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Abstract. Positioning of an intraoperative C-arm to achieve clear visualization of a particular anatomical feature often involves repeated fluoroscopic views, which cost time and radiation exposure to both the patient and surgical staff. A system for virtual fluoroscopy (called FluoroSim) that could dramatically reduce time- and dose-spent “fluoro-hunting” by leveraging preoperative computed tomography (CT), encoded readout of C-arm gantry position, and automatic 3D–2D image registration has been developed. The method is consistent with existing surgical workflow and does not require additional tracking equipment. Real-time virtual fluoroscopy was achieved via mechanical encoding of the C-arm motion, C-arm geometric calibration, and patient registration using a single radiograph. The accuracy, time, and radiation dose associated with C-arm positioning were measured for FluoroSim in comparison with conventional methods. Five radiology technologists were tasked with acquiring six standard pelvic views pertinent to sacro-iliac, anterior–inferior iliac spine, and superior-ramus screw placement in an anthropomorphic pelvis phantom using conventional and FluoroSim approaches. The positioning accuracy, exposure time, number of exposures, and total time for each trial were recorded, and radiation dose was characterized in terms of entrance skin dose and in-room scatter. The geometric accuracy of FluoroSim was measured to be 1.6 ± 1.1 mm. There was no significant difference ($p > 0.05$) observed in the accuracy or total elapsed time for C-arm positioning. However, the total fluoroscopy time required to achieve the desired view decreased by 4.1 s (4.7 ± 3.6 s for conventional, compared with 0.5 ± 0.0 s for FluoroSim, $p < 0.05$), and the total number of exposures reduced by 4.0 (6.4 ± 4.8 for conventional, compared with 2.0 ± 0.0 for FluoroSim, $p < 0.05$). These reductions amounted to a 50% to 78% decrease in patient entrance skin dose and a 55% to 70% reduction in in-room scatter. FluoroSim was found to reduce the radiation exposure required in C-arm positioning without diminishing positioning time or accuracy, providing a potentially valuable tool to assist technologists and surgeons. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JMI.5.1.015005]

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1 Introduction

Mobile C-arm fluoroscopy is widely used for guidance and verification in surgical interventions. Commonly performed procedures such as pedicle-screw placement in spine surgery and open-reduction and internal-fixation in trauma surgery regularly use fluoroscopy to visualize anatomy relative to surgical instrumentation and implants.^{1,2} The multiple degrees of freedom available with a mobile C-arm need to be efficiently and accurately positioned to obtain the desired radiographic views. Repeated image acquisition as the C-arm is positioned through trial-and-error (commonly referred to as “fluoro-hunting”) achieves this at the expense of time and radiation exposure to the patient and surgical staff. Certain views can be challenging to obtain, requiring clear understanding of the anatomy and skilled operation of the C-arm to visualize a particular structure

of interest—e.g., a pedicle, fracture fragment, or joint space. When the patient is draped, it introduces additional challenges to the technologist to determine reference locations in patient anatomy. To save time and radiation dose, we propose a method for virtual fluoroscopy as an assistant to the surgeon and/or radiology technologist in C-arm positioning. The method (referred to as FluoroSim) uses the patient’s preoperative computed tomography (CT) to automatically register to the intraoperative space and compute virtual fluoroscopic images in real time that align accurately with the true radiographic image. Patients with preoperative CT, an imaging modality that is commonly acquired during the diagnostic workup prior to many orthopaedic procedures, could benefit from this solution.

