Development of a Prototype Intraoperative Safety Device for HDR Brachytherapy Channel Verification

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ABSTRACT

Purpose: Modern brachytherapy afterloaders have a capacity of up to 50 channels for complex high dose rate (HDR) treatments. For interstitial treatments, needles must be accurately matched to the correct channel on the afterloader, else the dwell times will be erroneously delivered. Incorrect catheter connection is a failure mode of HDR brachytherapy that is challenging to detect. The inadvertent swapping of channels can result in a consequential loss of target coverage while simultaneously delivering excessive dose to normal tissues. In this work, a prototype brachytherapy template attachment is demonstrated that detects and alerts clinicians of an erroneous catheter connection prior to delivery.

Methods: As a pre-delivery safety measure, clinical afterloaders advance a non-radioactive 'dummy' wire through each catheter channel to verify an unobstructed source path. To independently verify correct channel-needle correspondence during this process, a custom HDR template attachment was developed incorporating embedded solenoid inductors driven by a micro-controller operating a metal-detecting circuit. The system detects the presence of a dummy wire within a solenoid and compares to the expected.

Results: The prototype template attachment consistently detected the dummy wire within gynecological interstitial needles. Comparison between the planned delivery sequence and connections were actively made by the device, and an error signal was reliably produced in real time when there was an erroneous connection.

Conclusion: This work introduces a prototype design for a brachytherapy HDR template attachment that provides intraoperative safety validation of appropriate catheter connection, which could assist in minimizing human error during HDR treatment delivery, particularly in complex cases with multiple catheters.

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INTRODUCTION

Several brachytherapy failure mode and effects analysis (FMEA) studies have mentioned incorrect catheter connection as a failure mode, scoring high in severity and low in detectability, with human error being the primary cause[1-3]. The current lack of independent verification makes automated quality assurance of correct channel-needle connection a crucial, but missing element of current practice, and a prime candidate for investigation. An ideal device should achieve the following goals:

- Detect accidental channel swaps
- Operates before dose delivery
- Can be added to HDR systems without modifying commercial products

We introduce a customizable prototype safety accessory for intraoperative HDR brachytherapy treatments that aims to alert clinicians of incorrect channel-needle correspondence during the pre-delivery dummy wire check. Our device is novel because there are currently no broadly available technologies that allow for real-time verification of correct catheter connection by detecting the dummy wire.

METHODS AND MATERIALS

The prototype safety device was manufactured (Figure 1) and tested using a Varian Bravos afterloader (Varian Medical Systems; Palo Alto, CA, USA). The device was 3D printed using BioMed Clear Resin (Formlabs; Somerville, MA, USA) allowing for autoclave sterilization. Solenoids are embedded within the device (Figure 2) and operated as a metal-detecting circuit driven by an Arduino micro-controller.

Before treatment delivery, clinical afterloaders perform a safety check to verify that the channel path is clear. The check advances a non-radioactive 'dummy' wire through each path before the radiation source is deployed. The proposed safety device detects the presence of a 'dummy' wire within a solenoid and compares to the expected channel. Confirmation is made that channel-needle assignments are connected in the predefined order, and the user is notified if a wire is detected in a needle out of the expected sequence.

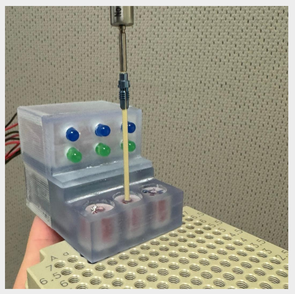

Figure 1. A photo of the safety device attached to a prostate grid template. An interstitial needle passes through the solenoid bore before the grid template.

Figure 2. A photo of the safety device with an embedded solenoid exposed.

RESULTS

The prototype template attachment demonstrated consistent detection of the dummy wire within the gynecological interstitial needles. The device actively compared signal detections against the planned delivery sequence (Figure 3) and reliably generated a real-time error signal in the event of a misconnection (Figure 4).

The prototype indicates a dummy wire detection by triggering a green LED. The expected channel detection is given by a triggered blue LED, and mismatches trigger a set of red LEDs.

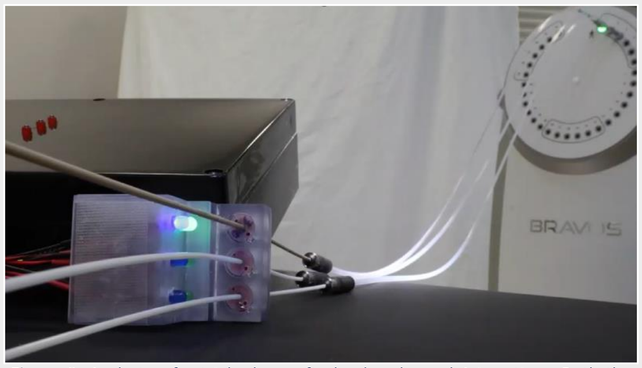

Figure 3. A photo of a trial where afterloader channel 1 is active. Both the blue and green LEDs are active on channel 1 indicating a correct channel connection

