Designing a Laser-based System for Locating Kidney Stones in Surgeries through Percutaneous Nephrolithotomy (PCNL)

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Abstract

Background: The number of kidney stone surgeries is increasing worldwide. One of the most effective methods of removing kidney stones is percutaneous nephrolithotomy (PCNL) surgery. The PCNL surgery is a minimally-invasive procedure for extracting kidney stones through a small puncture made on the skin. This technique is most suitable for removing stones that are present near the pelvic region. Every standard PCNL operation requires 60 to 70 seconds of fluoroscopy imaging during which both the surgeon and the patient are exposed to X-ray radiation. This amount of radiation can be dangerous as surgeons may have several surgeries per week.

Objective: To design and use a laser-based device along with fluoroscopy imaging for locating a desired target, resulting in less fluoroscopy exposure time, in comparison to the conventional method.

Methods: A piece of lead wire is used as the target. The laser-based device is placed under the surgical bed. Steel was used as the major material for different parts of this device. Two linear lasers are used to point at the target. This device uses two step motors to aim the lasers towards the target.

Results: A small piece of lead was used as the target. Using the proposed method, 10 experiments were conducted. The mean ±SD for radiation exposure time of the fluoroscopy device in 10 experiments was 2.4 ±0.49 (range 1.8 - 3) seconds and the mean ±SD of the total error in locating the target was 13.2 ±4 (range 7.8 - 22) mm.

Conclusion: The device was able to locate the target using fluoroscopy imaging. By building a more accurate structure and using step motors with more resolution, better results can be achieved. This approach reduces the radiation exposure time in PCNL surgery.

Key words: Kidney stone, Fluoroscopy device, Laser, Locate

Introduction

Kidney stone is a solid and crystalline material which is usually formed inside the renal pelvis due to the accumulation of a high amount of specific minerals. These stones are sometimes called renal calculi (1). About 80 percent of these stones are made of oxalate and calcium phosphate (2). The diameter of renal stones is usually less than one centimeter (3). In several countries, the average global prevalence was reported as 3.25% in the 1980s and 5.64% in the 1990s (4). In research done in 2005, it was concluded that in the United States of America, about 5 percent of women and 12 percent of men will suffer from kidney stone disease at some time in their life (2).

Four common treatments that are used on kidney stones are as follows.
- When the stone is very large or the anatomy of the patient's body is so complicated or unusual, open surgery will be recommended. Less than 1 percent of patients will need to use this method in which the skin is split to the extent that the surgeon can access the entire kidney tissue (5).
- If the stone is in the urethral duct, ureteroscopy will be used for accessing the ureter. In this method, a ureterescope is passed through the bladder and then reaches the ureter. The surgeon may use laser energy or other tools for fragmenting and then removing the kidney stones (6).
- In another method, the physician or surgeon breaks the stone using high frequency ultrasound waves. These shock waves break the stones to smaller pieces so that they can pass through the urinary tract (7).
- When the kidney stone is in the renal pelvis, a technique called Percutaneous NephroLithotomy (PCNL) is preferred (8). The first PCNL operation was done in 1976 (9). This technique is most suitable for removing stones that are present near the pelvic region (8). Also, it is a minimally-invasive procedure for extracting kidney stones through a small puncture made on the skin. In the first step, by using fluoroscopy imaging, the location of the stone will be mapped. Then the surgeon inserts the tip of the needle into the patient's body in such a way that the needle direction, extends beyond the renal pelvis. In order to find out the distance between the needle tip and the renal pelvis, the surgeon readjusts the angle of the fluoroscopy C-arm in a different angle and places the needle into the drainage system of the kidney close to the stone being treated. During the whole procedure fluoroscopy imaging will be used. If the surgeon fails to access the renal pelvis, the whole procedure will be repeated (10).

In comparison to open surgery, PCNL surgery is a more effective procedure for extracting relatively large kidney stones (9). After the operation, the patient may only need one or two days of rest (11).

