

# Experimental Study on MRI-TRUS Image-guided Prostate Puncture

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**Abstract:** At present, the incidence of prostate cancer in men is increasing year by year. Prostate puncture surgery requires doctors to manually segment the contours of the prostate and tumor based on the patient's Magnetic Resonance Imaging (MRI) images before surgery to develop a surgical plan. During the surgery, Transrectal Ultrasound (TRUS) images are used for real-time guidance, and the doctor performs manual puncture. The accurate segmentation of the prostate and tumor boundary contours during this process is the basis for achieving precise puncture, but the accuracy of segmentation is limited by the subjective experience of doctors. In addition, the instability of manual puncture during the surgical process will further increase the puncture error. Therefore, this article combines the high soft tissue contrast of preoperative MRI with the low-cost real-time imaging of intraoperative TRUS to build an MRI-TRUS image-guided robot prostate puncture experimental platform. The experimental results showed that the maximum and average puncture errors of the puncture experiment were 1.93mm and 1.41mm, respectively. The experiment verified that using MRI-TRUS image-guided prostate puncture surgery can effectively improve the accuracy and reliability of prostate puncture surgery.

**Keywords:** Prostate Cancer; Prostate Biopsy; MRI-TRUS Image Guidance; Prostate Puncture Accuracy.

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## 1. Introduction

At present, in prostate puncture surgery, doctors need to manually puncture and continuously adjust the position of the ultrasound probe to ensure clear images. This method has problems such as high dependence on personal experience for puncture accuracy, long surgical time, and high workload for doctors. Using robots to assist doctors in prostate puncture is an effective way to solve the above problems. In addition, combining the high soft tissue contrast of MRI images with the low-cost real-time imaging advantages of TRUS, the use of MRI and TRUS images to guide puncture surgery has become a research hotspot both domestically and internationally. For example, Xiao et al. designed and developed a 3-degree-of-freedom transurethral prostate biopsy robot guided by MRI-TRUS images. This robot uses a team-developed flexible needle with 2 degrees of freedom for rotation and bending as the biopsy needle. The biopsy needle enters from the inside of the prostate to shorten the needle path and reduce the risk of needle deflection. The flexible needle is integrated into a continuous tube and can bend freely within the range of 16.0 to 55.8 degrees. This robot can launch biopsy needles from multiple angles in a small space and has a shorter puncture path. This transurethral puncture method can effectively avoid the influence of the pubic arch on the puncture. This is the first prostate biopsy robot with transurethral needle insertion, but the robot has only undergone kiwi phantom testing and has not yet undergone clinical trials [2].

Miah et al. designed and developed a 6-degree-of-freedom prostate biopsy robot guided by MRI-TRUS images. The robot consists of a linear degree of freedom for adjusting the insertion depth of the ultrasound probe and five rotational degrees of freedom for adjusting the spatial position of the biopsy needle tip. The biopsy needle guide bracket and

ultrasound probe guide bracket of the robot body are both automatically adjusted by motors. After the robot adjusts its position automatically, the doctor performs a manual puncture biopsy with the assistance of the biopsy needle guide bracket. Wang et al. designed and developed a 5-degree-of-freedom serial prostate biopsy robot guided by MRI-TRUS imaging. The module for adjusting the position of the puncture needle in this robot includes two translational degrees of freedom for needle insertion and one rotational degree of freedom for adjusting the needle posture. The ultrasound probe pose adjustment module includes a linear degree of freedom for adjusting the insertion depth of the ultrasound probe and a rotational degree of freedom for adjusting the ultrasound probe pose. Due to the long puncture needle, this robot adopts two translational degrees of freedom for needle insertion to effectively reduce the size of the robot, with an average puncture error of 1.4mm [4].

The above-mentioned robots have achieved automated puncture, but there are still certain limitations in clinical applications, such as low puncture accuracy and instability of manually operated ultrasound probes, which, to some extent, reduce puncture accuracy. To address the aforementioned issues, this article first analyzes the overall design requirements for the clinical operation and robot system of prostate puncture, clarifying the composition and workflow of the prostate puncture robot system. Secondly, the classic segmentation algorithm U-Net [5] in the field of medical image segmentation was used to segment the MRI and TRUS image sequences of the prostate puncture phantom separately, and the segmented image sequences were reconstructed and registered in three dimensions. Based on this, the preoperative MRI and intraoperative TRUS images were registered through ultrasound calibration and joint movement of the ultrasound probe clamping mechanism, thus obtaining the information of the preoperative target puncture point. Once

again, conduct ultrasound calibration experiments to complete the spatial registration of the prostate puncture robot, and based on this, build a multimodal image-guided prostate puncture robot experimental platform. Finally, a multimodal image-guided prostate puncture experiment was conducted to verify the effectiveness of the MRI-TRUS image-guided prostate puncture robot scheme proposed in this paper.

