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A Simple Technique for Interventional Tool Placement Combining Fluoroscopy With Interventional Computed Tomography on a C-Arm System

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Abstract

BACKGROUND: Flat-panel cone-beam computed tomography (FP-CBCT) has recently been introduced as a clinical feature in neuroangiography radiographic C-arm systems.

OBJECTIVE: To introduce a method of positioning a surgical tool such as a needle or ablation probe within a target specified by intraoperative FP-CBCT scanning.

METHODS: Two human cadaver and 2 porcine cadaver heads were injected with a mixture of silicone and contrast agent to simulate a contrast-enhanced tumor. Preoperative imaging was performed using a standard 1.5-T magnetic resonance imaging scanner. Intraoperative imaging was used to define the needle trajectory on a GE Innova 4100 flat panel–based neuroangiography C-arm system.

RESULTS: Using a combination of FP-CBCT and fluoroscopy, a needle was successfully positioned within each of the simulated contrast-enhanced tumors, as verified by subsequent FP-CBCT scans.

CONCLUSIONS: This proof-of-concept study demonstrates the potential utility of combining FP-CBCT scanning with fluoroscopy to position surgical tools when stereotactic devices and image-guided surgery systems are not available. However, further work is required to fully characterize the precision and accuracy of the method in a variety of realistic surgical sites.

Keywords

Ablation; Interventional computed tomography; Needle placement; Tool placement

Minimally invasive devices and techniques continue to be developed for all areas of surgery, driven in large part by increasingly detailed and sophisticated image guidance. Interventional procedures using multiple imaging modalities (magnetic resonance imaging [MRI], conventional angiography, and computed tomography [CT]) continue to be developed and refined. There are unique challenges in developing minimally invasive image-guided tools and procedures for intracranial use, but potential applications for image-guided tool placement procedures are numerous. Newer potential applications in the head and neck include difficult ventriculostomy placement, image-guided percutaneous brain biopsies, intraoperative imaging/guidance during complex surgical cases, ablation of nonoperable intracranial brain tumors, ablation for movement disorders, percutaneous sclerotherapy of vascular malformations/hemangiomas of the head and neck, and local radiosensitization delivery before radiation therapy treatment.

For many procedures, particularly those involving more superficial lesions, image guidance with single-plane projection images is sufficient. However, for deep and/or small lesions, particularly those surrounded by eloquent structures, the addition of in-suite interventional CT in planning and executing the needle/instrument/probe trajectory promises to significantly improve placement accuracy compared with single-projection image guidance (ie, fluoroscopy).

Flat-panel cone-beam CT (FP-CBCT) is a recently developed feature of digital neuroangiography C-arm systems.^{1–3} Trade names for these systems include Innova CT (GE Healthcare, Waukesha, Wisconsin), Dyna CT (Siemens Medical Solutions Inc, Iselin, New Jersey), and 3D-RX (Phillips Medical Systems, Eindhoven, the Netherlands). These new systems allow instant switching of imaging modalities from continuous fluoroscopy to CT imaging with increasingly rapid reconstruction times. Thus, 1 machine creates a complete interventional-operative platform to produce 2-dimensional fluoroscopic guidance and 3-dimensional volumetric reconstruction.

FP-CBCT plus fluoroscopy may also be combined with other recent technological advances in operative procedures. FP-CBCT could be used in conjunction with image-guided surgery (IGS) systems using intraoperatively acquired FP-CBCT image volumes instead of relying on preoperative imaging. It could also be used in conjunction with advances in endonasal endoscopy^{4,5} to place probes and monitor cryoablation of cranial base lesions.

Using a combined fluoroscopy and FP-CBCT platform for neurointerventional and less invasive surgical procedures requires a sequence of steps including fabrication of a custom frame, acquiring FP-CBCT for targeting, and identification of entry and the destination

positions, gantry positioning, fluoroscopy-guided tool placement, and confirmational FP-CBCT to verify the final tool position. We present our early results from a cadaver study using FP-CBCT, along with standard fluoroscopy, for direct intraoperative image-guided placement of interventional tools.