A standard PCNL operation requires about 60 to 70 seconds of fluoroscopy imaging during which both the surgeon and the patient are exposed to radiation (12). In a recent study, while PCNL surgery was effective for extracting relatively large stones, yet in 17% of patients, some stones were not extracted during the first operation (13). In this case, another surgery was carried out. In each surgery, fluoroscopy imaging will be used, resulting in more radiation exposure (13). In another research conducted on 178 patients who had kidney stone, only in 60% of the patients, kidney stone was completely removed (14). But, others had to do another PCNL surgery which led to more radiation exposure time (14).

In order to minimize the exposure time in PCNL surgery, several methods have been suggested as follows.
- In 2012, Rassweiler et al, by application of augmented reality technique for kidney stone surgery, could observe anatomical details such as the location of adjacent bones and kidney arteries. In this procedure, iPad is used as a camera which takes images from the patient's skin; after which they are compressed and sent to a server placed in the control room via Wi-Fi. The server applies a pre-written algorithm on these images so that they are registered with previously taken CT images. Afterwards the created images are sent back to the iPad in real time. These images allow the surgeon to simultaneously observe the kidney and surrounding tissues during the surgery (15).
- In 2006, in another research done by Kagadis et al, combining MRI and CT imaging leads to more accurate results in locating the renal pelvis, however, in comparison to PCNL surgery, this technique does not decrease the absorbed dose of radiation (16).

While these two techniques provide better details about the surrounding tissues of the kidney, they are not preferred over the conventional PCNL surgery as they require CT imaging prior to the surgery and increase the cost of the operation as well as the radiation dose absorbed by patients.

The rate of received dosage by personnel while working with fluoroscopy device, depends on several factors such as the surgeon's talent and the X-ray exposure time. With the increasing demand for PCNL surgery, reducing the exposure time in PCNL surgery becomes more essential (17).

Our goal in this paper is to find an approach that can decrease the radiation exposure time in conventional PCNL surgery, with enough accuracy in locating the renal pelvis. In the proposed method, with the help of a low cost laser-based device and the fluoroscopy, we are able to locate a desired target.

Materials and Methods

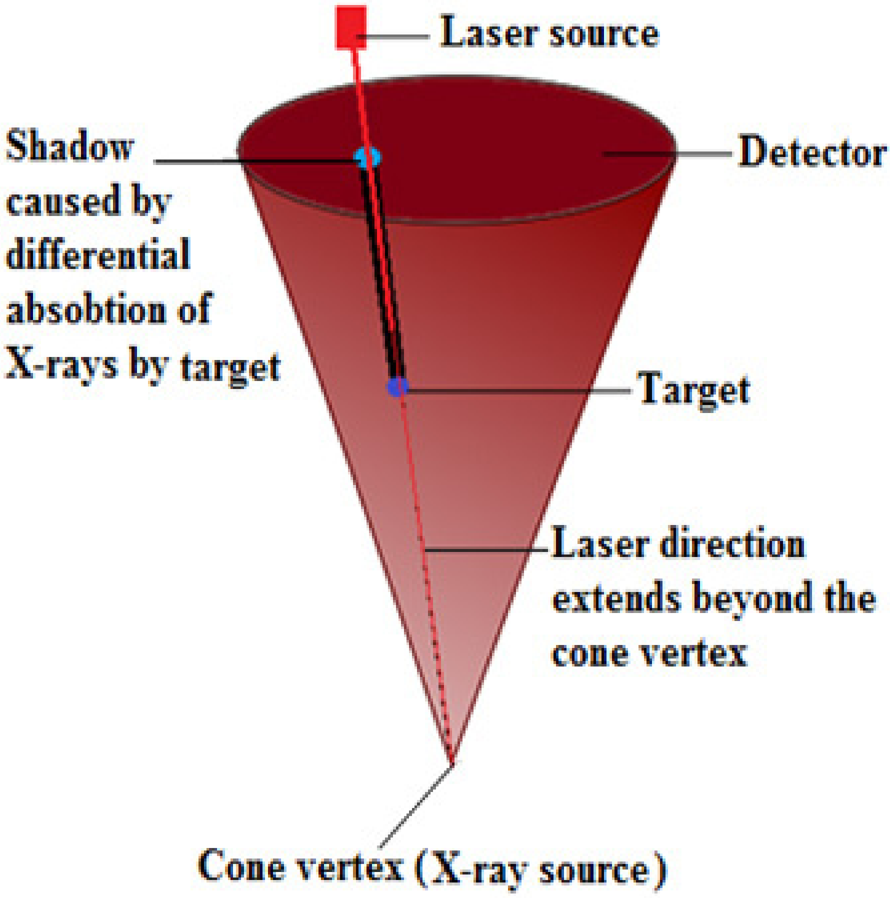
The aim of the conventional PCNL surgery is to access some part of the renal pelvis. For this purpose, a device was designed in such a way that it is able to show the best location and angle for insertion of a surgical needle into the patient's body, so that the renal pelvis could be reached by inserting the needle in the specified direction. In this paper we propose a method for reducing the fluoroscopy radiation exposure time, in PCNL surgery.

