Recent Technology Innovations in Prostate Brachytherapy

J. Adam M. Cunha, Ph.D.
University of California (UCSF)
San Francisco, CA

Disclosure
Partial research support from Philips Healthcare

Learning Objectives.
Upon completion of this lecture, you will have:

A knowledge of the TG-192 report and the current status of robotic brachytherapy.
An understanding of image-guided adaptive brachytherapy in the context of prostate.
A familiarity with electromagnetic (EM) tracking and its potential use in brachytherapy.
In skilled hands, brachytherapy works.
- 90% survival at 12 y
- 98% survival at 4 y
- 41% impotence
- 26% G3+ UT

But side effects can be significant (especially if procedure skill is nominal)

Robots in Brachytherapy: Motivation

- Surgical procedure – Highly skill dependent – learning curve
- # of needle insertions required is an inverse function of years of experience
- Needle puncture trauma to target and normal tissues
- Imaging access (real-time feedback needed for needle insertion)
- Geometric restrictions to brachytherapy. E.g. Pubic arch interference
- Hard to intra-operatively “fix” misplacements
**Working Group on Robotic Brachytherapy**

- Commenced in 2008 under the Brachytherapy SC of Therapy Physics Committee
- Convened Task Group 192 to work with GEC-ESTRO brachy group.

**Change**

1. Introduction to robotic brachytherapy: History, classifications, definitions, nomenclature.
2. Review of current research and development - approaches and systems for procedures like brachytherapy, biopsy, etc.
3. QA & calibration issues - robotic space, patient space, design & development issues, safety & reliability issues, hazard analysis, FTA & FRECA analysis, system calibration.
5. Future development - suggestions for improvement.


---

**Robot Definition**

Simple Definition of robot: a real or imaginary machine that is controlled by a computer and is often made to look like a human or animal: a machine that can do the work of a person and that works automatically or is controlled by a computer.

The Robotic Industries Association (RIA) defines robot as follows: “A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks.”

---

**Robot Classifications**

Robotics Institute of America:
- Class 1: Devices that manipulate objects with manual control
- Class 2: Automated devices that manipulate objects with predetermined cycles
- Class 3: Programmable and servo-controlled robots with continuous point-to-point trajectories
- Class 4: Robots of the last type (Class 3) that also acquire information from the environment and move intelligently in response

Ex Machina: Universal Pictures (2015)
Anthropomorphic
Robot Classifications

Robotics Institute of America:
- Class 1: Devices that manipulate objects with manual control.
- Class 2: Automated devices that manipulate objects with predetermined cycles.
- Class 3: Programmable and servo-controlled robots with continuous point-to-point trajectories.
- Class 4: Robots of the last type (Class 3) that also acquire information from the environment and move intelligently in response.


Robot Classifications

Robotic Industries Association:
- Class 1: Devices that manipulate objects with manual control.
- Class 2: Automated devices that manipulate objects with predetermined cycles.
- Class 3: Programmable and servo-controlled robots with continuous point-to-point trajectories.
- Class 4: Robots of the last type (Class 3) that also acquire information from the environment and move intelligently in response.

For brachytherapy, TG-192:
- Level I. A human controls each movement; each machine actuator change is specified by the operator.
- Level II. A human specifies general moves or position changes and the machine decides specific movements of its actuators.
- Level III. The operator specifies only the task; the robot manages to complete it independently.
- Level IV. The machine will create and complete all its tasks without human interaction.

Robot Classifications

Humans
- Need real-time imaging

Robots - Stereotactic
- Fixed coordinate system

Robots - Servo
- Extension of a human
Humans, robots: different strengths

Tele-robotics

Mitigate skill/geography disparity

Co-Robots

Integration of human and robot

TG-192 REQUIREMENTS OF MEDICAL ROBOTIC SYSTEMS

1. Safety for the patient, clinicians, and staff,
2. Ease of cleaning and decontamination,
3. Compatibility with sterilization,
4. Methods for review of planned dose distributions and robot motions before needle placement,
5. Visual (mandatory) and force (optional) feedback during needle insertion,
6. Visual confirmation of each needle-tip placement and seed deposition,
7. Provision for reverting to conventional manual brachytherapy at any time,
8. Quick and easy disengagement in case of emergency,
9. Robust and reliable operation, and
10. Ease of operation in the procedure environment.