## 2. Overall Scheme and Workflow of The Robot System

TRUS has become the main imaging method used in puncture surgery due to its advantages of low cost, dynamic real-time imaging, and portability in image-guided methods. However, due to the low contrast of TRUS images, the ability to only scan locally. MRI has high soft tissue imaging contrast and good three-dimensional imaging ability, which helps doctors to more comprehensively evaluate the location, range, and relationship with surrounding tissues of lesions. However, the use of MRI image guidance is limited by issues such as slow imaging speed, the requirement for robots to be made of non-magnetic materials, the need for robots to adapt to narrow scanning cavities, and high usage and maintenance costs. Based on the above analysis, this article combines the high soft tissue contrast of MRI images with the advantages of low-cost real-time imaging of TRUS. Preoperative MRI images are registered with intraoperative TRUS images, and multimodal images are used to jointly guide puncture surgery to achieve precise puncture.

Figure 1 shows the overall scheme of the multimodal image-guided prostate puncture robot system, which mainly includes the UR5e robotic arm, the end puncture mechanism developed by our team, the optical positioning navigator, the ultrasound probe clamping mechanism, and ultrasound imaging equipment.

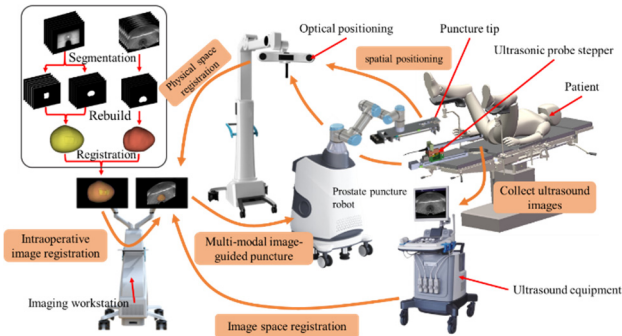


**Figure 1.** Overall scheme of multimodal image-guided prostate puncture robot system

To achieve multimodal image-guided puncture, robot-assisted doctors in puncture surgery, it is necessary to first collect patient MRI and TRUS image sequences before surgery. After the acquisition is completed, image segmentation and 3D reconstruction are performed separately, and the two are registered. Secondly, the TRUS images obtained during the surgery are registered with the joint motion information of the ultrasound probe clamping mechanism to the three-dimensional model reconstructed from the preoperative TRUS image sequence, thereby obtaining the target puncture point information of the intraoperative TRUS image corresponding to the preoperative MRI image. Finally, perform a spatial coordinate transformation between the intraoperative TRUS image coordinate system and the puncture needle endpoint

coordinate system to obtain the specific position of the needle tip point in the TRUS image. The visualization process of the coordinate transformation is shown in Figure 2, and its workflow is shown in Figure 3.

