifiers, it may be coincidence that some of the effects agree, although both systems use a CsI scintillator. While previous authors found that the scintillator response played a very small role in the overall temporal response of the a-Si detector,^{1,4} it is still possible that the scintillator affects the RSRF data. CsI is known to have a gain hysteresis,²³ which may add to the nonlinearity and time variance of the overall system. Note, the hardware approaches for correcting lag in the a-Si will never correct for scintillator response.

Yang *et al.*⁷ used an LTI model of lag for their simulations, which they justified after taking measurements at different exposures. However, some nonlinearity is evident in their measurements. Plus, their investigation of lag was over a much smaller dynamic range than ours. They irradiated the panel from 16 to 55% of saturation, as opposed to 0.5 to 84% in our case. The larger exposure range that we covered reflects the fact that we were also acquiring CT data sets of objects much larger than the breast. For large objects, the actual signal incident on the detector can be much less than 16% of saturation.

In summary, it was found that an IRF derived from FSRF data at low exposures best corrected for the radar artifact in CBCT reconstructions of pelvic and head phantoms.

ACKNOWLEDGMENTS

This work was supported in part by Varian Medical Systems, the Stanford-NIH Biotechnology Traineeship, NIH Grants EB003524 and HL087917, and the Lucas Foundation.

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