Introduction and Background
The scaphoid is one of the eight small carpal bones comprising the human wrist, situated just at the base of the thumb. It is the most commonly fractured carpal bone, typically resulting from a fall on an outstretched hand. Casting is the standard treatment for uncomplicated fractures, but limits mobility, and therefore percutaneous internal fixation is gaining popularity as a treatment alternative. The procedure involves drilling a guidewire along the length of the scaphoid over which a cannulated screw is placed. Both the wire and screw are inserted through the skin, requiring liberal x-ray imaging and posing an occupational hazard to surgeons who routinely perform these procedures. The mechanical stability and clinical outcome of the procedure have been linked to central screw placement and minimizing cortical breach, both of which can be difficult to achieve with conventional techniques.

Computer-assisted surgery has demonstrated improvements in accuracy and reduction in x-ray exposure in other orthopedic pin insertion procedures; however, the typical computer-assisted workflow does not translate easily to this procedure. A standard tracking device cannot be attached directly to the scaphoid for navigation due of the small size of this bone. Because the procedure is performed with minimal invasion (percutaneously), registering the images for navigation by collecting surface points on the scaphoid (i.e., patient-based registration), is counter-productive.

Recent developments in flat-panel fluoroscopy have made 3D cone-beam computed-tomography (CT) feasible for intraoperative use, and an ideal instrument to conduct image-guided navigation. This work aimed to use this technology to develop and test an image-guided navigation system for percutaneous scaphoid pinning and compare this to conventional approaches.

Methods
Two image-guided approaches were developed and tested: the first using volume-rendering of the 3D images similar to digitally-reconstructed radiographs, and the second using volume-slicing comparable to CT slices. Both methods made use of a 3D digital fluoroscopic “Innova” C-arm (GE Healthcare, France) that could rotate 360° about an isocentre to take a 3D cone-beam CT image. Navigation was performed using a ceiling-mounted optical tracking camera and active infrared markers attached to the wrist and drill guide. A preoperative calibration was performed to establish a spatial relationship between the internal coordinates of the marker and the tracking system; this allowed an intraoperative image to be used for navigation, without the need for patient-based registration or imager tracking.

Each navigated procedure began by taking a 3D image of the wrist and rendering it according to one of the two image-guidance methods. A surgeon used these images to create a preoperative plan by positioning a virtual drill path on the scaphoid. To navigate the plan, the real-time position of the drill was displayed relative to the wrist image on a computer monitor, by applying the preoperative calibration relationship to the pose data of the tracked drill guide (Figure 1).

Randomized trials were conducted in which both navigated procedures were compared to two conventional methods. The first conventional method utilized a standard fluoroscopic C-arm with 2D x-ray images, while the second used the Innova digital C-arm, but in 2D mode, analogous to a standard C-arm, except with digital imaging and magnification. Each study group had 24 trials.

The morphology of the scaphoid is highly variable, thus a model wrist with a replaceable scaphoid was selected as the basis for this study in order to permit direct comparison between the trial groups. The surgical goal was to insert a guidewire along the central axis of a model scaphoid to maximize both length and depth. After each trial, the scaphoid was removed with the wire intact and imaged using CT to generate 3D surface models of the drilled scaphoid. Algorithms were developed to determine the length of the drill path and the shortest distance from the drill path to the scaphoid surface, to be used as comparative measures of centricity. A virtual screw was positioned along the drill path to assess if cortical breach would have occurred. Procedure time, drilling attempts and radiation exposure were also recorded for each trial.

Results
Both image-guided approaches improved the precision of central guidewire placement compared to the conventional techniques (p<0.01). Volume-slicing resulted in increased length of the drill path (p<0.1). Volume-rendering reduced the incidence of simulated cortical breach. Fewer drilling attempts were required using both image-guided approaches (p<0.01), but both navigated approaches took longer to perform than conventional techniques (p<0.05). Image-guidance also significantly reduced x-ray exposure (p<0.01).

Discussion and Conclusion
Image-guidance achieved a more repeatable and reliable central pin placement, with fewer drill passes and with less radiation than conventional 2D techniques. Although both image-guided procedure times were significantly longer than the conventional techniques, likely due to the additional planning step, the average time for both image-guided procedures was under 4 minutes, well within the clinically-acceptable time frame. The positive performance in this preliminary study supports the progression of this technology for facilitating percutaneous scaphoid fixation.

This in-vitro study was a constrained evaluation to test our workflow for image-guided scaphoid fixation. This novel navigation technique does not require preoperative imaging or patient-based registration that is typical of most computer-assisted workflows. Another potential benefit may also include reduced radiation exposure to the surgical team. The next step will be to evaluate this technology under more realistic conditions using an ex-vivo model. Presently, a wrist positioning device is being evaluated for a cadaver study to secure the scaphoid and allow the wrist to be tracked for navigation.