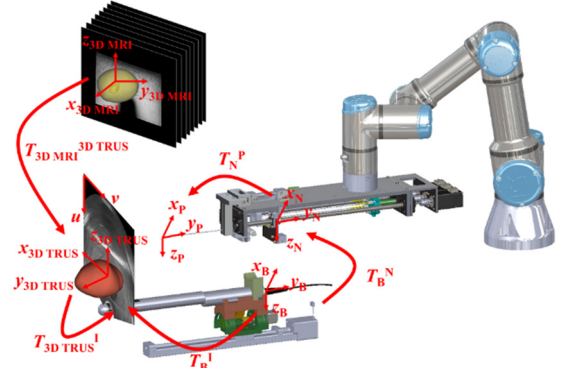


**Figure 2.** Schematic diagram of multi-modal image-assisted prostate puncture coordinate transformation

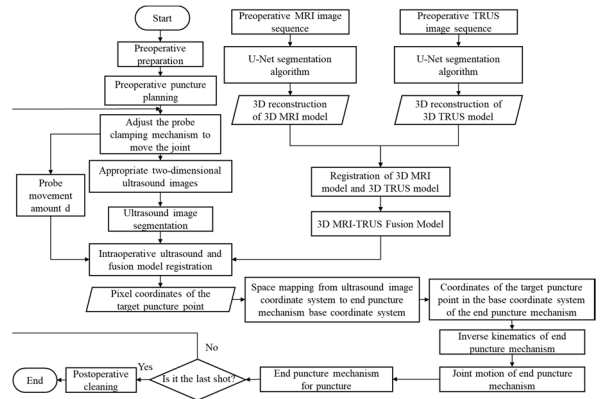


**Figure 3.** Workflow of a multi-modal image-guided prostate puncture robot system

## 3. Multi-modal image-guided Precise Prostate Puncture Experiment and Analysis

### 3.1. Three-dimensional Reconstruction And Registration of MRI-TRUS Images

Before conducting a multimodal image-guided prostate puncture experiment, it is necessary to first create a prostate puncture phantom to obtain equidistant MRI and TRUS images. The prostate puncture phantom prepared in this study is shown in Figure 4. It is necessary to perform equidistant scans of MRI and TRUS images on the prostate puncture phantom separately to obtain equidistant MRI and TRUS images, and to perform 3D reconstruction of MRI and TRUS images. Based on this, the transform matrices  $T_{3D MRI}^{3D TRUS}$  and  $T_{3D TRUS}^I$  are calculated separately to achieve registration of MRI image information with TRUS images in the experiment.

To obtain the specific value of  $T_{3D MRI}^{3D TRUS}$ , it is necessary to first complete the 3D reconstruction of MRI and TRUS images of the prostate puncture phantom. To establish a three-dimensional model of TRUS images for the prostate puncture phantom, this study used an ultrasound probe clamping mechanism to fix the ultrasound probe and collected 12 TRUS images at equal intervals using a 3mm moving ultrasound probe. Some of the images are shown in Figure 5. On this basis, the U-Net segmentation algorithm was used to extract the prostate boundary contour from the TRUS image

sequence, and some segmentation results are shown in Figure 6. To establish a three-dimensional MRI model of the prostate puncture phantom, the Philips Achieva 3.0T system was used at the cooperative hospital to scan the phantom with a scanning interval of 1mm. A total of 36 MRI image sequences were obtained, some of which are shown in Figure 7. The MRI image sequences were segmented using the U-Net segmentation algorithm to separate the prostate and tumor contours of the phantom. Part of the prostate contour is shown in Figure 8. To clearly observe the tumor contour, it is enlarged 5 times as shown in Figure 9.

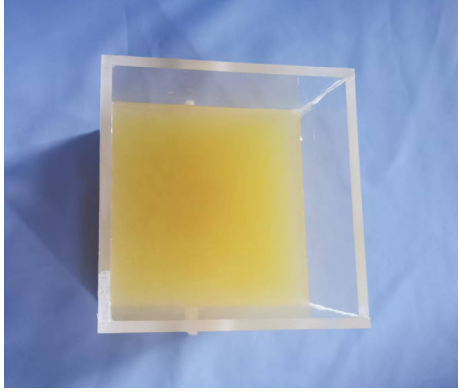


**Figure 4.** Prostate puncture phantom

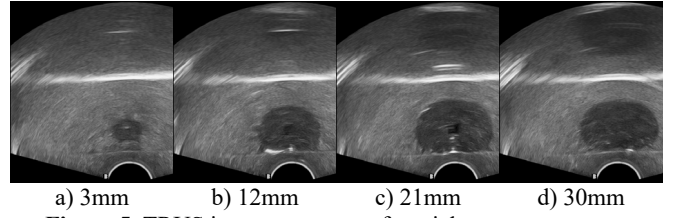


**Figure 5.** TRUS image sequence of partial prostate puncture phantom

This article uses open-source software 3D Slicer to perform 3D reconstruction on the extracted MRI images of prostate and tumor contours, as well as the TRUS images of prostate contours. Gaussian smoothing is applied to the reconstructed models. After completing the above steps, fix the 3D TRUS model and manually perform rigid registration between the 3D MRI and 3D TRUS models. The result of the MRI-TRUS reconstruction model registration is shown in Figure 10, and the resulting transformation matrix  $T_{3D\ MRI}^{3D\ TRUS}$  is as follows:

$$T_{3D\ MRI}^{3D\ TRUS} = \begin{bmatrix} 0.24 & 0.27 & 0.93 & 0.05 \\ 0.03 & 0.96 & -0.28 & -0.79 \\ -0.97 & 0.10 & 0.22 & 2.89 \\ 0 & 0 & 0 & 1.00 \end{bmatrix} \quad (1)$$

