Electromagnetic Tracking for Real-Time Guidance and Fast Channel Reconstruction in HDR Brachytherapy

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AAPM 2018 JUL 29–AUG 2
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DISCLOSURES

- Research grants and contracts on this topics:
  - National Sciences and Engineering Research Council of Canada (NSERC)
  - NSERC-Eleka Industrial Research Chair
  - Philips Healthcare

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Acknowledgements

Quebec's Team
Samir Boutaleb
William Foster
Louis Jay
Marie-Claude Lavallée
Fanny Moneger
Éric Poulin
Emmanuel Racine
Éric Vigneault

UCSF
Adam Cunha
I-Chow J Hsu

UK Erlangen
Christoph Bert and his team: K. Kallis, V. Strnad, M. Lotter, S. Kreppner, M. Kellermeier, T. Götz, J. Herbolzheimer, D. Elz, B. Hofmann

Elekta
F. de Vries, Y. Niatsetski, J. de Becker, E. Neijhus, B. van Veelen

B&W – Havard
Robert Cormack

Philips
Dirk Binnekamp
Antonio Bonilas
Roelof Feikema
Jack Geraats
Gilion Hauvast
Luc Koch
Jacek Kustra
Dave Senden

Learning Objectives

- Provide an overview of EM tracking technologies
- Understand the expected accuracy and precision of EM tracking
- Illustrate possible usage scenarios

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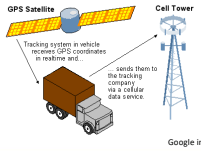
Definition - Tracking

Noun

- **1.** the act or process of following something or someone

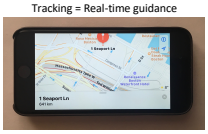
Collins English Dictionary. Copyright © HarperCollins Publishers



Google image search – PCMag.com

Tracking and beyond

Tracking = Real-time guidance



Augmented Reality

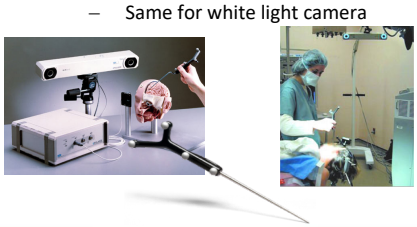
Daniel Burrus, LinkedIn 2013

Tracking in RT

Interventional Procedures / Optical Tracking

Limited to line of sight

- Same for white light camera



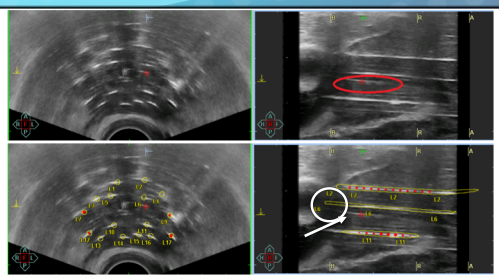
Tracking in Brachytherapy?

- Position of needle, catheter or applicator in real-time
  - Angulation/rotation
- Automated, fast and accurate channel reconstruction
  - Tip localization
  - Detection of catheter motions
- Potentially tracking in real-time the source position
  - Detection of wrong connection between transfer tube and afterloader
- Enabler for new brachytherapy and interventional procedures
  - True on the fly decision -> dynamical replanning

Technologies

- Image-based tracking: CT, MR or US
  - –Organ(s) and device(s) tracking

Accuracy of Catheter Reconstruction?



See e.g. F.-A. Siebert et al, Med Phys 36 (2009) 3406-3412.

Technologies

- Applicator-, catheter- and source-based tracking
  - Optical IR tracking } Need direct line of sight
  - **EM with passive sensors**
  - **EM with active MR coils** } MR compatible
  - Optical Fiber Shape Sensing

Electromagnetic tracking system (EMTS)

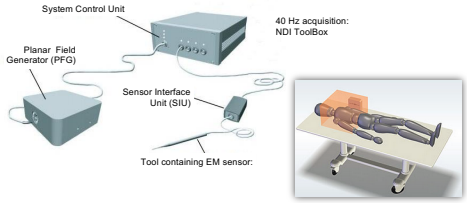
- **Electromagnetic Tracking in Medicine—A Review of Technology, Validation, and Applications**. Franz et al., IEEE Transactions on Medical Imaging **33** (2014)