TG-192 GOALS FOR BRACHYTHERAPY ROBOTIC SYSTEMS

1. Improve accuracy of needle placement and seed delivery (i.e., place the needle and seed correctly at the planned location),
2. Consistency of seed implantation procedure (i.e., eliminate inter-clinician variability),
3. Avoidance of critical structures (e.g., for prostate implants, urethra, pubic arch, rectum, bladder, structures of the penis),
4. Dose optimization,
5. Reduce the clinician's learning curve,
6. Clinician fatigue,
7. Staff radiation exposure, and
8. Streamline the brachytherapy procedure.
First brachytherapy robots

- 2001 Elliot et al.: US patent for a seed implantation system featuring automated XYZ motion with a seed cartridge.

![Image](https://example.com/first_brachytherapy_robots_2001_elliot专利.png)

United States Patent

4,600,000

Elliot, et al.

March 31, 1986

Abstract

An automated implantation system assists the implantation of radium or iridium seeds in a patient so as part of a brachytherapy procedure. A Z-axis automated motion control console sets an X-Y axis automated motion control system control a needle assembly. The X-Y axis automated motion control system positions an insertion site of the needle assembly relative to the patient. The Z-axis automated motion control console moves the needle assembly along the insertion axis to implant at least one radium seed. This process is repeated for a plurality of insertion sites in a treatment volume of the insertion axis. Probably, the radium seeds are contained in a replaceable cartridge and the needle assembly is also replaceable.

- 2002 Fichtinger et al.: CT-guided robot assistance for prostate biopsy and therapy.

![Image](https://example.com/first_brachytherapy_robots_2002_fichtinger.png)

Fichtinger et al. Academic Radiology 9(1) 2002

- 2001 Elliot et al.: US patent for a seed implantation system featuring automated XYZ motion with a seed cartridge.

- 2002 Fichtinger et al.: CT-guided robot assistance for prostate biopsy and therapy.

- 2002 Nucletron: Fully Integrated Real-time Seed Treatment (FIRST) goes to market.

![Image](https://example.com/first_brachytherapy_robots_2002_nucletron.png)

Rivard et al. JACMP 6;1 (2005)
**First Brachytherapy Robots**
- 2001 Elliot et al.: US patent for a seed implantation system featuring automated XYZ motion with a seed cartridge.
- 2002 Fichtinger et al.: CT-guided robot assistance for prostate biopsy and therapy.
- 2002 Nucletron: Fully Integrated Real-time Seed Treatment (FIRST) goes to market.
- 2004 Wei et al.: Integration of a commercial robot into the prostate brachy workflow.

**TG 192 reported on 13 robots in development**

**EUCLIDIAN**

**UMCU (Utrecht) MRI-guided robotic system**
Largerburg et al.

**TG 192 reported on 13 robots in development**

**JHU Robot**
Fichtinger, et al.
Classification of 13 TG-192 Robots

<table>
<thead>
<tr>
<th>Robot</th>
<th>Use</th>
<th>Imaging</th>
<th>DoF</th>
<th>Autonomy Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST (Nucletron)</td>
<td>PSI</td>
<td>US</td>
<td>2</td>
<td>Level II</td>
</tr>
<tr>
<td>EUCLIDIAN (TJU)</td>
<td>PSI</td>
<td>US</td>
<td>5+6</td>
<td>Level III</td>
</tr>
<tr>
<td>MRX II (TJU)</td>
<td>PSI/HDR</td>
<td>US</td>
<td>5+6</td>
<td>Level III</td>
</tr>
<tr>
<td>UMCU robot</td>
<td>PSI/HDR</td>
<td>MR</td>
<td>5</td>
<td>Level II</td>
</tr>
<tr>
<td>UW robot</td>
<td>PSI/HDR</td>
<td>US</td>
<td>6</td>
<td>Level II</td>
</tr>
<tr>
<td>JHU robot</td>
<td>PSI</td>
<td>US</td>
<td>4</td>
<td>Level I</td>
</tr>
<tr>
<td>MIR (JHU)</td>
<td>PSI</td>
<td>MR</td>
<td>4</td>
<td>Level III</td>
</tr>
<tr>
<td>JHU-3 MR</td>
<td>PSI</td>
<td>MR</td>
<td>3</td>
<td>Level II</td>
</tr>
<tr>
<td>BW-MR (JHU)</td>
<td>PSI</td>
<td>MR</td>
<td>6</td>
<td>Level II</td>
</tr>
<tr>
<td>UBC</td>
<td>PSI</td>
<td>US</td>
<td>4</td>
<td>Level II</td>
</tr>
<tr>
<td>RRI</td>
<td>PSI</td>
<td>US</td>
<td>4</td>
<td>Level II</td>
</tr>
<tr>
<td>OHU</td>
<td>PSI</td>
<td>US</td>
<td>5</td>
<td>Level II</td>
</tr>
<tr>
<td>MIRA V (UWO)</td>
<td>Lung seeds</td>
<td>US</td>
<td>5</td>
<td>Level II</td>
</tr>
</tbody>
</table>