Previous solutions for C-arm fluoroscopy simulation were primarily intended for surgical training purposes.^{3,4} Such systems mostly relied on external tracking systems to register the patient (or training phantom) to the coordinate system of

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the C-arm. Line-of-sight requirements and additional tracking hardware in the operating room (OR), including the direct cost and setup time of these systems, limit their broad utilization for the task of C-arm positioning. As a consequence, such solutions are not standard practice in image-guided surgery today. Dressel et al.⁵ proposed a virtual fluoroscopy solution for intraoperative C-arm positioning that could operate free of external tracking systems. In that solution, patient position estimation was performed using 3D–2D registration, whereas C-arm tracking was achieved using a camera-augmented mobile C-arm⁶ in which an optical camera tracked a marker configuration attached to the patient. This system was implemented with the x-ray source positioned over the patient, deviating from the more typical C-arm setup (x-ray source positioned under the table) and carrying some potential disadvantages of increased x-ray exposure to staff and patient. In the solution described below, the patient position is also estimated via 3D–2D image registration and utilizes the analog/digital encoders of the C-arm gantry to track the position of the C-arm during operation. Using such simple position encoders and an image-based method for patient registration, FluoroSim generates virtual fluoroscopy without additional hardware and operates within standard surgical workflow and standard position configurations of the C-arm. The image-intensity-based 3D–2D registration method is the same as that underlying the LevelCheck algorithm^{7–9} and known-component registration method,^{10,11} leveraging the same graphics-processing-unit accelerated techniques for high-speed calculation of digitally reconstructed radiographs (DRRs).

This work presents the FluoroSim methodology and investigates its potential benefit in decreasing the time and radiation dose spent in C-arm positioning. The experiments evaluated the geometric accuracy of FluoroSim and assessed the utility using a realistic, anthropomorphic pelvis phantom with five trained radiology technologists as operators. Radiation dose measurements were performed to relate the savings in fluoroscopy time to the dose reduction to the patient as well as in-room personnel.

2 Materials and Methods

2.1 Virtual Fluoroscopy

The FluoroSim workflow starts with registration of the patient preoperative (or intraoperative) CT image to the C-arm coordinate system using a single radiographic view of the patient. Virtual fluoroscopy can then be generated in real time as the C-arm is repositioned about the patient. When the virtual

fluoroscopic view is judged by the operator to be the desired view, an actual radiograph is acquired. Note that intraoperative updates such as surgical instruments/implants or reduction of the fracture are not displayed in the virtual fluoroscopic view, and the up-to-date visualization of such instruments is achieved from the actual radiograph—i.e., FluoroSim guides C-arm positioning with respect to the patient anatomy. In surgeries with intraoperative changes to patient anatomy (such as fracture reduction), FluoroSim visualization could achieve an approximate target view from a preoperative CT that lies within close proximity to the desired target view.

Generating virtual fluoroscopy involves computing a simulated x-ray image (referred to as a DRR) from the patient's preoperative CT.¹² A typical fluoroscopy frame (768 × 768 pixels) can be computed in 0.15 ± 0.01 s yielding a frame rate of ~7 frames per second. The geometric accuracy of the DRR at a given C-arm position depends on the accurate estimation of the relative position between the C-arm and the patient, calculated via two operations. First, patient position is estimated by registering a single radiograph to the CT image via a 3D–2D image registration algorithm that has been shown in previous work to be robust over a wide variety of clinical imaging scenarios, including the presence of surgical instrumentation and soft-tissue deformation.^{8,9,13,14} During this registration, a gradient-orientation⁹ similarity metric between the radiographs and DRRs from the CT image is optimized using a multistart covariance-matrix-adaptation evolution strategy (ES)^{15,16} to yield a robust solution in the rugged, nonconvex optimization search space. Second, the current position of the C-arm is calculated using electromechanical encoders that track its motion. For example, the C-arm used in the current work provides an encoder readout of two rotational directions with 0.1 deg precision as shown in Fig. 1(a): (1) rotation about the lateral (LAT) axis within the plane of C (referred to as “orbital” and denoted θ) and (2) rotation about the longitudinal axis (referred to as “angular” and denoted Φ). The C-arm position for all (θ , Φ) combinations is determined by a one-time precalibration of the C-arm geometry.¹⁷ Considering the nonisocentric geometry of the C-arm and possible geometric imperfections of its gantry motion (for, e.g., due to gravity), calibration was performed at each (θ , Φ) combination, and projection matrices were stored in the form of a look up table. Additional encoders would allow readout of additional degrees of freedom—e.g., adjustment of C-arm height, motion along the LAT direction (used to center the patient in posterior–anterior (PA) view or change magnification in LAT views), or even encoding of the C-arm wheels for positioning relative to the floor.