The fluoroscopy lamp and the detector are placed below and above the surgical bed, respectively. The X-ray beams are emitted from anode and, until they reach the detector, they travel on a cone-shaped path in the space between the lamp and the detector. The vertex of the aforementioned cone is under the surgical bed and inside the fluoroscopy lamp and the base of the cone is the detector.

Here, a small piece of lead, which was placed on the surgical bed, was used as target. When the X-ray beams collided with the target, they cast a shadow on the detector.

If we radiate a laser beam along the shadow of the target, so that the length of the laser beam extended beyond the vertex of the cone, then the length of the beam will also extend through the target (Figure 1). So, if we move a surgical needle in the direction of the laser beam and toward the target, the tip of the needle eventually reaches the target.

Figure 1: Radiating a laser along the shadow of the kidney stone



The coordinates of the shadow, relative to the center of the detector, could be obtained by means of two rulers with lead grading that are perpendicular to each other, and are attached below the surface of the detector, so that the centers of the rulers are located at the center of the detector (Figure 2 - opposite page).

Using the fluoroscopic image, we could obtain Cartesian coordinates of the shadow of the target relative to the center of the image (Figure 3).

When the coordinates of the target are specified, we can align the laser beam along the shadow of the target. For this purpose, we can align the interface of two laser planes, which is a line, with the shadow of the target, to locate the target through the use of the laser beam.

Using two step motors as follows, we could point the luminous planes of the lasers toward the target. Each laser was mounted on a C-shaped arm. The other end of each arm was attached to a step motor that was in turn mounted to a supporting box under the bed (Figure 4).

The rotation axes of the stepper motors are perpendicular to each other (Figure 5). The fluoroscopy lamp was placed in the box in such a way that the rotation axes of the stepper motors passed through the vertex of the cone. Also, the interface between these two luminous planes, which is a line in space, always crossed the vertex of the cone. Now, according to the Cartesian coordinates of the target, by rotating each of the arms with the help of the stepper motor, we could point at the target. Figure 5 illustrates how one of the lasers is mounted on its corresponding arm (Figure 5).