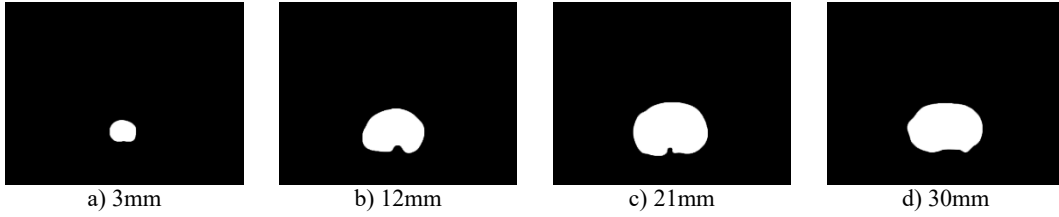


**Figure 6.** Segmentation results of the prostate in partial TRUS image sequences

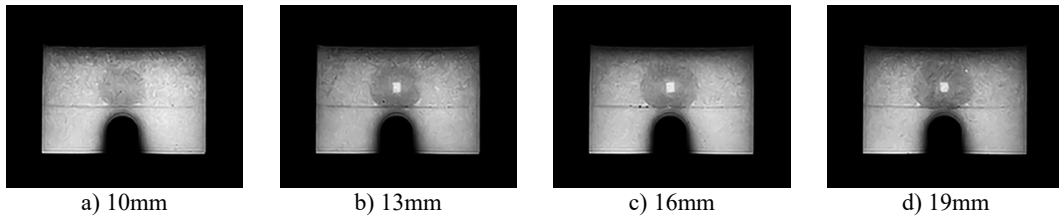


**Figure 7.** MRI image sequence of partial prostate puncture phantom

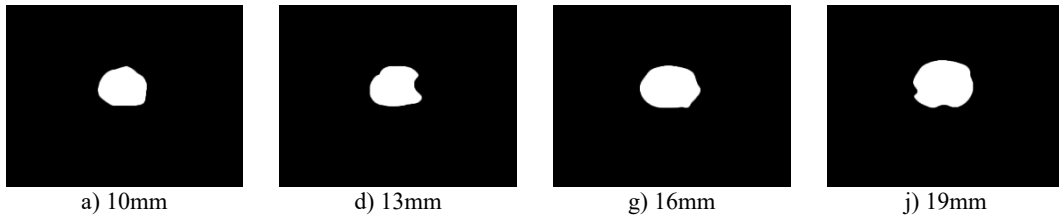


**Figure 8.** Segmentation results of the prostate in partial MRI image sequences

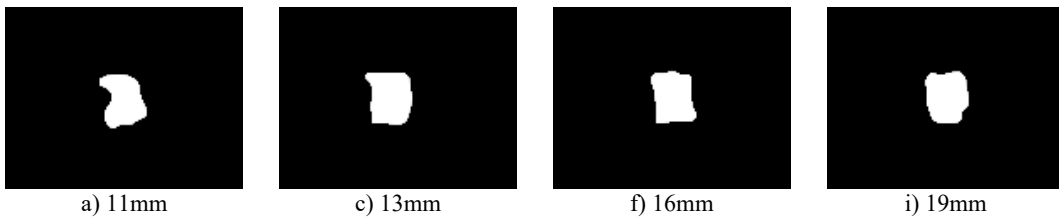


**Figure 9.** Tumor segmentation results in partial MRI image sequences

To solve the transformation matrix between the two-dimensional TRUS image and the three-dimensional TRUS model of the prostate puncture phantom in the experiment, it is necessary to make the rotation angle of the ultrasound probe clamping mechanism in the experiment the same as the rotation angle of the equidistant scanning TRUS image before the experiment. Based on this, calculate the linear movement  $d$  of the clamping mechanism from the current TRUS image to obtain  $T_{3D\ TRUS}^I$ . Multiplying  $T_{3D\ MRI}^{3D\ TRUS}$  and  $T_{3D\ TRUS}^I$  yields the transformation matrix  $T_{3D\ MRI}^I$  of the MRI image before the experiment and the TRUS image during the experiment, as shown below:

$$T_{3D\ TRUS}^I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$T_{3D\ MRI}^I = T_{3D\ MRI}^{3D\ TRUS} \cdot T_{3D\ TRUS}^I \quad (3)$$

According to formula (3), the intraoperative two-dimensional TRUS image can be fused with the corresponding preoperative MRI image.