MATERIAL AND METHODS

Surgical Model

Two female porcine cadavers and 2 human cadaver heads were used in this proof-of-principle study. For the porcine studies, these imaging and surgical procedures were performed on the same day that the animals were euthanized after being subjects for other internal review board–approved research projects. The female pigs were approximately 6 months old with a weight of approximately 40 lb. In the first pig, the head was severed and used alone for this experiment. After the head was severed, it was placed in a refrigerator for approximately 4 hours before imaging began. In the second porcine experiment, the entire porcine cadaver was left intact during the procedure, and this study was conducted immediately after the pig was euthanized. In each human cadaver case, the head was imaged and the procedure was performed after the head was severed from the body.

To test the guidance procedure described, a contrast-enhanced tumor was simulated using a mixture of a self-hardening silicone compound and metrizamide radiographic contrast. In the porcine model, the mixture was injected intracranially with a 50-mL syringe via a burr hole that was drilled with a manual hand drill. To make the simulated procedure more challenging, a second burr hole was drilled contralaterally and the device was advanced through the second hole into the target. Therefore, the device trajectories planned and performed are not the closest means of accessing the “tumor,” but were chosen because they are more challenging scenarios than using the original burr hole for both the silicon injection and subsequent device placement. The trajectories used are not intended to simulate realistic paths but were chosen to demonstrate the ability of the technique to perform in challenging scenarios. The size of the simulated tumors was measured quantitatively by manually segmenting the intraoperative trajectory planning images and using the region volume calculation feature on the GE Advanced Workstation (GE Healthcare). The first simulated tumor had a volume of 3 mL, whereas the second tumor had a volume of 1 mL. In the human cadaver case, the 2 tumors were simulated by contrast injection through a Bonopt biopsy cannula (Radi Medical Systems, Uppsala, Sweden) with an outer diameter of 15 gauges. The first was a superficial tumor accessed through the temporal lobe, and the second was a simulated pituitary tumor for which a transsphenoidal approach was simulated. In the human cadaver models, the surgical tool guided into position using this technique was a 1.7-mm PerCryo CryoProbe (Endocare, Irvine, California) used for cryoablation procedures.

Because the contrast agent is in a powder form, the rapid hardening of the silicon resulted in attenuation of the tumor such that it appears slightly heterogeneous in the FP-CBCT images.

Quantitative Assessment

In addition to the tasks described that demonstrate probe placement in simulated contrast-enhanced tumors, quantitative measurements were performed to assess the accuracy of the technique. Because simplistic phantoms do not provide an adequate assessment of the performance of a probe placement task, a dedicated porcine study was conducted. In this study, 4 separate individuals performed the same task, using the trajectory planning procedure described in the following. Each user was allowed to perform 2 practice runs to learn the procedure before data were acquired. For each trial, a given point in the image volume was established as the target point. After the needle was placed using the procedure described, the distance from the desired destination was assessed from a second FP-CBCT scan. The distance from the target was measured on the second FP-CBCT scan using the 3-dimensional distance measurement tool on the GE Advanced Workstation.

Imaging Devices

Preoperative MRI was conducted on a GE Signa Excite 1.5-T scanner (GE Healthcare) using the standard head coil. Two representative images from the preoperative imaging are included here to visualize the simulated lesion in the pigs (Figure 1). The coronal slice (Figure 1A) was acquired using a fast recovery, fast spin echo sequence where the parameters were TR = 3400 ms, TE = 71 ms, flip angle = 90 degrees, number of excitations = 2, slice thickness 4 mm on 5-mm spacing, 0.625-mm pixel spacing, and a bandwidth of 31.2 kHz. The sagittal slice (Figure 1B) was acquired with a T1 fluid-attenuated inversion recovery sequence with imaging parameters: TR = 2221 ms, TE = 11.48 ms, flip angle = 90 degrees, slice thickness = 5 mm, number of excitations = 2, 0.71-mm pixel spacing, and a 15.6 kHz-bandwidth. The preoperative imaging was not used explicitly in the trajectory planning, but rather is provided here for reference examples of preoperative imaging of the porcine heads and to demonstrate that this model for a contrast-enhanced tumor enables MRI as well.