- **Electromagnetic tracking for catheter reconstruction in ultrasound-guided high-dose-rate brachytherapy of the prostate**. Bharat S, Kung C, Dehghan E, Ravi A, Venugopal N, Bonillas A, Stanton D and Kruecker J. Brachytherapy 13 (2014) 640–50
- **EM-Navigated Catheter Placement for Gynecologic Brachytherapy: An Accuracy Study**. Mehrtash A, Damato A, Pernelle G, Barber L, Farhat N, Viswanathan A, Cormack R and Kapur T. Proc Soc Photo Opt Instrum Eng (2014) 9036 90361P
- **A system to use electromagnetic tracking for the quality assurance of brachytherapy catheter digitization**. Damato A L, Viswanathan A N, Don S M, Hansen J L and Cormack R A. Med. Phys. 41 (2014) 101702
- **Fast, automatic, and accurate catheter reconstruction in HDR brachytherapy using an electromagnetic 3D tracking system**. Poulin E, Racine E, Binnekamp D and Beaulieu L. Med. Phys. **42** (2015) 1227–32
- **Performance and suitability assessment of a real-time 3D electromagnetic needle tracking system for interstitial brachytherapy**. Boutaleb S, Racine E, Filion O, Bonillas A, Hauvast G, Binnekamp D and Beaulieu L. J Contemp Brachytherapy 7 (2015) 280–9
- **Real-time electromagnetic seed drop detection for permanent implants brachytherapy: Technology overview and performance assessment.** Racine E, Hautvast G, Binnekamp D and Beaulieu L Med. Phys. 43 (2016) 6217–25

- **And many more since 2016…**

Electromagnetic tracking system (EMTS)

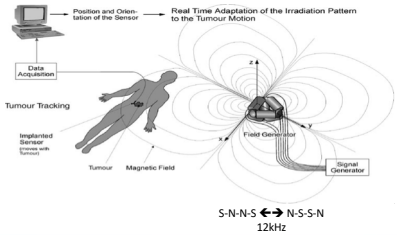
Example: Aurora® from Northen Digital Inc. (Ontario, Canada)



http://www.ndigital.com/msci/products/aurora/

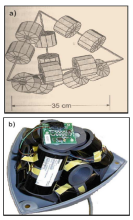
Planar field generator - AC

- NDI Aurora system (Principal: Seiler *et al.* PMB 2000)



S-N-N-S ↔ N-S-S-N
12kHz

Six differential coils



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

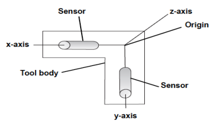


Figure 5-5 Sample 6DOF Tool

TABLE III
ASSESSMENT STUDY RESULTS

(a) **Standardized assessment according to Hummel *et al.* [61]**: Shows the mean RMS error over 90 positions as precision (Prec.) and the mean error of 161 measured 5 cm distances between these points as positional accuracy (Acc.). The rotational accuracy (Rot.) is given as the mean error of thirty-one 11.5° measurements for two axes, because 5 DoF sensors were used for most assessments.

System FG	Environment	Ref.	Pos. [mm] Prec.	Acc.	Rot. [°]
NDI Aurora					
Planar FG	Laboratory	[59]	0.17	0.25	0.2/0.9
	Laboratory	[102]	0.20	0.80	1.2/1.0
	CT Suite	[102]	0.18	4.40	1.2/1.0
	X-Ray Suite	[15]	-	1.31	-
Tabletop FG	Laboratory	[102]	0.05	0.30	0.8/0.7
	CT Suite	[102]	0.05	0.90	0.8/0.7
Compact FG	Laboratory	[102]	0.05	0.50	1.0/0.8
	CT Suite	[102]	0.06	0.50	1.0/0.8
	US probes	[39]	<0.2	<2.5	<3
Ascension microBird					
Mid Range FG	Laboratory	[61]	0.14	0.69	0.04
Ascension 3D Guidance					
Mid Range FG	Laboratory	[117]	0.15	0.24	.05/.06
Flat FG	Laboratory	[117]	0.20	0.18	.02/.02

From Franz et al, 2014

Active MR micro-coils

- Use the MR as an intrinsic field generator.
- Sensors are active micro-coils
- Sensors positions are *de facto* in the imager reference frame!