Figure 2. Connecting the Rulers to the Detector

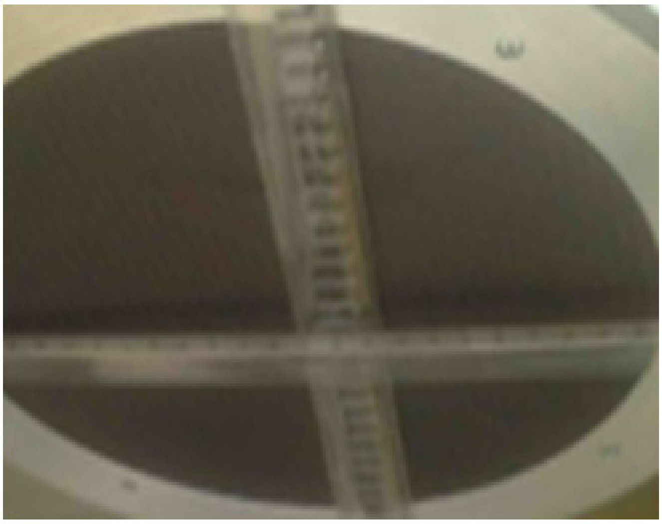


Figure 3. Specification of the lead wire's coordinates

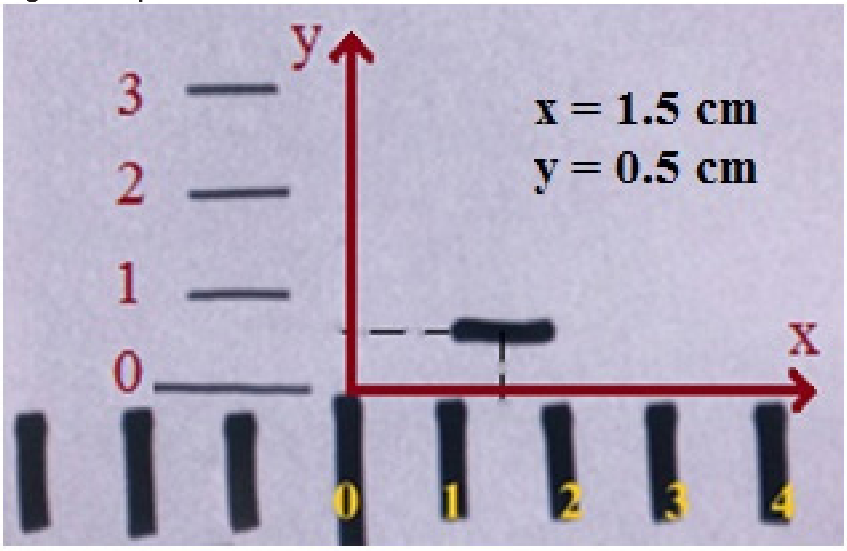


Figure 4. Placing the x-ray tube inside the box

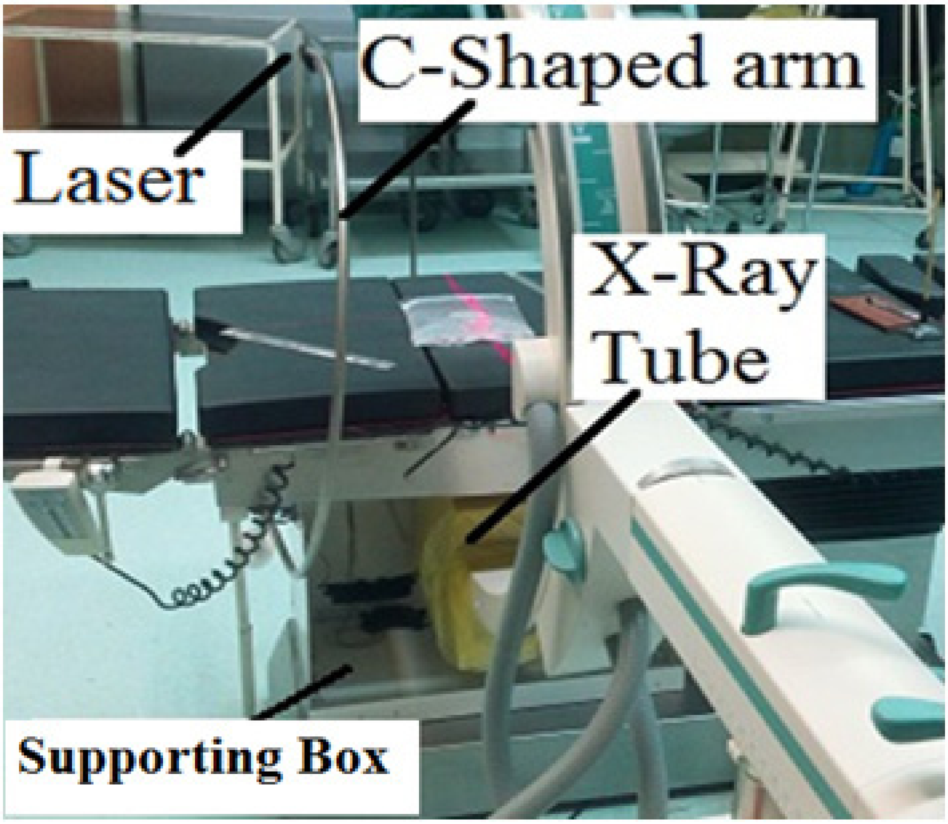
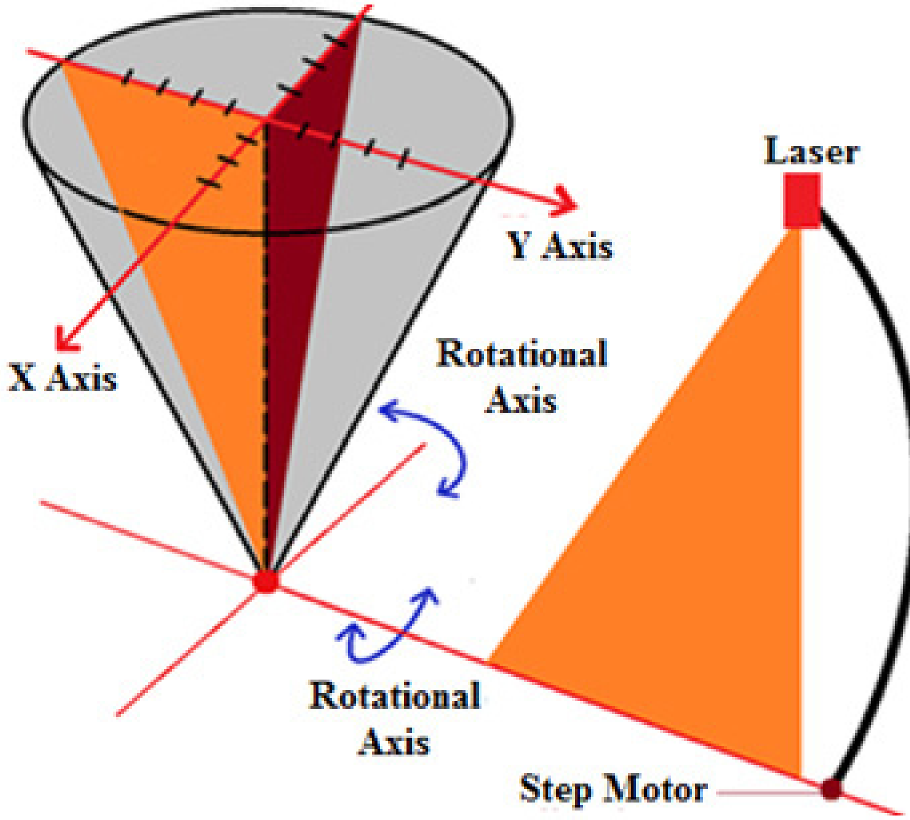
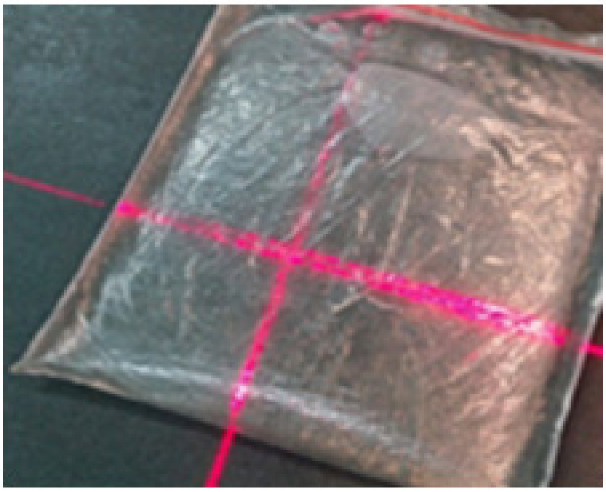


Figure 5. The interface of the luminous planes of a line passing through the X-rays



Each laser produce a luminous line on the surgical bed. The step motors rotate 1.2 degrees per step. With each step, every line was displaced about 10 mm on the surgical bed. In order to find out how accurately these luminous lines have pointed at a desired target, two rulers are needed to measure the distance between the target and each line. Placing the target inside an animal complicates this procedure, therefore, animal experiments were not preferred. A total of 10 experiments were carried out using the stated technique. In each experiment, by placing the target under a liquid-filled bag, and using the X-ray image of the target, the coordinates of the target were determined (Figure 6).