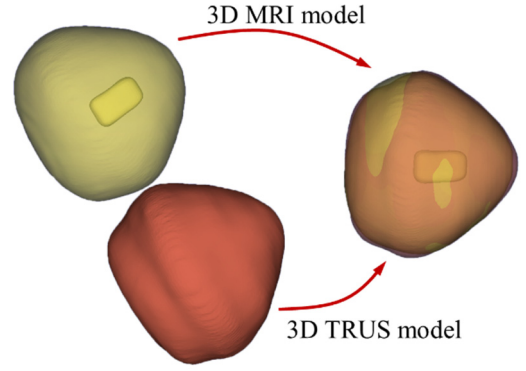


Figure 10. The registration results of the MRI-TRUS image reconstruction model

### 3.2. Multi-modal image-guided Prostate Puncture Experiment and Analysis

Before starting the experiment, select the target puncture point within the tumor area in the MRI image as shown in Figure 11a). Secondly, in the experiment, an ultrasound probe clamping mechanism was inserted into the prostate puncture phantom to obtain a two-dimensional TRUS image, as shown in Figure 11b). Subsequently, the MRI image information was registered and displayed in the two-dimensional TRUS image as shown in Figure 11c). Finally, the display of the target puncture point in the two-dimensional TRUS image is shown in Figure 11d).

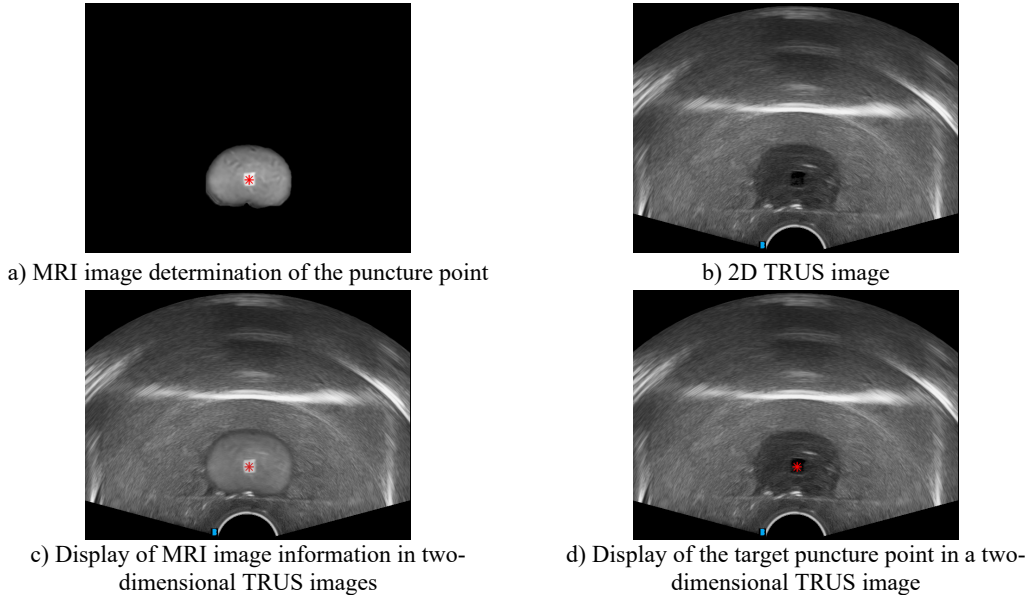


Figure 11. The process of obtaining target puncture point information from TRUS images

This article realizes the spatial mapping between the coordinate system of the end puncture mechanism and the needle tip coordinate system based on the size of the puncture end mechanism developed by our team. On this basis, the ultrasound experimental platform built according to Figure 12 realizes the spatial mapping between the ultrasound image coordinate system and the ultrasound probe clamping mechanism coordinate system, and calculates the value of the scaling factor  $R$  as 0.175mm/pixel.

This article constructs a puncture experiment as shown in Figure 13. The end puncture mechanism and the ultrasound probe clamping mechanism in this experimental platform are respectively equipped with optical positioning guides to complete the spatial mapping between the ultrasound image

coordinate system and the needle tip coordinate system, thereby enabling the end puncture mechanism to puncture under the guidance of multimodal images.