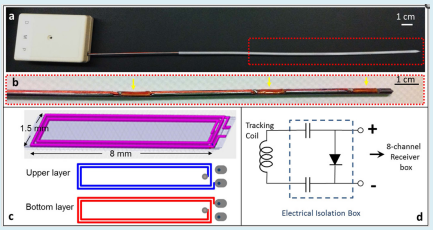
Magnetic Resonance in Medicine 73:1803–1811 (2015)

Real-Time Active MR-Tracking of Metallic Stylets in MR-Guided Radiation Therapy

Wei Wang,[1,2]* Charles L. Dumoulin,[3] Akila N. Viswanathan,[2] Zion T.H. Tse,[4] Alireza Mehrtash,[1] Wolfgang Loew,[3] Isaiah Norton,[1] Junichi Tokuda,[1] Ravi T. Seethamraju,[5] Tina Kapur,[1] Antonio L. Damato,[2] Robert A. Cormack,[2] and Ehud J. Schmidt[1]

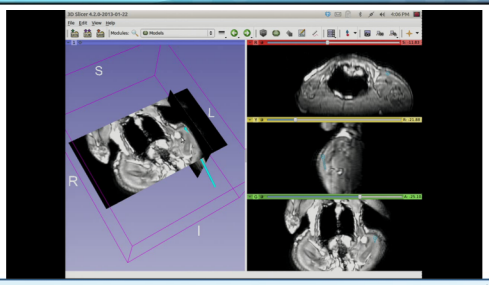
Damato, 2017-06-13

ACTIVE MR TRACKING



Wang et al., Magn Reson Med. 2015 May; 73(5):1803-11

Needle Guided MR Resampling of Initial Scan



Courtesy: Robert Cormack

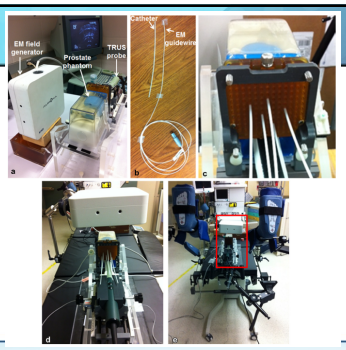
EMT in the Clinical Environment

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

Shyam Bharat[1,*], Cynthia Kung[1], Ehsan Dehghan[1], Ananth Ravi[2], Niranjan Venugopal[2], Antonio Bonillas[1], Doug Stanton[1], Jochen Kruecker[1]

[1]Department of Ultrasound Imaging and Interventions, Philips Research North America, Briarcliff Manor, NY
[2]Department of Radiation Oncology, Sunnybrook Health Sciences Center, Toronto, ON, Canada

Brachytherapy ***13*** *640–50*



EMT in the Clinical Environment

Table 6
Performance accuracy of EM catheter mapping system in the OR environment

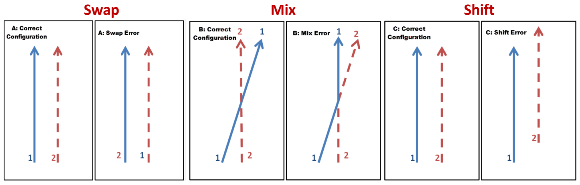
	In-plane discrepancy (mm)			Out-of-plane discrepancy (mm)		
EM vs. TRUS (in OR)	Mean	Standard deviation	Maximum	Mean	Standard deviation	Maximum
Calibrating and testing in a "low distortion" environment	0.4	0.2	1	0.8	0.4	1.7
Calibrating in a "low distortion" environment and testing in distorting environment	1	0.2	1.5	1.1	0.8	1.9
Calibrating in a "low distortion" environment and testing in distorting environment, after updating the calibration in the distorting environment	0.3	0.2	1.1	1.1	0.8	1.9
Calibrating and testing in distorting environment	0.6	0.3	1.5	0.4	0.2	0.6

EM = electromagnetic; OR = operating room; TRUS = transrectal ultrasound.
In the OR, a "low distortion" environment refers to the absence of clinical equipment other than the treatment table and the ultrasound system near the testing area. A distorting environment refers to an environment that includes the presence of other clinically used brachytherapy equipment, such as leg stirrups, stepper holder, treatment planning computer, treatment afterloader, instrument table, and others, in their typical positions.