The intraoperative imaging was performed with the GE Innova 4100 single-plane flat panel-based neuro C-arm system. During the course of the experiments, fluoroscopic and cone beam CT image acquisitions were used to provide complementary information during the device guidance procedure. The 3-dimensional CT projection data were acquired over an angular range of approximately 210 degrees, with a gantry rotation of 20 degrees/s where the detector read-out rate was 30 frames per second. The geometry of the permanently mounted isocentric neurointerventional C-arm system is shown in Figure 2, which illustrates the system's rotation during a sample CT image acquisition. The 3-dimensional images were reconstructed on a $512 \times 512 \times 512$ cubic grid using the standard manufacturer software. The bone reconstruction kernel was used for all reconstructions. The visualization and image manipulation were performed on a GE Advanced Workstation. Typically, there are 5 images displayed on 2 monitors during the visualization procedure: 3 orthogonal planes, 1 oblique plane, and 1 volume rendering of the full head. The standard fluoroscopic mode was used for the fluoroscopy portion of the procedure.

External Landmarks

A disposable Uni-frame perforated thermoplastic mask from Medtec (Kalona, Iowa) (1.6-mm, MT-APU-12-1.6) was used to secure the head and neck (Figure 3A). These masks are heated in warm water until they become soft, at which point they are placed on the subject and allowed to harden. The entire process only takes 5 to 10 minutes. These masks are frequently used in radiation oncology. The individual perforations served here as the possible choices for entrance positions. To easily relate the patient space with the imaging space, several small metallic spheres were used as fiducial markers. The subject was not moved in between the intraoperative FP-CBCT and the fluoroscopic guidance, so the fiducials are not used to register coordinate systems, but rather simply to enable easy identification of the entry position within the mask for the clinician. In a commercial implementation, this could be accomplished in a variety of ways, several of which we are investigating.

Trajectory Planning Procedure

As outlined previously, the procedure followed for each trajectory plan was as follows. (1) A planning FP-CBCT was performed in which a contrast-enhanced simulated tumor had been implanted in the surgical model. (2) The external point of entry and the destination position are identified in the 3-dimensional volume model. These 2 endpoints define a line segment that we refer to as the planned trajectory. (3) The depth of descent is measured on the 3-dimensional volume and marked on the device using a Vernier caliper. Figure 4 demonstrates the visualization of the trajectory as well as the depth that the device must traverse from the surface of the Uni-frame mask in a human case. (4) On the GE Advanced Workstation, a volume rendering is displayed with the superimposed device trajectory (Figure 3B). The volume is rotated until the line that corresponds to the device trajectory projects to a single point. The rendering software uses parallel projections, but in the limit that the entry point is near the center of the field of view, the beam divergence is low and parallel beams approximate the system's divergent radiographic projection acquisition. Thus, the gantry positioning information corresponding to the view where the line projects to a single point is sent to the GE Innova motion controller. Therefore, the gantry will be positioned so that the device is seen in a bull's-eye view. The device is inserted in the center of a given hole in the mask, as specified by the planning trajectory. As the device is inserted, the angle of descent is monitored by fluoroscopic guidance such that the device always projects to a single point on the detector. A photograph taken during the procedure (Figure 3C) demonstrates that the fluoroscopic guidance may use significant collimation to reduce the dose to the subject and the clinician's hands. In the future, device advancement will be performed with robotic guidance, minimizing any radiation to the clinician. (5) The final step, which is optional depending on the clinical task, is to perform a second FP-CBCT scan to verify the final tool position. The outcome of the verification scans are given in the Results section.