A comment on Degrees of Freedom

- Degrees of freedom (DoF) define the ability of the robot to be positioned in space to place a needle or seed. It is based on dimensionality of the motion to be executed.
- Placement of the robot’s shoulder in (x,y,z) for positioning: 3 DoF
- Parallel movement of the needle in an x-y coordinate system (not shown): 2 DoF
- Rotation of needle about tip location or other RCM (pitch, yaw): 2 DoF
- Insertion of needle: 1 DoF
- Rotation (rifling) of the needle about axis: 1 DoF

Degrees of freedom = 7 + 6 + 3
**Clinical Trials**

Can I implant yet?

- First in 2008: 5 patients on Phase I trial
- Average 36 needles per plan inserted using robot guidance.

**Current Status of Robots from TG-192 Report**

- Robarts Research Institute (RRI) Robot, Aaron Fenster licensed to Eigen (Grass Valley, CA)
- Currently being used in the clinic for HDR brachytherapy
- Looking to translate to breast and/or gyn.
The Prosper robot (CHUG, France robot) has gone through a design iteration and is now on version 2.

Preparing protocol for evaluation in patients.

JHU3-MR (Axel Krieger) technology was commercialized with Sentinelle Medical Inc., and Howlogic.

Sentinelle product line is part of InVivo (Philips) prostate biopsy technology.

Uses EM tracking too!

Also created Sentinelle prostate MR coil (no biopsy or brachy function)

Learning Objectives

Upon completion of this lecture, you will have:

- A knowledge of the TG-192 report and the current status of robotic brachytherapy.
- An understanding of image-guided adaptive brachytherapy in the context of prostate.
- A familiarity with electromagnetic (EM) tracking and its potential use in brachytherapy.
**Learning Objectives.**
Upon completion of this lecture you will have:

- A knowledge of the TG-192 report and the current status of robotic brachytherapy.
- An understanding of image-guided adaptive brachytherapy in the context of prostate.
- A familiarity with electromagnetic (EM) tracking and its potential use in brachytherapy.

---

**Adaptive Brachytherapy Workflow**

1. Image
2. Contour
3. Plan seed & needle positions
4. Place seeds
5. Post implant dose evaluation

**Stereotactic Robot PPI Workflow**

1. Imaging System (US, CT, MRI) → Treatment Planning System → Delivery → Evaluation

**Image Guided Intra-Operative Adaptive Brachy**

<table>
<thead>
<tr>
<th>PPI Brachytherapy Workflow</th>
<th>PPI Adaptive Brachytherapy Workflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Image</td>
<td>1. Image</td>
</tr>
<tr>
<td>2. Contour</td>
<td>2. Contour</td>
</tr>
<tr>
<td>3. Plan seed &amp; needle positions</td>
<td>3. Plan seed &amp; needle positions</td>
</tr>
<tr>
<td>4. Place seeds</td>
<td>4. Place some seeds</td>
</tr>
<tr>
<td>5. Post implant dose evaluation</td>
<td>5. Re-image</td>
</tr>
<tr>
<td></td>
<td>6. Locate dropped seeds</td>
</tr>
<tr>
<td></td>
<td>7. Evaluate contours / re-contour</td>
</tr>
<tr>
<td></td>
<td>8. Evaluate dose distribution</td>
</tr>
<tr>
<td></td>
<td>9. Re-optimize</td>
</tr>
<tr>
<td></td>
<td>10. Place remaining seeds</td>
</tr>
<tr>
<td></td>
<td>11. Final implant dose evaluation</td>
</tr>
</tbody>
</table>
**Learning Objectives.**
Upon completion of this lecture you will have:

- A knowledge of the TG-152 report and the current status of robotic brachytherapy.
- An understanding of image-guided adaptive brachytherapy in the context of prostate.
- A familiarity with electromagnetic (EM) tracking and its potential use in brachytherapy.
Eve, for now.