- Sub-mm and 1° accuracy/precision
- Insensitive to US probe and needles/catheters
- Metal close to (but not in) the field OK as long as the configuration does not move/change during the procedure (e.g. stir-up)

HDR Brachytherapy Applications

Error Simulations – 15 catheters

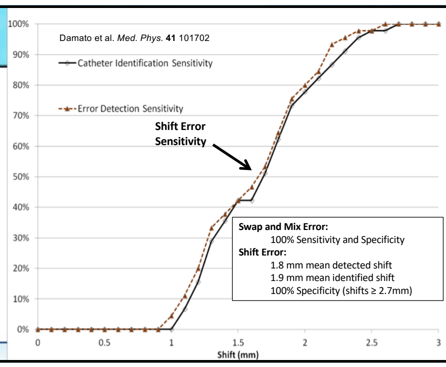


105 possible swap errors

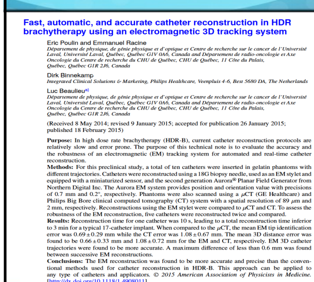
105 possible mix errors

from 0 to 3 mm shifts
(in 0.1 mm increments)
↓
465 possible shift errors

Damato et al. *Med. Phys.* **41** 101702



Auto. Catheter/Applicator Channel Reconstruction



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

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Département de physique, de génie physique et d'optique et Centre de recherche sur le cancer de l'Université Laval, Université Laval, Québec, Québec G1V 0A6, Canada and Département de radio-oncologie et Axe Oncologie du Centre de recherche du CHU de Québec, CHU de Québec, 11 Côte du Palais, Québec, Québec G1R 2J6, Canada

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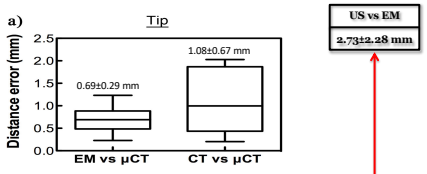
(Received 8 May 2014; revised 9 January 2015; accepted for publication 26 January 2015; published 18 February 2015)

Purpose: In high dose rate brachytherapy (HDR-B), current catheter reconstruction protocols are relatively slow and error prone. The purpose of this technical note is to evaluate the accuracy and the robustness of an electromagnetic (EM) tracking system for automated and real-time catheter reconstruction.
Methods: For this preclinical study, a total of ten catheters were inserted in gelatin phantoms with different trajectories. Catheters were reconstructed using a 18G biopsy needle, used as an EM stylet and equipped with a miniaturized sensor, and the second generation Aurora® Planar Field Generator from Northern Digital Inc. The Aurora EM system provides position and orientation value with precisions of 0.7 mm and 0.2°, respectively. Phantoms were also scanned using a μCT (GE Healthcare) and Philips Big Bore clinical computed tomography (CT) system with a spatial resolution of 89 μm and 2 mm, respectively. Reconstructions using the EM stylet were compared to μCT and CT. To assess the robustness of the EM reconstruction, five catheters were reconstructed twice and compared.
Results: Reconstruction time for one catheter was 10 s, leading to a total reconstruction time inferior to 3 min for a typical 17-catheter implant. When compared to the μCT, the mean EM tip identification error was 0.69 ± 0.29 mm while the CT error was 1.08 ± 0.67 mm. The mean 3D distance error was found to be 0.66 ± 0.33 mm and 1.08 ± 0.72 mm for the EM and CT, respectively. EM 3D catheter trajectories were found to be more accurate. A maximum difference of less than 0.6 mm was found between successive EM reconstructions.
Conclusions: The EM reconstruction was found to be more accurate and precise than the conventional methods used for catheter reconstruction in HDR-B. This approach can be applied to any type of catheters and applicators.
[http://dx.doi.org/10.1118/1.4908011]

- EM reconstructions at 40 Hz
- µCT reconstruction (GE) at 89 µm (reference)
- CT reconstructions (Philips BigBore) at 2 mm
- Reconstructions using the EM stylet were compared to µCT and CT (3D distances used; tips as reference).

Medical Physics 2015;42(3):1227–32.

Auto. Channel reconstruction



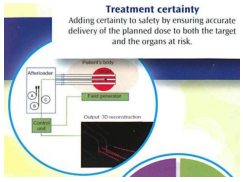
US vs EM
2.73±2.28 mm

Unpaired Student t-test show statistically significance difference
Poulin et al, Medical Physics 2015;42(3):1227–32.