FP-CBCT X-Ray Dose Measurements

The dose measurements for the CT image acquisition were made using the standard 16-cm acrylic phantom that is typically used for CT dose index measurements. In the cone-beam

case, it is appropriate to use a small spherical chamber for the dose measurement.^{6,7} In this case, we used a 0.6-mL Farmer chamber, which was read out using a Keithley electrometer (Model 6517 A; Keithley, Cleveland, Ohio), each of which was calibrated by an accredited dosimetry calibration laboratory. The chamber was calibrated over a range of beams and found to have a flat response (ie, varied by <1%) for half value layers of 3-mm Al to 7-mm Al.

RESULTS

Confirmation FP-CBCT

In this proof-of-principle study, the primary results are the confirmation FP-CBCT images taken after the procedures. The same radiographic and imaging parameters were used to acquire the confirmation image volumes that had been used in acquiring the planning volumes. These images demonstrate that in each of the 2 porcine cadaver studies and the 2 human cadaver studies, the surgical tool was successfully inserted into the simulated tumor. In the case of the first pig, the device was well positioned with the center of the tumor volume (Figure 5A). However, the relatively large size (3 mL) of this first tumor model reduced the difficulty of the device placement procedure. Thus, for the second porcine cadaver, the size of the simulated tumor was reduced to 1 mL. In the second case, the device was incident on the periphery of the tumor volume (Figure 5B,C). In the human cadaver studies, the cryoprobe was well positioned in a superficial tumor (Figure 6) and a simulated contrast-enhanced pituitary tumor that was accessed via a transsphenoidal approach (Figure 7). A microscopic view after dissection demonstrates the model used here for the simulated pituitary tumor and its relationship to sensitive structures (Figure 7D).

Quantitative Measurements

As described previously, quantitative measurements were performed in a porcine model. A total of 10 device placement experiments were conducted with 4 different individuals. Challenging rather than superficial tasks were simulated with an average depth of needle insertion of more than 60 mm. The average error in the position of the end of the needle for each of the 4 users was 4.1 mm, 4.6 mm, 4.7 mm, and 5.1 mm. The average error in the position of the end of the needle for all users was 4.6 mm with a standard deviation of 0.95 mm. The minimum and maximum errors over all trials were 2.7 mm and 5.6 mm, respectively.

Dose Measurements

The weighted average dose for the FP-CBCT scans was computed by averaging 8 peripheral measurements and multiplying this average by a 2/3 weighting factor. The central dose measurement was weighted by 1/3. The measured dose for the mode used in these scans was 4.42 mGy per scan. In this case, we used the normal detail mode that corresponds to a higher radiographic dose than the low detail mode. Thus, when relatively high contrast targets are of interest, a lower dose scan is feasible. For the lower dose mode, the measured dose was 2.74 mGy. Three rotational speeds are available on this system, and because the dose and view do not change with the rotational speed, this parameter may also be used to modify the delivered dose. The 20-degrees/s mode was used in the work reported here. If the 40-

degrees/s mode was used, the dose would be reduced by a factor of 2. Likewise, using the 10-degrees/s mode would increase the dose by a factor of 2 compared with the measurements reported here. The dose scaling with rotational speed was also confirmed experimentally.

For the acquisition mode used during these imaging studies, the dose of 4.42 mGy per scan (~0.14 mSv) was measured in the central plane, and in low-dose mode, this corresponds to 2.74 mGy (~0.1 mSv).⁸ These doses should be compared with the typical dose of 2 mSv for a diagnostic head CT scan. Thus, multiple interventional CT scans (~6 or more depending on the parameters) may be performed for the same radiation dose received during a diagnostic CT scan.

DISCUSSION

We demonstrated a simple FP-CBCT- and fluoroscopic-guided technique for percutaneous interventional device placement. This technique was verified in 2 porcine cadaver and 2 human cadaver models with simulated contrast-enhanced tumors. In each case, the combination of FP-CBCT and fluoroscopy was sufficient to place a device within the simulated tumor volume, as confirmed with an additional FP-CBCT scan. The accuracy of the technique, as measured in a porcine model, was 4.6 ± 0.95 mm. These measurements provide an upper limit on the achievable accuracy of the procedure. In the measurements performed, readjustment of the needle position based on a second FP-CBCT scan was not permitted, whereas in clinical practice, the device may be readjusted based on subsequent scans. For more superficial targets, we would expect improved accuracy. In addition, the tests were conducted without an external frame. An external frame used to guide the surgical drill and the inserted device would significantly improve the accuracy of the procedure. The inclusion of a surgical frame in the procedure is a subject of future study.