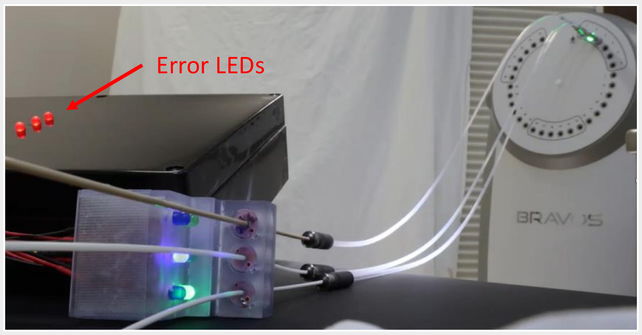

Figure 4. A photo of a trial where afterloader channel 2 is active. The blue is triggered on channel 2 indicating that the device expects a signal detection on channel 2. The green LED is active on channel 3 indicating the dummy wire passed through channel 3. The mismatch causes the red LED error light to trigger.

Additionally, the dosimetric impact of the failure mode has been investigated. Preliminary analysis involved simulating channel swaps of anonymized patient plans (Figure 5-6). The simulation and dose calculation were performed using an in-house MATLAB script. The script can produce images with isodose lines and dose volume histograms.

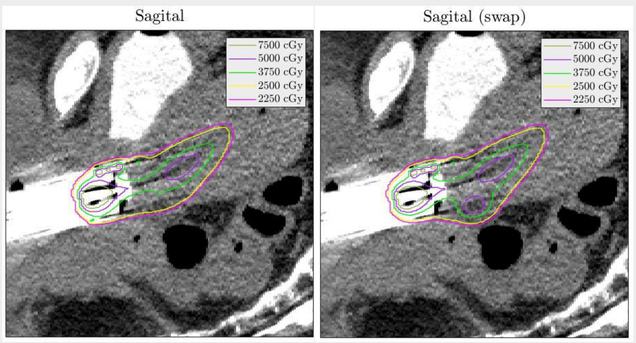

Figure 5. A sagital view comparison of isodose lines without (left) and with (right) a catheter swap.

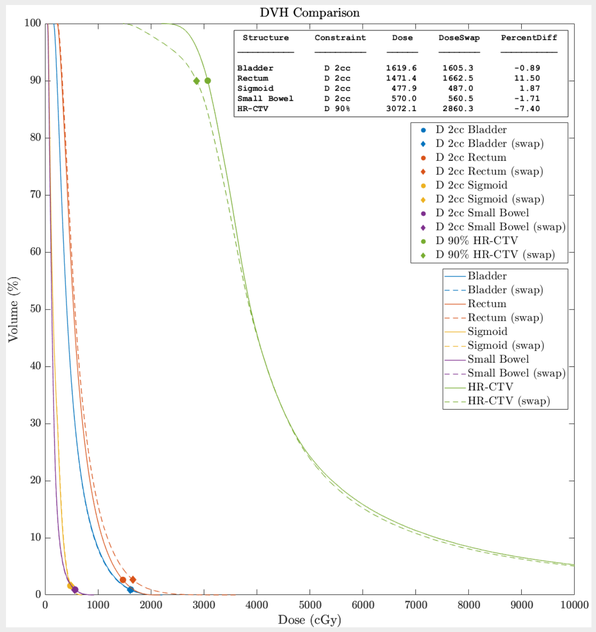

Figure 5. A Dose Volume Histogram (DVH) comparing the dose to key structures with (dashed) and without (solid) a catheter swap. Notable dose constrains such as D_{2cc} and $D_{90\%}$ are marked for curves with (diamond) and without (dot) a catheter swap. Doses used in the table comparing D_{2cc} and $D_{90\%}$ are given in cGy.

DISCUSSION

The device is currently unable to produce enough signal to detect the dummy wire within a stainless steel prostate needle. A stronger signal can be created by increasing the number of solenoid loops or by increasing the frequency of pulses in the metal detective circuit beyond what a simple micro-controller can achieve. Hardware improvements are needed to increase the signal to detect within prostate needles as well as to allow for the inductors to be made smaller for densely packed brachytherapy templates.

CONCLUSIONS

A prototype design for an HDR brachytherapy template attachment is introduced, which offers intraoperative safety validation for catheter connections. This system aims to reduce human error during treatment delivery, particularly in complex procedures utilizing multiple catheters.

This initial prototype represents a promising foundation for a clinically viable safety device. Moving forward, the next phases of development for this safety device will include:

- Upgrade circuitry to increase signal and allow for use with prostate needles
- Use the device to trigger an interlock on the afterloader when errors are detected
- Investigate modifying current brachytherapy templates to include dummy wire detection without a secondary attachment

REFERENCES

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