Fig. 1 FluoroSim assistant to C-arm positioning. (a) Illustration of C-arm orbit and angulation (θ and Φ), (b) example DRR computed from preoperative CT, and (c) experimental setup showing the C-arm positioned using FluoroSim.

2.2 Experiments

Experiments were performed to assess the geometric accuracy of virtual fluoroscopic images computed by FluoroSim and to evaluate its potential utility in reducing time and radiation dose associated with C-arm positioning. As detailed below, the studies involved trained technologists operating a mobile C-arm relative to realistic anatomy in a laboratory OR environment.

2.2.1 Experimental setup

A mobile C-arm (Cios Alpha, Siemens Healthineers, Erlangen, Germany) was used in the experimental setup shown in Fig. 1(c) with encoder readout of orbital and angular motions. An anthropomorphic pelvis and abdomen phantom (Rando body phantom, The Phantom Laboratory, Greenwich, New York) was placed supine on a carbon fiber fluoroscopy table. Patient registration was performed using a single PA radiograph of the thorax phantom.

Five trained radiology technologists who routinely operate the C-arm in pelvic surgery were tasked to position the C-arm to six clinically relevant radiographic views, as shown in Fig. 2. Each target view was defined by a board-certified orthopedic trauma surgeon once relative to the anthropomorphic phantom, providing a specific instantiation of the radiographic view to be achieved by the technologist. Each such view was common to fluoroscopic guidance in orthopedic surgery—e.g., screw insertions in regions of the sacro-iliac (SI) joint, anterior–inferior iliac spine (AIIS), and superior–ramus (SR) and definition of the target view in terms of a singular instance (rather than a general heuristic range or potentially vague anatomical concept) was believed to be less subject to interoperator variability. The technologists positioned the C-arm to each target view using both conventional “fluoro-hunting” and FluoroSim methods. For the FluoroSim approach, virtual fluoroscopy was continuously displayed during C-arm maneuvering, whereas, in the fluoro-hunting approach, technologists intermittently acquired fluoroscopy using a foot pedal. For purposes of

these experiments, virtual fluoroscopic views—rather than actual exposure—were displayed with each press of the foot pedal so that no dose was imparted to the operators in the experiment; however, the foot pedal press provided realistic simulation of conventional fluoro-hunting, wherein technologists were mindful to minimize the amount of exposure time. Each view was repeated for each technologist twice on different days, and the order of views was randomized to minimize bias associated with learning effects.

2.2.2 Geometric accuracy

To measure the geometric accuracy of FluoroSim images, the C-arm was positioned systematically in 10 deg increments over a range $-40 \text{ deg} < \theta < 40 \text{ deg}$ and $0 \text{ deg} < \Phi < 30 \text{ deg}$. An actual radiograph was acquired at 12 different C-arm positions and compared with the corresponding virtual fluoroscopy image in terms of the distance between 223 manually identified homologous point pairs between radiographs and the CT image. For each landmark identified in the radiographs (x_r^i), the corresponding location that would result in the projected landmark was found in the CT image (x_{CT}^i). The conspicuous extrema of bone boundaries (e.g., corners of vertebrae) were selected as anatomically homologous landmark locations. The projection distance error (PDE) was then calculated using a projection matrix found after registration (T_{reg}) according to the following equation:

$$\text{PDE} = \sqrt{\frac{\sum_{i=1}^N [x_r^i - T_{\text{reg}}(x_{CT}^i)]^2}{N}},$$

where N is the total number of landmark pairs independently identified between images. The resulting PDE refers to this point-based distance in the detector plane. The intrareader variability in the point-pair identification process was estimated via three trials repeated on different days.

Fig. 2 Six standard target views of the pelvis. Each was defined by an orthopedic trauma surgeon, including PA, right LAT, inlet, outlet, right tear drop, and obturator inlet views.