There are several reasons for selecting the radiography-based C-arm platform for image guidance of these procedures. Although MRI has excellent soft-tissue imaging capabilities and is used extensively for image-guided procedures,^{9,10} there are many cogent reasons for choosing an FP-CBCT platform. First, conventional CT is already extensively used for image-guided therapy.^{11–13} Additionally, there is a trend for the newest digital neuroangiography machines with CBCT capabilities to be integrated into the operating room area proper, allowing the creation of a true neurointerventional operating room. Radiation dose reductions for FP-CBCT scans allow multiple interventional scans to be performed at the equivalent dose of a standard head CT scan, making repeated interactive use of this imaging modality a viable tool for interventional and conventional operative cases.

The multifunctionality of this new type of operating room increases the potential for full-time room use. Prospective cases include routine neuroendovascular surgery, conventional neurosurgical surgery, or a combination of both approaches in the same case. No portable radiographic/CT equipment would need to be brought into the room, and the patient would not have to be moved during surgery.

Second, the image quality is excellent. CT, including FP-CBCT, has the ability to image low-contrast structures such as soft tissue and has superior ability, compared with MRI, to image bone. There is no need to modify existing neurointerventional (eg, catheters, wires) or surgical equipment or tools because of the magnetic field of MRI. Fluoroscopy/FP-CBCT is readily usable in patients with non-MRI compatible hardware (eg, pacemakers, pumps, older aneurysm clips). As with any CT image acquisition, metallic devices in the field of view, such as aneurysm clips, can lead to streaking artifact caused by photon starvation at the detector where the beam is heavily attenuated by the metallic objects. These artifacts reduce low-contrast visibility, but, as demonstrated in this study, acceptable image quality for many localization tasks is achievable even with metallic objects present in the field of view (eg, the needles and cryoablation probes used here).

The geometry of these systems was designed for neurointerventions, which dictates an open nature, ie, the C-arm design. These C-arm systems use flat-panel imagers, just as the portable O-arm units¹⁴ (Medtronic, Louisville, Colorado). Compared with the portable O-arm units, these C-arm systems provide easier access to the patient during fluoroscopy and do not require a large gantry to be moved in and out of position during the procedure. Both the C-arm and O-arm systems fall into the general category of providing FP-CBCT because each system uses a flat panel imager and single cone-beam acquisition. In comparison, standard diagnostic CT scanners use multirow CT detectors and several rotations to acquire the projection data.

Although it is envisioned that the technique presented here will have broader applicability than neurosurgical sites, it is important to place this work within the context of current image-guided neurosurgery procedures. In image-guided neurosurgical procedures, there are currently 2 regimens: (1) insert the device using standard stereotaxy and then use CT/MRI to confirm placement and (2) use CT or MRI in conjunction with a stereotaxy device during the trajectory planning. The second technique is termed prospective stereotaxy and was first demonstrated using interventional MRI.^{15–17} In the work presented here, a stereotaxy device was not used. In future implementations of this technique for guiding neurosurgical device placement, we envision incorporating a device for tool guidance. In that case, the technique presented here represents a hybrid between these 2 regimens. Interventional FP-CBCT will be used to plan the trajectory (ie, prospective stereotaxy), intermittent fluoroscopy may be used to guide deployment, and a separate FP-CBCT scan will be used for confirmation after the device has been deployed.

