Optical Camera-Assisted Quality Assurance for Catheter Digitization in Ultrasound-Guided HDR Prostate Brachytherapy

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ABSTRACT

To evaluate the feasibility and accuracy of an optical camera-assisted QA workflow for verification of catheter digitization in ultrasound-guided HDR prostate brachytherapy, the proposed method combines optical imaging, computer vision, and 3D model registration to verify catheter grid positions and free lengths while reducing manual measurements performed under sterile conditions.

A patient-specific 3D catheter model was generated from manually recorded catheter positions and free lengths using automated scripting on an open-source visualization platform. Optical images acquired during treatment setup were processed using Gaussian filtering, Canny edge detection, and Hough line transformation for catheter segmentation. Camera-derived catheter features were registered to the projected 3D model for verification of template positions and free lengths.
Sixteen catheters from one HDR prostate implant were analyzed. The patient-specific 3D model was generated in less than one minute. Grid-template positions identified from optical images agreed with manual measurements for all catheters. Free-length verification was performed using linear fitting between manually measured lengths and lengths derived from Hough-transform segmentation, yielding a standard deviation of ±2.1 mm. Residual differences were primarily attributed to catheter curvature and image noise.

Optical camera-assisted verification demonstrates a practical, touchless QA solution for HDR prostate brachytherapy. The approach improves digitization verification while reducing manual effort and establishes a foundation for automated real-time catheter reconstruction and validation.

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INTRODUCTION

Accurate catheter reconstruction is critical for HDR prostate brachytherapy because treatment quality depends on precise source positioning. Current workflows require manual measurement of catheter free lengths under sterile conditions, increasing procedure time and introducing the potential for human error. We developed an optical camera-assisted quality assurance (QA) workflow that combines computer vision and 3D model registration to provide rapid, touchless verification of catheter positions and free lengths.

METHODS AND MATERIALS

An optical camera-assisted verification system was implemented during HDR prostate brachytherapy procedures. Catheter grid positions and free lengths were recorded and used to generate a patient-specific 3D model through automated scripting.

Optical images acquired during treatment setup were processed using Gaussian filtering to suppress noise, followed by Canny edge detection and Hough line transformation for catheter segmentation. Segmented catheter trajectories were registered to the projected 3D model for verification of template positions and free lengths. Illustrated in Fig 1, the camera-assisted digitization workflow consisted of two components: grid-template localization and free-length reconstruction.

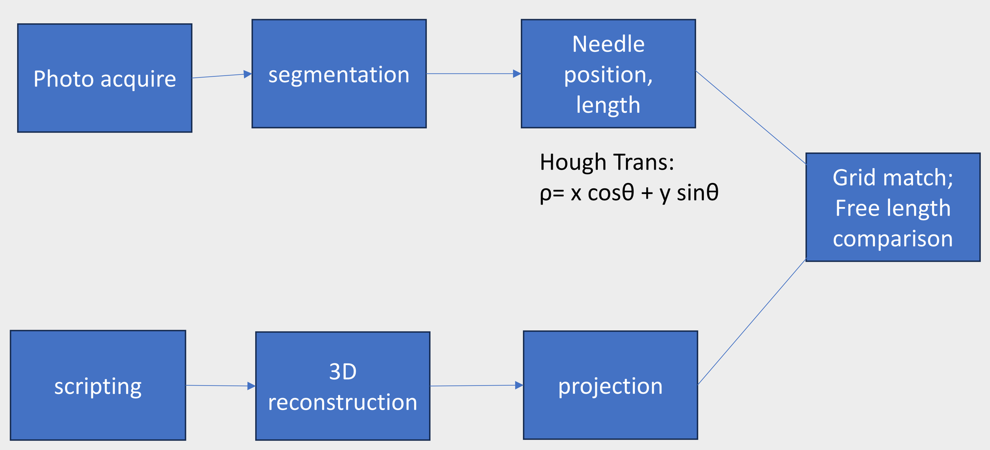

Fig 1. Flow chart of catheter free length QA

Fig 2. 16 needles inserted during HDR Prostate procedure.

RESULTS

Optical images enabled accurate identification of grid-template positions. Fig 2 shows a conventional HDR prostate setup with 16 implanted catheters passing through a 2D template. Using automated scripting, a patient-specific 3D catheter model was generated in less than one minute (Fig 3). Grid-template positions were subsequently verified through perspective registration between the optical image and the 3D model projection (Fig 4).

- A patient-specific 3D catheter model was generated in <1 minute.
- Camera-based grid localization correctly identified template positions for all 16 catheters.
- Free-length verification demonstrated good agreement with manual measurements.
- The standard deviation between reconstructed and measured free lengths was ±2.1 mm.
- Primary sources of uncertainty were catheter curvature and overlap, and image noise.