This article uses the coordinate distance between the actual needle tip point  $(u_{pn}, v_{pn})$  and the target puncture point  $(u_{tz}, v_{tz})$  in the TRUS image in the experiment as the puncture accuracy. The calculation of  $(u_{pn}, v_{pn})$  uses the region growing method to segment the needle points in the TRUS image and solve for their centroid. The prostate puncture robot designed in this article was used for 21 puncture experiments, and the formula for puncture error is as follows:

$$d_e = \sqrt{(u_{pn} - u_{tz})^2 + (v_{pn} - v_{tz})^2} \cdot R \quad (4)$$

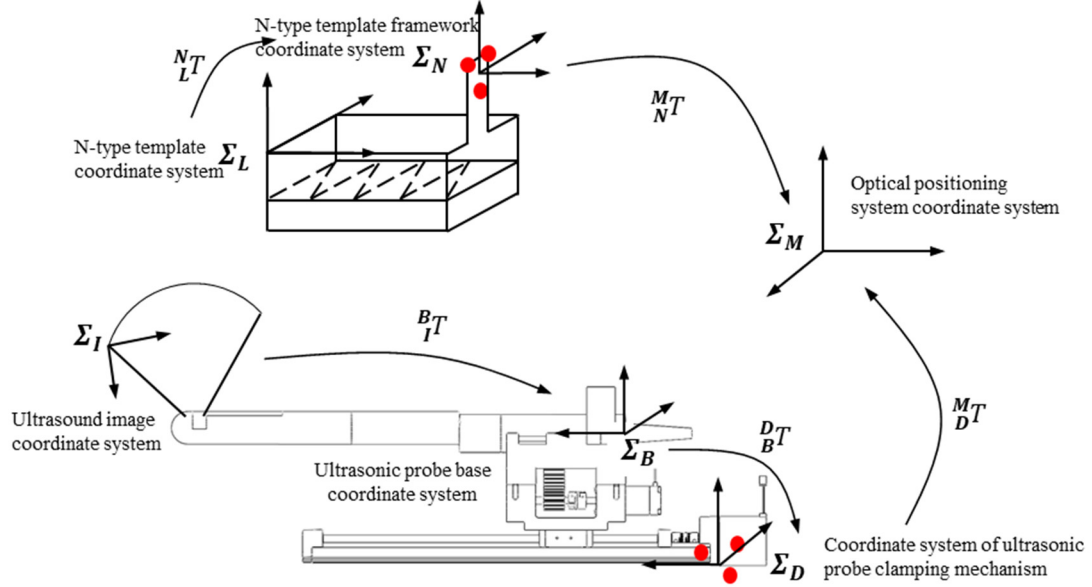


**Figure 12.** Visualization of ultrasound probe calibration coordinate system

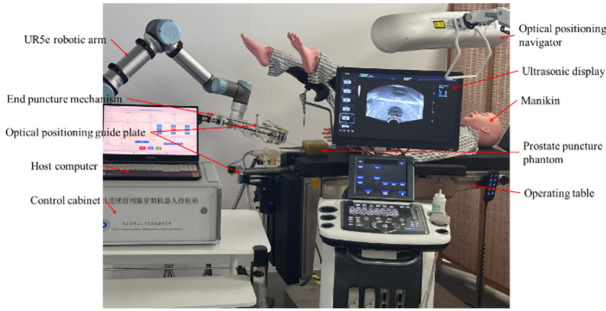


**Figure 13.** Multi-modal image-guided prostate puncture experiment

The puncture error calculation was performed on the experimental results to obtain the puncture error of 21 puncture experiments. The experimental results showed that the average puncture error was 1.41mm and the maximum puncture error was 1.93mm.

## 4. Conclusion

The puncture error of the multimodal image-guided prostate puncture experiment is a comprehensive reflection of the combined effects of multiple factors during the surgical process. According to the system workflow, its sources include image segmentation error, 3D reconstruction error, registration error between MRI and TRUS reconstruction models, registration error between intraoperative TRUS images and MRI-TRUS fusion models, and errors introduced by the multi-needle continuous prostate precise puncture robot itself. According to the experimental results, the multimodal image-guided prostate puncture robot system constructed in this paper has high puncture accuracy, with

maximum and average puncture errors of 1.41mm and 1.93mm, respectively. It has the advantages of good repeatability and stability. The experimental results verify the effectiveness of the proposed multimodal image-guided prostate puncture robot scheme.

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