2.2.3 Utility: positioning accuracy, time, and radiation exposure

For each technologist, target view, and positioning method (FluoroSim versus fluoro-hunting), measurements were recorded for each C-arm positioning trial to characterize the improvements in utility in terms of positioning accuracy, time, and radiation exposure. C-arm positioning accuracy was measured as the difference in angles (θ and Φ) between the technologist-acquired view and the surgeon-defined ground truth. For each trial, the total C-arm positioning time required to obtain the target view and the number of exposures were recorded. Exposure time was measured as the cumulative duration for which the technologist ran fluoroscopy (via foot pedal).

2.2.4 Radiation dose measurements

Radiation dose was measured for PA and LAT views in terms of (1) entrance skin dose (ESD) and (2) in-room scatter radiation dose. An exposure meter (Model-1050 radiation-monitor with $10 \times 5 - 60$ ionization-chamber, RadCal Corporation, Monrovia, California) was positioned on the surface of the phantom to measure ESD, and an ionization survey meter (Fluke 451, Fluke Electronics Corporation, Everett, Washington) was positioned at distances 64 and 100 cm from the patient at a height of 100 cm from the floor to measure in-room scatter. A distance of 64 cm from the patient was taken as the typical position of in-room staff, such as the surgeon or scrub nurse, and a distance 100 cm was taken as the typical distance for staff, such as the radiology technologist and anesthesiologist. Fluoroscopy techniques were set by automatic exposure control from the C-arm and were in a range typical for the pelvis (67 to 90 kV and 3 to 5 mA).

3 Results

3.1 FluoroSim Geometric Accuracy

The geometric error between FluoroSim virtual images and actual radiographs in the thoracic phantom was 1.6 ± 1.1 mm (mean $\pm$ std). Errors in patient registration, C-arm calibration, and observer variability in fiducial localization are contributors to this overall error. The last (fiducial localization error) measured from repeated trials was found to be 0.5 ± 0.4 mm (mean $\pm$ std). Although corresponding anatomy in rigid structures (e.g., vertebrae) was identified during the validation process, previous clinical studies^{8,13,18} showed the registration algorithm to be robust against mismatch due to nonrigid structures, such as the diaphragm. Figures 3(a) and 3(b) show the distributions in PDE as a function of orbital and angular positions, respectively, demonstrating comparable performance over the full range of motion investigated. Figure 3(c) shows the alignment of FluoroSim and actual radiographs qualitatively at multiple C-arm positions. These image pairs exhibit a high degree of similarity supporting visual feedback to the C-arm operator in positioning the C-arm at the desired orientation prior to acquiring actual fluoroscopy. In the current implementation, after the initial radiograph acquisition, 3D-2D registration to estimate the patient position was performed in <1 min.

3.2 C-Arm Positioning Accuracy

Figures 4(a) and 4(b) show the C-arm positioning accuracy achieved with conventional fluoro-hunting and with FluoroSim at each target view. Minor overall improvement in positioning accuracy was observed for FluoroSim, giving $\text{error}_\theta = 1.7 \text{ deg} \pm 2.0 \text{ deg}$ and $\text{error}_\Phi = 2.2 \text{ deg} \pm 2.5 \text{ deg}$ compared

Fig. 3 Geometric accuracy of FluoroSim. Distribution of PDE at various (a) orbital and (b) angular orientations of the C-arm, showing alignment within ~ 2 mm across the full range of motion. (c) Comparison of (top row) actual radiographs, (middle row) actual radiographs overlaid with (yellow) gradient edges computed from the FluoroSim virtual images, and (bottom row) FluoroSim images.

Fig. 4 C-arm positioning accuracy for conventional fluoro-hunting (gray) and FluoroSim (blue) in six target views [(a) orbital (θ) and (b) angular (Φ)] as well as results pooled “overall.”

with the conventional method with $\text{error}_\theta = 1.9 \text{ deg} \pm 2.5 \text{ deg}$ and $\text{error}_\Phi = 2.7 \text{ deg} \pm 2.6 \text{ deg}$. Pooling all measurements as shown in Fig. 4, a paired t -test failed to detect statistical significance ($p = 0.13$). We, therefore, conclude that the methods offer comparable performance in C-arm positioning accuracy within $\sim 2 \text{ deg}$ of the target projection view.