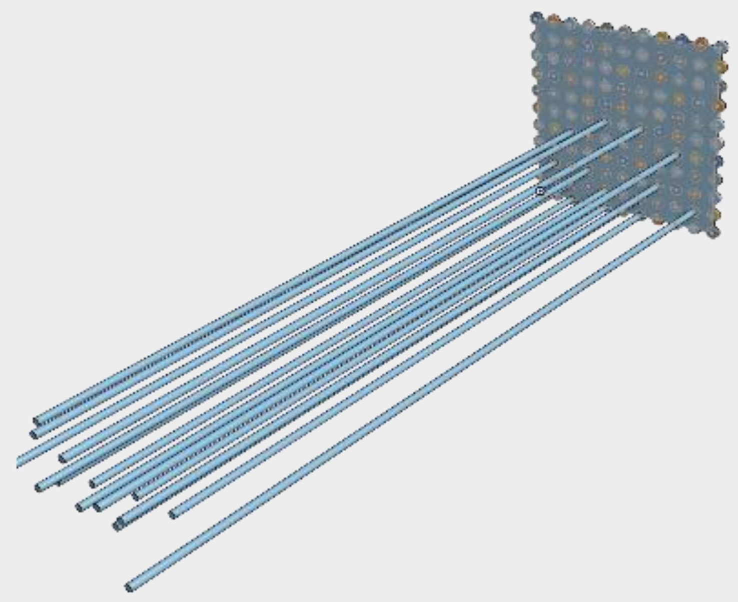

Fig 3. Catheters and grid template created by scripting.

Fig 4. Overlay of 3D model with the photo from camera.

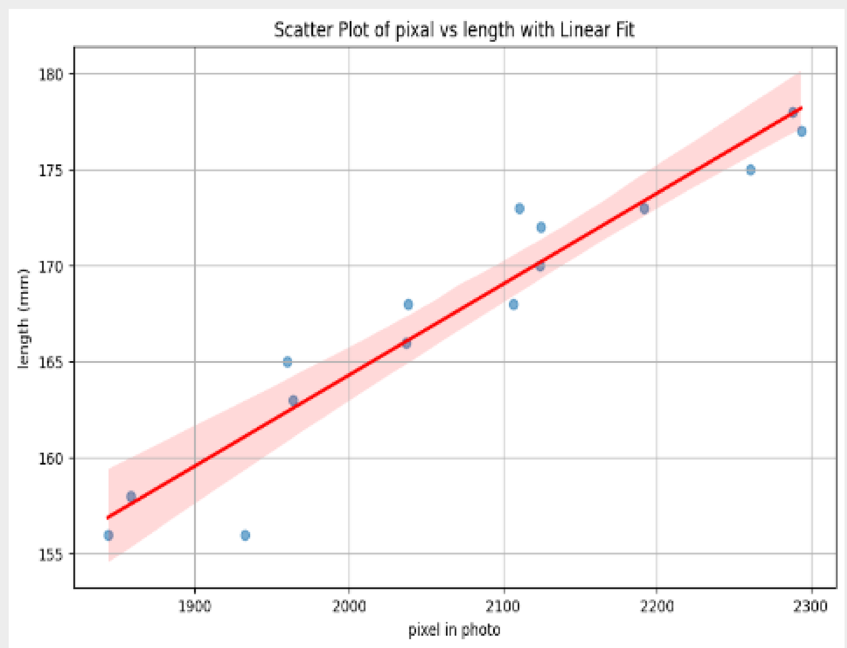

Fig 5. Correlation of free length from reconstruction & measurements

DISCUSSION

The proposed workflow demonstrates the feasibility of optical imaging as a rapid, touchless QA tool for HDR prostate catheter reconstruction.

The primary sources of uncertainty were catheter curvature and overlap within a single 2D camera projection. Because the Hough transform assumes a linear trajectory, curved catheters may produce inaccurate length estimation. In addition, overlapping catheters can obscure individual boundaries, creating ambiguity during segmentation and reconstruction.

Future work will investigate stereo and multi-view imaging using two to three synchronized cameras positioned around the treatment template. Multi-view imaging can provide depth information through triangulation, improving localization accuracy, reducing overlap-related ambiguity, and enabling explicit reconstruction of catheter curvature.

Potential reconstruction algorithms include:
- Stereo triangulation
- Structure-from-Motion (SfM)
- Multi-view geometry
- Epipolar-constrained catheter tracking
- Deep-learning-based catheter segmentation and pose estimation

In addition, Microsoft TRELLIS.2 offers a promising framework for image-to-3D reconstruction by generating structured 3D representations directly from optical images. Integration of multi-view imaging and AI-driven 3D reconstruction may ultimately enable automated real-time verification of catheter geometry, free lengths, and implant quality.

CONCLUSIONS

- Optical imaging combined with 3D model registration provides a practical touchless QA solution for HDR prostate catheter digitization.
- Camera-based verification accurately identified template positions and verified free lengths with a standard deviation of ±2.1 mm
- The workflow reduces manual measurements performed under sterile conditions and may improve clinical efficiency.
- Future integration of multi-camera imaging and AI-based 3D reconstruction (e.g., Microsoft TRELLIS.2) may enable fully automated real-time catheter verification.

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