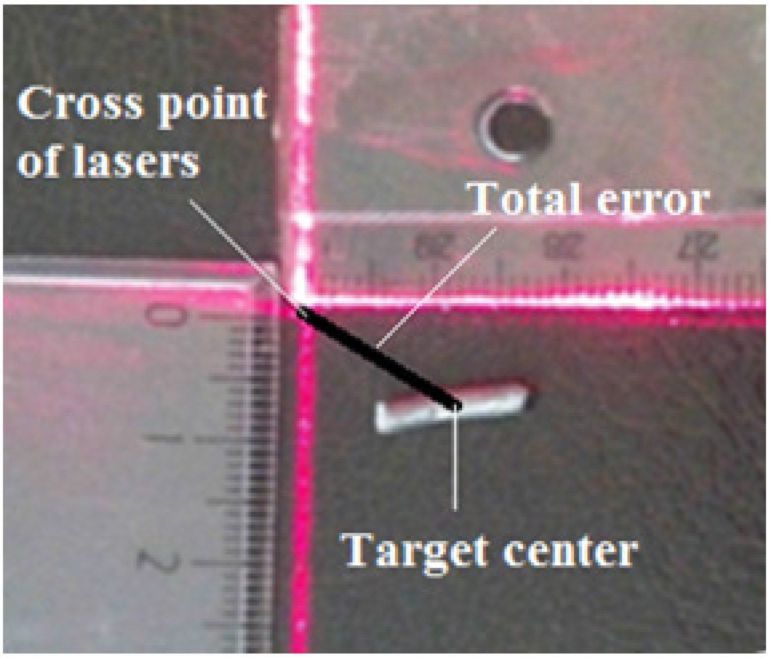
Figure 6. Placing the liquid-filled bag on the target



In accordance with the obtained Cartesian coordinates (x and y), the arms are rotated to the extent that the luminous lines be placed in the intended coordinates.

Then, by removing the bag, the error is measured in millimeters using two rulers. The distances between the target center and the vertical and horizontal lines show the value of error along X and Y axis respectively. The total error is the distance between the target center and the cross point of lasers (Figure 7).

Figure 7: Lasers pointed the target with some error



Results

Using the proposed method, 10 experiments were carried out. The average fluoroscopy X-ray radiation exposure time was 2.4 seconds with a standard deviation of 0.49 seconds. The mean total error in pointing at the target was also measured 13.2 mm with a standard deviation of 4 mm.
The results table is as follows:

Table 1: Results Table

Experiment	1	2	3	4	5	6	7	8	9	10	Mean	Standard Deviation
Absolute value of Error Along X in millimeters	5	11	12	10	7	3	11	13	4	17	9.3	4.4
Absolute value of Error Along Y in millimeters	6	8	5	12	4	11	7	6	15	14	8.8	3.9
Total Error (mm)	7.8	13.6	13	15.6	8.1	11.4	13	14.3	15.5	22	13.4	4
X-ray Exposure time in seconds	3	3	3	2.4	2.4	1.8	2.4	1.8	1.8	2.4	2.4	0.49

Discussion and Conclusion

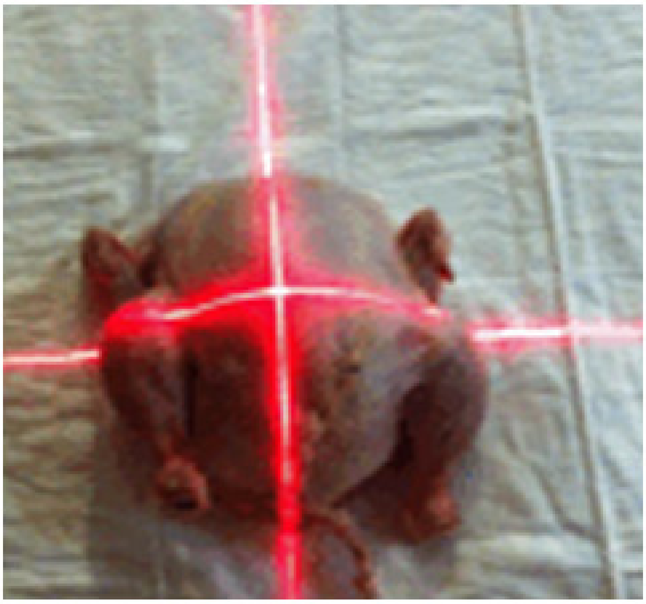
Although there was some error in pointing at the target, the device was able to approximately find the location of the lead wire by using an X-ray image. Most of the errors that appeared were due to the accuracy of the stepper motors' angular rotation. The used stepper motors, rotated 1.2 degrees per step. Using stepper motors with smaller steps and higher resolution, could lead to better results.