Learning Objectives.
Upon completion of this lecture you will have:

- A knowledge of the TG-192 report and the current status of robotic brachytherapy.
- An understanding of image-guided adaptive brachytherapy in the context of prostate.
- A familiarity with electromagnetic (EM) tracking and its potential use in brachytherapy.

Bye, for now.

What is Electromagnetic (EM) Tracking

- Tracking = Real time guidance
- First papers on concept of using EM fields to track location (1979 & 1980)
- Standardized protocols in 2005 lead to rapid increase in clinical applications.
- Nice review paper:

Electromagnetic Tracking in Medicine—A Review of Technology, Validation, and Applications
Alfred M. Fraser*, Tanja Hölzger, Wolfgang Heidherr, Kevin Clancy, Tony M. Peters, and Lone Mater-Hol

Planar field generator - AC

NDI Aurora system (theorie Sellier et al. PMB 2000)

Six differential coils

1-12kHz
Planar field generator - AC

- Sensor = induction coil
- Alternating current of ± 2 A at 12 kHz for 3.3 ms each differential coil will create 6 different voltages at the sensor
- If 5DOF needle: 6 measurements and 5 unknown
- If 6DOF: 2 sensor coils

**Example: NDI Aurora**

- Detection volume is not perfectly cubic
- Deviation from expected positions increase with distance (Z) and close to edges (XY plane)
  - ± 1 mm in the first 30 cm
  - ±10 mm at 55 cm
  - Angle < 2% first 30 cm
  - ±8 to -10% at 55 cm

*Detection Volume*

Boutaleb et al. J Contemp Brachytherapy 7: 280-9
Summary of Performance

- Needs to be used within the first 30 cm of the field generator
- Needle parallel to the field generator yield better angular accuracy
- Field generator generate heat: not under the patient
- Interference seen only for CRT monitor and bulky metallic arms (not shown)
  - Insensitive to US probe and needles/catheters
  - Metal close to the generator (but not within the field) can be OK as long as the configuration does not move/change during the procedure

---

**EM Tracking Systems**

- Continuously monitor implant quality. Trigger an on-the-fly re-optimization if errors in placed seeds will create a non-compliant dose plan.
- Use electromagnetic tracking to detect needle AND actual seed positions.

---

**Table of Performance**

<table>
<thead>
<tr>
<th>Description</th>
<th>Under Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard PPI needle</td>
<td>EM-tracked hollow needle</td>
</tr>
</tbody>
</table>

---

**Steps of Enriching Process**

1. Place seeds
2. Re-image
3. Locate dropped seeds
4. Evaluate seeing / re-contour
5. Evaluate dose distribution
6. Re-optimize
A hollow brachytherapy electromagnetic needle prototype was recently developed by Philips Healthcare.

- Detects seed drops by exploiting local changes of electromagnetic properties in the medium.
- Preserves standard tacking capabilities.

Registration of detected seed distributions. True seed positions were obtained from a μCT scan (GE, 89 μm slice thickness).

Racine et al, AAPM 2015; Submitted to Medical Physics
Some clinical challenges in HDR Brachytherapy

- Catheter digitization is absolutely critical in the accurate delivery of the planned dose.
- On MR & US, precise catheter digitization is even more difficult than CT.
- Intra-user variability can be significant, especially with systems where the dwell positions are defined from the tip and therefore placement error propagates down the entire catheter.

EM Guidance can address

Real-time catheter tracking for high-dose-rate prostate brachytherapy using an electromagnetic 3D guidance device: A preliminary performance study

S. Bhora, J. Naik, K. Wang, J. D’Silva, and D. Parikh

Med. Phys. 41(2), February 2014

Electromagnetic tracking for catheter reconstruction in ultrasound-guided high-dose-rate brachytherapy of the prostate

S. Bhora, K. Wang, J. D’Silva, C. Naik, J. Han, and D. Parikh

Acoustical Science and Technology 36(1), 1-9 (2015)

Fast, automatic, and accurate catheter reconstruction in HDR brachytherapy using an electromagnetic 3D tracking system


Acoustical Science and Technology 36(1), 1-9 (2015)

A system to use electromagnetic tracking for the quality assurance of brachytherapy catheter digitization

V. C. O’Sullivan, A. Liu, S. Naik, D. Parikh, S. D. Liu, and S. Bhora

Med. Phys. 42(3), March 2015

EM Tracking in HDR Brachytherapy

- For US-based planning (red square is the EM coordinate)
10 catheters were inserted in gelatin phantoms with different trajectories.
**Auto. Channel reconstruction**

Unpaired Student t-tests show statistically significant difference

Poulin et al., Medical Physics 2015;42(3):1227–32.