Additionally, the context for this technique within the large field of navigational work should be discussed. The technique presented here is not proposed to displace current IGS systems.^{18–20} These IGS systems incorporate feedback on the position of devices within the patient based on fiducial markers, which are optically or electromagnetically tracked.^{21,22} In the future, however, an IGS system may be used in conjunction with the technique presented here in which the IGS system would use intraoperatively acquired FP-CBCT image volumes rather than preoperative imaging. This would improve intraoperative target location because the target can shift when a craniotomy is performed or a burr hole is made, and preoperative imaging is unable to account for such shifts. Robotic guidance has also been used for needle/tool positioning within a patient. Because robotic guidance is a large area of active research,

we consider it beyond the scope of this article. However, we also envision that the combination of FP-CBCT and fluoroscopic guidance may be used in conjunction with robotic guidance for verification and treatment purposes.

CONCLUSION

We present experimental results demonstrating the combination of FP-CBCT and fluoroscopy to place interventional devices such as needles or cryoablation probes. Realistic contrast-enhanced tumor models were used in animal and cadaver models, and verification reconstructions demonstrated the placement of the interventional devices within the simulated targets. We verified with dose measurements in a standard head equivalent phantom that multiple FP-CBCT scans can be performed with the same radiation dose as a standard head CT scan, thereby enabling repeated FP-CBCT scans throughout the procedure. Considerable work still remains to be done, but new imaging tools, such as digital angiography machines with both fluoroscopic and FP-CBCT capabilities, may allow the creation of true neurointerventional/neurosurgical operating suites and enhance treatment of complex lesions.

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ABBREVIATIONS:

FP-CBCT	flat-panel cone-beam computed tomography
IGS	image-guided surgery

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FIGURE 1.

Example magnetic resonance imaging acquisitions of the enhanced tumor model. **A**, coronal slice of a fast recovery, fast spin echo T2-weighted volume, with 5-mm slice thickness. **B**, sagittal slice taken with the T1-weighted fluid-attenuated inversion recovery sequence. Both images are from the first pig.

FIGURE 2.

Four photographs of an isocentric C-arm system taken during a standard cone-beam computed tomography image acquisition. The starting gantry position is shown (A), and subsequent positions are given (B-D); the final position shown in D. Dashed line in A indicates the position of the detector throughout the acquisition.

FIGURE 3.

A, first pig's head is given after the thermoplastic mask had been applied. **B**, volume rendering of the reconstructed volume in which the planned needle path is given by the line between the 3 fiducial markers. **C**, device needle guidance procedure in which the collimated fluoroscopy is used for guidance (upper arrow) and nonmetallic hemostats are used to guide the device (lower arrow).

FIGURE 4.

Demonstration of the planning trajectory of the simulated superficial contrast-enhanced tumor in which the cryoprobe was placed through a lateral entry through a burr hole in the temporal lobe. Projection of the trajectory onto coronal (**A**) and axial (**B**) image slices is shown as well as the trajectory on the volume rendering. The image volume is shown before rotating to the down the bull's eye orientation (**C**) and after rotation (**D**).

FIGURE 5.

Results demonstrating the ability to place the device within the simulated tumor in the first pig (A) and in the second pig (B-D). A, B, oblique slices that roughly follow the needle path are shown and a thick-slab axial maximum intensity projection (C) to visualize device position with respect to the target. D, a volume rendering.

FIGURE 6. Reconstructed images after the cryoprobe was placed in the simulated contrast-enhanced tumor as depicted by a coronal slice (A), an oblique slice (B), and a volume rendering (C) in which much of the skull has been removed before rendering to improve target visualization.

FIGURE 7.

Reconstructed images after the cryoprobe was placed in the simulated contrast-enhanced pituitary tumor as depicted by a sagittal slice (**A**), an oblique slice (**B**), and a maximum intensity projection through probe and tumor (**C**), where it is clear that the tip of the probe is well positioned within the simulated tumor; note that the tip is isolated from the shaft to define the size of the iceball. **D**, photograph of the simulated tumor after dissection. Superior microscopic view shows the simulated pituitary tumor and its relationship with neurovascular structures. ON, optic nerve; OCh, optic chiasm; OT, optic tract; ICA, internal carotid artery; MCA, middle cerebral artery; ACA, anterior cerebral artery; RAH, recurrent artery of Heubner; SPT, simulated pituitary tumor; III, third nerve.