3.3 C-Arm Positioning Time

Positioning the C-arm to a given target view required an average of $36.4 \pm 33.2 \text{ s}$ using FluoroSim, compared with $41.0 \pm 30.9 \text{ s}$ for conventional fluoro-hunting. The difference was not statistically significant ($p = 0.39$), and we conclude that C-arm positioning time is comparable for both methods within $\sim 5 \text{ s}$. However, in the conventional approach, the technologist needs to intermittently activate the foot pedal, which involves minor additional activity (and occasional fumbling with the foot pedal), whereas continuous display of the FluoroSim image during C-arm maneuvering appeared to provide more natural interaction and could lead to reduced positioning time given increased familiarity.

3.4 Exposure Time and Number of Exposures

Figures 5(a) and 5(b) show the distribution in fluoroscopy time and number of exposures acquired for each target view for FluoroSim and conventional fluoro-hunting methods. A major reduction in exposure time and number of exposures was observed for the FluoroSim method. On average, fluoroscopic exposure time required to achieve a given target view decreased by 4.1 s with FluoroSim—specifically, 4.7 s of fluoro-hunting time versus 0.5 s for FluoroSim. Similarly, the number of exposures reduced for FluoroSim—specifically, an average of 6.4 exposures acquired in conventional fluoro-hunting, compared with two exposures of FluoroSim (which is simply the exposure associated with the actual radiograph plus the one image acquired at the beginning of the case for initialization of 3D–2D registration). Paired t -test indicates statistically significant improvements ($p < 0.05$) for all cases, with the exception of the PA view ($p = 0.06$), owing to the relative ease in obtaining this view.

ESD and scatter radiation measurements for PA and LAT views of the pelvis are summarized in Table 1, showing dose levels that are consistent with other studies reported in the

Fig. 5 Comparison of conventional and FluoroSim methods in terms of (a) fluoroscopy exposure time and (b) number of fluoroscopy exposures.

Table 1 Dose measurements for PA and LAT views of an anthropomorphic pelvic/abdominal phantom.

View	kV	mA	Delivered dose (mGy/min)	Entrance skin dose rate (mGy/min)	Scatter dose rate measured at 64 cm (μ Gy/min)	Scatter dose rate measured at 100 cm (μ Gy/min)
PA	67	3.4	163.1	16.7	22.6	5.2
LAT	90	4.8	1337	133.3	170.4	8.7

literature.^{19–21} Figure 6 compares ESD and in-room scatter radiation associated with C-arm positioning using FluoroSim, with reductions compared with conventional fluoro-hunting in proportion to the exposure time and number of exposures discussed above. These findings suggest a 50% to 78% reduction in patient ESD (0.3 to 2.2 mGy for conventional approach, compared with 0.6 to 10.2 mGy with FluoroSim). They also demonstrate a 55% to 70% reduction in in-room scatter radiation (0.4 to 2.8 μ Gy for conventional approach, compared with 0.9 to 13.0 μ Gy with FluoroSim). Similar to the results in Fig. 5, these results were statistically significant ($p < 0.05$).

4 Discussion

FluoroSim provides a method to decrease radiation dose in the OR by minimizing fluoroscopy time associated with “fluoro-hunting” in the course of C-arm positioning. The studies reported above demonstrated substantial savings in fluoroscopy exposure time and the number of exposures, reducing radiation exposure in most cases simply to (one) image acquired early in the case to initialize the 3D–2D registration plus the (one) desired image acquired at a particular C-arm view. For initialization, the radiographic view needs to capture general anatomical information related to patient pose and does not require the alignment of the C-arm relative to any specific location within the anatomy. Therefore, multiple acquisitions after repositioning the C-arm were not necessary to obtain the initialization radiograph for image registration. This initialization radiograph can come from a localization image at the beginning of the surgery, such as the PA view, which is relatively easy to position. FluoroSim is less susceptible to errors in the depth direction when the initial radiograph is acquired closer to the desired

view. If more accuracy in the depth direction is desired, then registration could be performed with multiple initial radiographs acquired with angular separation.