* Comparison between EM vs US-only reconstruction, Brachytherapy **15** S194–5 (2016)

Tracking the Source Position: Afterloading Brachy

- Automated applicator/catheter reconstruction
- Online channel set-up QA



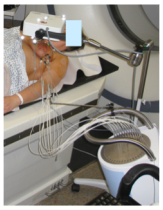
Vision 2020 BrachyNext meeting, Miami, 2014

Next slides will present Research/Investigational Devices

- Not clinically available yet
  - Only to provide a sense of what such systems could look like
- One is waiting for Health Canada approval as investigational device for first-in men study
  - Extension of the UroNav™ EM tracked Biopsy System
    - New real-time TPS for brachytherapy
- Another is taking data under institutional ERB approval.
  - EMT system integrated in the afterloader.

Example: Flexitron with integrated EMT

- EMT data of ~50 patients collected since 2015
- 07/2016: Flexitron with EMT sensor on additional drive
- New acquisition workflow and algorithms
- Integration of sensor position data from afterloader feasible

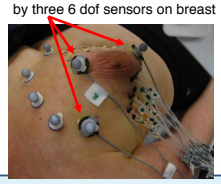


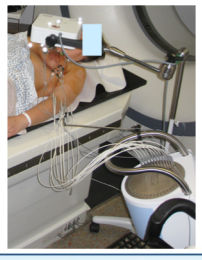
Courtesy: C. Bert

Karoline Kallis et al. Phys. Med. Biol. 2018

Breast Data Collection

- Treatment: microSelectron EMT measurements: Flexitron prototype
- Improved sensor placement on skin
  - Compensation for breathing motion by three 6 dof sensors on breast





Courtesy: C. Bert

Karoline Kallis et al. Phys. Med. Biol. 2018

Example data

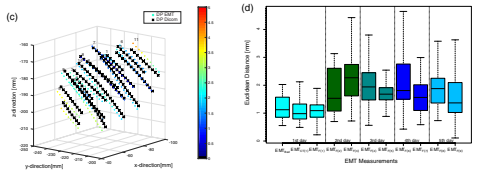
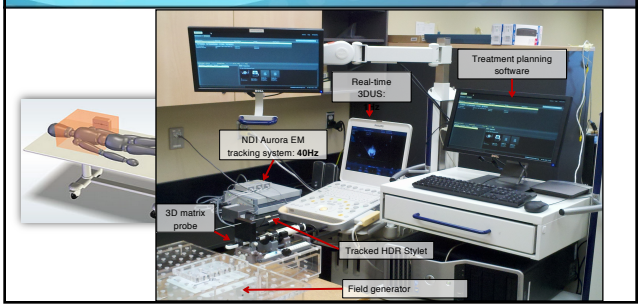


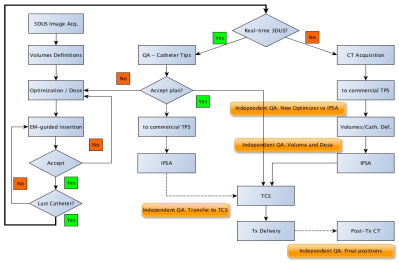
Figure 6. Exemplary comparison of DP CT to DP EMT for patient 15. Figure (a) shows the EMT measurement after the third fraction of irradiation. The colored stars represent the superficial reference sensors. Figure (b) presents the DP (colored points) and catheter traces, indicated by the black crosses, defined in the planning CT image, which served as reference. Figure (c) shows the deviations of the DPs at the 4th fraction. Figure (d) presents the course of the DP deviations within the week of treatment. In the boxplots outliers are not presented. Outliers are defined as points 1.5 times the interquartile range above the upper (3rd) quartile and below the lower (1st) quartile. The bottom and the top of the whisker represent the 75th percentile and 25th percentile. The band inside of the box indicates the median value.