\* Comparison between EM vs US only reconstruction, see poster # 2016-A-418-ABS

---

**Some clinical challenges in HDR Brachytherapy**

- Catheter digitization is absolutely critical in the accurate delivery of the planned dose.
- On MR & US, precise catheter digitization is even more difficult than CT.
- Intra-user variability can be significant, especially with systems where the dwell positions are defined from the tip and therefore placement error propagates down the entire catheter.

**EM Guidance can address**

Fast, accurate, and automated catheter reconstruction in HDR brachytherapy using an electromagnetic 3D tracking system

A system to use electromagnetic tracking for the quality assurance of brachytherapy catheter digitization

---

**EM Tracking: Error Check Catheter Reconstruction**

Prostate

\((x1,y1,z1)\)
\((x2,y2,z2)\)
\((x3,y3,z3)\)
\((x4,y4,z4)\)
EM Tracking: Automatic Catheter Reconstruction

3 main errors in catheter digitization

Swap Mix Shift

(Damato et al. MedPhys (2014))

Summary: EM Tracking in Brachytherapy

- Depending on setup, full digitization can be done on the order of seconds to several minutes.
- Can be used to QA a manually generated catheter geometry by systematically evaluating differences in geometry
- Can be used to generate the catheter geometry
- Calibration to US/CT/MR planning images is critical!

HDR Brachytherapy

- Seed implant brachytherapy
  - Monitor seed placement
  - If able to integrate with a treatment planning system,
    - real time update of implanted dosimetry,
    - can adapt plan to accommodate misplacement of seeds
  - Real-time adaptive brachytherapy

Cautions

- Have to be careful with setup because metal may induce interference and therefore uncertainties in measurements.
- Precision is on the order of 1 mm (Field generator specs.)
- Accuracy highly dependent on calibration.

Workflow Element  | Current Practice | Robotic Brachy
--- | --- | ---
Imaging (placement) | US for real-time needle location feedback | US/MR/CT imaging using stereotactic registration
Needle orientation configuration | Template for needle placement precision: All needles are parallel, can avoid normal structures (penile bulb) | Robot motor control system with 6+ d.o.f.
Source position optimization | Can allow for non-parallel needle geometries (can avoid puncture of penile bulb) | Can allow for non-parallel needle geometries
Needle insertion/retraction; seed deposition | Physician | Physician or robot motor control
Seed location verification | Post-implant CT (intra-op CT) | Robot maintains stereotactic position info, real-time implant CT
Extend brachy to new anatomical sites | Need cavity-based US imaging accessible, or naked-eye visible | MR or CT allows for access to any area of the body
A robot will be truly autonomous when you instruct it to go to work, and it decides to go to the beach instead.

- Brad Templeton

**RECENT TECHNOLOGY INNOVATIONS IN PROSTATE BRACHYTHERAPY**

J. Adam M. Cunha, Ph.D.
University of California (UCSF)
San Francisco, CA

**EM GUIDED WORKFLOW**

- Guidance is always on – no needle searching
- Catheter reconstruction
  - On fly
  - Link to dose calculation and inverse planning
  - Not a bottleneck anymore
- Streamline interface and workflow – 1 hr procedure?
- Workflow is same for whole gland and focal therapy
- Tips position accuracy and comparison to CT
Procedure time

- Image acquisition: 1 sec
- Contouring: 5-15 min
- Planning: 7.6±2.5 sec \textit{⇒} more time reviewing/rerun!
- Insertion:
  - 27.6±6.7 sec/catheter or needle on phantom
  - \approx 60 sec/catheter or needle expected for actual patient
- Catheter/Tip Reconstruction:
  - First one included with insertion time (free!)
  - Additional: 10.5±3.1 sec/catheter or needle

Complete procedure under 1 hour potentially feasible