FluoroSim intends to eliminate qualitative interpretation of continuous fluoroscopy during “hunting” with quantitative registration obtained from initialization by a single exposure. Such initialization is likely to hold as long as the patient is in a stable position on the table and the C-arm is not moved in an unknown (unencoded) manner. Thus, FluoroSim assumes that there is no patient motion between the initial patient registration radiograph and the C-arm positioning. For example, flipping the patient or adjusting the position of the operating table would require reinitialization, as would moving the C-arm wheels (which were not encoded on the current system). Although patient motion is always accommodated in the fluoro-hunting approach, a reregistration update at the cost of one radiograph is required for FluoroSim in instances of patient motion. Moreover, the accuracy of FluoroSim could be limited when patient anatomy changes intraoperatively (e.g., fracture reduction). In such scenarios, the registration achieves the best rigid alignment of the anatomy visible in the radiograph and FluoroSim could provide an approximate view of the desired target view from preoperative anatomy.

The obturator inlet view appeared to be the most challenging target view in the current study, requiring an average of 9.5 exposures to obtain via fluoro-hunting. In such an oblique view, both orbital and angular directions need to be concurrently positioned and rely strongly on the operator’s judgment to predict the presentation of 3-D anatomy in the 2-D projection domain. The PA view, on the other hand, typically required only the orbital alignment of the C-arm and was the least challenging to achieve, requiring an average of 3.3 exposures with fluoro-hunting.

In FluoroSim, the accuracy of patient registration and DRR generation could depend on the image quality of the preoperative CT and/or intraoperative radiographs. Previous clinical studies^{8,9,13} found acceptable accuracy in patient registration using fairly standard CT imaging protocols (e.g., 120 to 140 kVp, 80 to 660 mAs, and voxel size (or slice thickness) ranging from 0.2 to 3.00 mm). Previous studies²² also indicate that accurate image registration can be performed with radiographs acquired at a significantly lower dose (a factor of 5 or lower) than typical dose levels for intraoperative imaging. Thus, FluoroSim does not appear to require imaging protocols

Fig. 6 Comparison of conventional and FluoroSim methods in terms of (a) entrance skin exposure to the patient and (b) scatter radiation exposure to personnel measured at 64 cm and 1 m from the patient.

other than those already common in CT and radiographic imaging within the standard of care.

C-arm positioning in this study was governed by the target views defined by the surgeon, and the criteria associated with such target views were understood well by each operator (e.g., the PA view was defined to align the pubic symphysis with the top of S4). Such clear definition/communication between the surgeon and technologist may be less reliable in practice, commonly resulting in increased trial-and-error and longer exposure times to achieve the desired view. The variability observed in positioning accuracy for the more challenging target views (e.g., the tear drop and obturator inlet views) could be similarly attributable to broader interpretation or less distinct anatomical landmarks meeting the surgeon's definition of the target view. In such scenarios, the benefit of FluoroSim is likely even greater. The required accuracy of C-arm positioning to acquire a specific anatomical view is dependent on multiple factors such as the presence of surgical instrumentation/implants in the field of view and/or the complexity of anatomical features in the radiographic view. In the simplest terms, the specified precision of 0.1 deg in the current gantry encoders corresponds to a PDE of ~ 2 mm at the detector plane for a feature at isocenter. Alternatively, one could argue that a feature (e.g., joint space) of 1 mm in size requires angular precision of 0.05 deg in positioning. However, the required accuracy in angle encoding to obtain a particular desired view is likely to vary widely, depending on the anatomy and view angle.

Although FluoroSim imparted substantial radiation dose savings, C-arm positioning time was comparable for conventional and FluoroSim methods. The learning curve associated with FluoroSim could have somewhat inhibited the potential savings in positioning time in these experiments. Furthermore, an alternative implementation of FluoroSim would involve a graphical software interface (rather than actual physical motion of the C-arm gantry) and could yield even more time savings. In such an implementation, the technologist could quickly set the desired C-arm position via the graphical interface, and, when the desired virtual fluoroscopic view was obtained, the motorized gantry would drive to the position set by the software.

