Towards real-time ultrasound image-guided abdominal radiotherapy

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History liver radiotherapy

- Prognosis after radiotherapy of liver cancer patients was poor
- Tumors needed a higher radiation dose for local control
- Impossible due to normal tissue constraints
- With current techniques, IMRT, SBRT, able to treat at higher dose levels without increasing the dose at organs at risks.
- Clinical trials demonstrated: highly effective to treat liver tumors with high dose levels

Image guidance of the liver

Accurate targeting liver lesions is a challenge:

- Assumption lesion moves within margin
Accurate targeting liver lesions is a challenge with current techniques:
- Soft-tissue contrast is poor
- Lesions are not visible

Bone structures as alternative?
- Liver position
- Liver motion
- Liver deformation

Criteria for the ideal IGRT solution
- Integrated with RT
- High precision
- Good resolution
- Soft-tissue contrast
- Non invasive
- Real-time imaging (live view)
- Also during treatment
- Not too expensive

Fiducials:
- Invasive
- Tumor spill
- Distance from lesion
- Liver inflammation

KV cone-beam:
- Soft-tissue contrast not sufficient
- (Blurring due to breathing)

Clarity 4D prostate system (Elekta): Novel transperineal ultrasound scan

US imaging:
Long term experience in diagnostic applications

References:
Towards abdominal, real-time, volumetric, soft-tissue image guidance with ultrasound

Combination of:
- 3DUS volumetric imaging
- 2DUS time series of the organ motion
- Robotic US probe placement
- US auto-contouring
- Contrast enhanced ultrasound (CEUS)

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US image guidance

New modality: 3DUS for liver SBRT Clarity 3DUS system (Elekta)
Overview of scan directions for Liver imaging

Feasibility study of IGRT with repeated 3D US imaging for liver lesions

Breath hold control

To obtain US scans in breath hold, we used the SDX spirometer system (DynR, France)
Match and scan accuracy free breathing (FB) vs breath hold (BH)

Reproducibility and inter- & intra-observer variability
3DUS volumetric imaging: Conclusion

- US scanning of liver lesions:
  - free breathing causes artifacts, reducing image quality;
  - in a predefined breath hold phase accurate (reference and daily scans are acquired with the liver in the same fixed position);
- The combined uncertainty (1SD) of US scanning and matching (inter and intra observer):
  - in free breathing 4mm
  - in breath hold 2mm
- With 3D US imaging, accurate online interfraction image guidance of liver lesions and/or surrogates is feasible. Recommended during breath hold.
- Nevertheless, integration of liver motion monitoring during treatment is still lacking.

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2DUS time series with spatial information

Steady probe position and orientation
2DUS time series with spatial information

Dedicated software
- RAW data
- Spatial information

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Robot System Requirements

• Develop a robot system to:
  – Record placement of US probe by expert clinician during CT simulation
  – Assist general clinician to place US probe, considering recorded position, force, and image
  – Hold ultrasound probe (or dummy) in place during CT acquisition and radiation treatment

Technical Approach

• Cooperative control with soft motion constraints (virtual fixtures):
  – Cooperative control: move robot by applying forces at the end-effector
  – Motion constraints: restrict motion to guide user to desired target
  – Soft motion constraints: allow motion away from desired target, but with larger effort

Prototype System

• Adapted existing JHU Steady Hand robot, initially designed for retinal microsurgery
• Use Claron Micron tracking system as surrogate for Clarity optical tracking system
Experimental Procedure

1. Use cooperative control to guide probe to target
2. Record information (position, force)
3. Starting from an arbitrary position, use cooperative control with soft virtual fixture to guide user back to target position
4. Measure position difference using optical tracking system and robot (possible because robot base not moved during experiment)
   - Optical tracking system is less accurate than robot

Experimental Results

- Performed three trials:
  - 3 different targets
  - 3 different users
- In each trial:
  - user defines target
  - returns to target 3 times
- User Impressions:
  - Robotic assistance made it quick and easy to accurately reproduce initial placement

<table>
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<th>Trial</th>
<th>Robot Diff., mm</th>
<th>Tracker Diff., mm</th>
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</table>

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### Automated Multimodal 3D Contouring for Prostate 3D Ultrasound

**Research by TAlab Tecnologie Avanzate Srl, Udine, Italy**

**Problems with single modality contouring algorithm:**
- Low stability due to the lack of a complete set of features to detect the prostate boundary in CT and US images.
- US:
  - upper boundary → well enhanced
  - lower boundary → sometimes a bit more confused
  - Lateral boundaries → more confused
- CT:
  - sharp edges and high contrast between tissues with very different densities
  - But not enough contrast in the soft-tissue range (like between prostate and its surrounding tissues)

### Multimodal 3D proposed algorithm

**Research by TAlab Tecnologie Avanzate Srl, Udine, Italy**

Full and direct use of all 3D information available from a scan.

Easily extensible to a multimodal approach:
- retrieve information from different imaging modalities
- use them simultaneously in the segmentation process

### Algorithm

**Research by TAlab Tecnologie Avanzate Srl, Udine, Italy**

- Projection of 3D data and/or surface boundary into projected image (PI)
- Generation of Probability Mask (PM)
- Multimodal features extraction (Huber, 2012)
- Multimodal features concatenation
- Generation of Probability Mask (PM)
- by application classifier (trained)
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Example

Research by TAlab Tecnologie Avanzate Srl, Udine, Italy

Contrast enhanced ultrasound imaging

Diffused liver metastases
2.4 ml injection, 8 min contrast enhancement

With Contrast
Without Contrast

Microbubbles Structure
SF₆
Phospholipids
Hydrophilic pole
Hydrophobic chain


Images from
Dr Lars Thorelius, Linkoping, Sweden

Baseline
Arterial phase
Portal late phase
Late phase

Hypervascular

Hypovascular

Images from
Dr Lars Thorelius, Linkoping, Sweden

Baseline
Arterial phase
Portal late phase
Late phase

Hypervascular

Hypovascular

Liver Metastasis

Bracco Imaging

Baseline
Arterial phase
Portal late phase
Late phase

Bracco Imaging

Baseline
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Bracco Imaging

Baseline
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And beyond....
And beyond………

Elastography (Young’s modulus estimation)
[European Urology, 54:1354-62, 2008]

Histoscanning
(Frequency spectrum classification)
[BJU International, 101:293-98, 2008]

Contrast Ultrasound Dispersion Imaging (CUDI)
Mischi et al., IEEE IUS, 2009 & IEEE TUFFC, in press.
Smeenge et al., World J Urol, 2011.

Tissue characterization

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