Karoline Kallis et al. Phys. Med. Biol. 2018

Real-time EMT System: Lab Prototype



Workflow



Beaulieu *et al.* Brachytherapy **17** (2017) 103–10

Workflow Efficiency

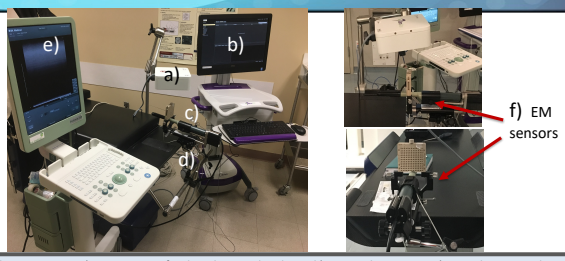
Running time (min)
5-15
10-20
26-36
30-40

- Image acquisition: 1 sec
- *Contouring: 5-15 min*
- Planning: 7.6±2.5 sec ➔ more time reviewing/rerun!
- Insertion:
  - *27.6±6.7* sec/catheter or needle on phantom
  - *≈ 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

Beaulieu *et al.* Brachytherapy **17** (2017) 103–10

Real-time EMT Prostate HDR System: First-in-Men



UronavTherapy system: a) EM generator fixed on the articulated arm, b) UronavTherapy cart, c) US probe mounted on the stepper, with the DK template in place and two EM sensors, d) stepper, e) BK 400 ultrasound, f) EM sensors, one on the side of the template and the other one on the right side of the stepper.

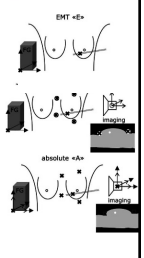
Key Issue: Calibration to a **Relevant Reference Frame**

- Sensor to needle/stylet tip or relevant applicator position
- Template (if used) to EM coordinate system
- Image to EM coordinate system
  - i.e. US to EM in the example shown previously

Each of the above will have an impact on the overall accuracy of the clinical system

Possibilities / Limitations

Quality item	Detectability			EMT coordinate system	Error probability and effect [23]	
	IVD	Imaging	EMT		Probability of error	Effect
Source calibration	✓	✗	✗	–	Low	Low-high
Afterloader source positioning and dwell time (non-patient specific)	✓	✗	(✓)	E	–	–
Afterloader malfunction	✓	✗	(✓)	E	Low	Low-high
Patient identification	✗	✓	(✓)	E/F	Low	High
Correct treatment plan	✓	✗	✓	E	Low	High
Intra- and interfraction organ/applicator movement	✓	✓	✓	E/F/A	–	–
Applicator reconstruction	✓	✓	✓	E	Intermediate	Low-intermediate
Applicator length/source indexer length	✓	✗	✓	E/F	Intermediate	Low-high
Source step size (patient specific)	✓	✗	✓	E	Low	High
Interchanged guide tubes	✓	✗	✓	E/F	Intermediate	Low-high
Recording of dose	✓	✗	✗	–	–	–



Courtesy: C. Bert

Bert et al. JCM 2016

EM Tracking Technologies

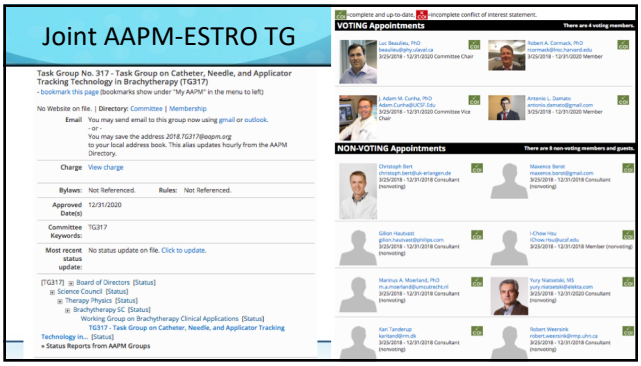
They are coming

- Real-time position/angulation information
- Can be used in or couple to needle, catheter or applicator (*iCatheter* and *iApplicator*!)
- Fast and accurate HDR channel and tips reconst.

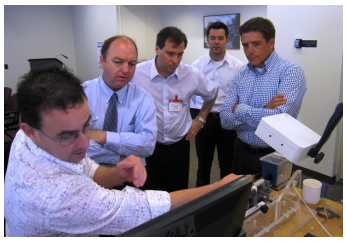
Could be incorporated in specific workflows

- Automated imaging plane display
- Real-time continuous dosimetry and replanning (Seed, HDR, Focal, …)
- QA of channels (reconstr., swapped, …)

Joint AAPM-ESTRO TG



In memory of Jean Pouliot



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