Certain procedures require repeated fluoroscopies of the same set of views. For example, screw placement procedures may involve repeatedly switching between PA, inlet, and outlet views to monitor the position of instrumentation within bone corridors. In the studies reported above, technologists demonstrated comparable performance in achieving a target view twice across two repeated trials. This suggests that once the previous position was lost (due to C-arm and/or patient motion) the technologist is similarly repeatedly challenged to position the C-arm, although s/he had previously achieved the view within the same session. Therefore, for procedures involving repeated acquisitions of the same set of views, the improvements reported in the study may scale approximately linearly in terms of the number of exposures and the associated dose reductions.

The experiments were performed using virtual fluoroscopy to guide positioning (to avoid radiation exposure to the study participants). Recognizing that such could artificially bias the technologists to acquire more images than in clinical practice, the studies included several elements intended to minimize such bias. First was the use of an actual fluoro pedal to acquire (virtual) fluoroscopy, which is believed to subscribe to a technologist's training and muscle memory in minimizing the amount of time that the pedal is depressed. Second was the

incorporation of a visual and audible signal to realistically alert the technologist that (virtual) x-rays were being acquired. Finally, the technologists were explicitly directed to position the C-arm in a manner consistent with real clinical use—specifically, to do so with the lowest number of (virtual) radiographs as possible. As a basis of comparison and a check against potential bias, we retrospectively analyzed the clinical use of the same C-arm system in three pelvic procedures and found that that technologists acquired 6.6 ± 4.9 (range: 2 to 14) images to position the C-arm in a routine clinical setting. This range agreed with the findings reported in this paper, suggesting that the potential bias in the number of views using virtual fluoroscopy was minimal.

Although the relative benefit of FluoroSim is less for simple views, such as the PA view, one can envision that the manually positioned PA view is that which provides initialization, thereby minimizing additional overhead in readying FluoroSim for subsequent use during the case. For example, patient registration (initialization) could be realized using one or more localization radiographs typically acquired at the start of surgery without additional workflow. Subsequently, the patient registration can be updated with every actual radiographic acquisition throughout the procedure. Therefore, each target view does not require two exposures (as conservatively assumed in the results reported above). Instead, FluoroSim could achieve upward of $\sim 50\%$ to 78% reduction in dose without any additional radiographs from those already acquired in standard workflow and would remain up to date throughout the procedure using the last acquired image for registration. Moreover, while the system in this study required a constant 0.5 s to acquire two fluoroscopy shots, other modern C-arms equipped with single-shot capability and pulsed fluoroscopy can acquire an image in <0.1 s fluoroscopy time. FluoroSim, in such a single-shot mode, could reduce radiation dose even beyond that reported above.

In the current study, we invoked only two degrees of freedom (angular and orbital rotation) on the C-arm. However, FluoroSim can be extended to additional degrees of motion as needed by attaching mechanical encoding to the C-arm—e.g., vertical/lateral translation and swivel/wag. In the current work, collaboration with the C-arm manufacturer facilitated access to the encoder readings for FluoroSim, enabling the work reported here as well as future translation to clinical studies in which the x-ray technologist can activate FluoroSim through a research interface. As mobile C-arms become increasingly motorized in their motion (cf., manual rotation), one may anticipate that such position encoders will become more common and, hopefully, easily accessible along with other digital information reported by the system. Recovery from unrecorded motion of the patient, support table, or C-arm can be accomplished by acquisition of a single radiograph to reestablish registration, allowing FluoroSim to resume its operation.

In conclusion, the presented method was shown to provide virtual fluoroscopy as a potentially valuable assistant in C-arm positioning. The method demonstrated reduction in radiation dose by more than a factor of 2 compared with conventional fluoroscopy, did not compromise positioning accuracy or time, operated without addition of tracking systems to the operating environment, and required little or no additional workflow.

Disclosures

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Biographies for the authors are not available.