The proposed method is simple and low cost, and compared to the conventional PCNL surgery, the x-ray radiation exposure time is relatively short, which will reduce the amount of received doses.

Combined methods in which other equipment, in addition to fluoroscopy, are used, will usually increase the received radiation dose and the expense for the patient.

In an article, in order to access the kidney, a Uro Dyna_CT of a phantom was performed for 8 seconds. Based on the data from the 3D imaging of the Uro Dyna_CT, iGuid laser guidance system installed on the device, was used to position the needle on the phantom's surface. Fluoroscopy imaging is then used to insert the needle towards the kidney (Figure 8) (14).

Figure 8: Using Uro Dyna_CT to position the needle

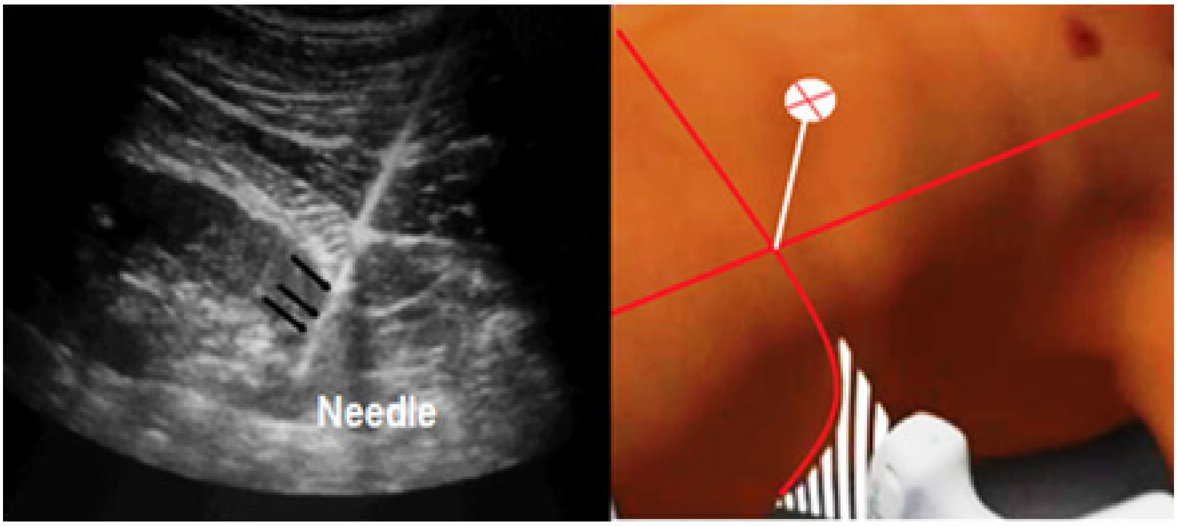


On average, the fluoroscopy is used for 27±17 seconds, which adds to the radiation exposure caused by the Uro Dyna_CT device. While this technique is very useful for complicated cases, the amount of exposure and the cost of operation is much higher than the conventional method. This method is only recommended for patients with complicated and unusual anatomy (14).

By developing the proposed technique in this paper, a surgeon may insert the needle based on the luminous planes so that the tip and the end of the needle are placed where the lines meet each other, on the patient's skin.

Also, an ultrasound device may be used to simultaneously observe the depth of the needle and the kidney tissue. The ultrasound device can show the boundary of the kidney tissue (Figure 9).

Figure 9. Use of ultrasound to observe the depth of the needle



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