What is urology?

- Uro-genital apparatus of men
- Urinary apparatus of women
- Main organs: kidney, bladder, prostate
Clinical context

- Multi-modal imaging
- Mini-invasive procedures (coelioscopic surgery, brachytherapy, HIFU, etc.)
  - Potential benefit from computer-assistance for
    - Diagnosis and planning
    - Therapy
    - Training

Tools proposed to the urologist

- Modeling and simulation
- Image processing
- Image fusion
- Navigation
- Augmented reality
- Robotics
Robots in urology

- Prostate
  - Trans-Urethral Resection of the Prostate
  - Cancer
    - Radical prostatectomy
    - Biopsy
    - Brachytherapy
- Kidney
  - Percutaneous access
  - Destruction of stones
  - Biopsy
  - Destruction of tumours (Hyperthermia, RF)
  - MIS: adrenalectomy, pyeloplasty, nephrectomy, etc.
  - endoscope holders

Urology applications – J. Troccaz

A pioneering application: TURP

- Trans-Urethral Resection of the prostate (hyperplasia)
- Image-guided (endoscope)
A pioneering work [Davies et al.]

- First version: PUMA560
- Main idea: to constrain the tool to conical motions only (for safety)
- Second version: motorized frame

First patient operated in 1991
Small series (40 patients)
Not easy to automatically couple the robot control to the imaging data (US)

PRrobot (Davies et al. – Imperial College of London)
Prostate cancer

- Most frequent cancer of men in the western developed countries
- In 2005 in France: 62245 new cases (1\textsuperscript{st}), 9202 deaths (4\textsuperscript{th}, 2\textsuperscript{nd} in men)
- Estimates in 2008 in US: 186320 new cases (1\textsuperscript{st}), 28660 deaths (4\textsuperscript{th}, 2\textsuperscript{nd} in men)
- Diagnosis: rectal palpation, PSA, biopsies
- Treatments: none (careful watching), surgery (open, MIS), chemotherapy, radiotherapy, brachytherapy, HiFU, cryoablation, etc.

Robots in prostate cancer applications

- DaVinci’s leader application (radical prostatectomy)
- Image-guided (US/MRI) prostate biopsy
- Image-guided (US/MRI) prostate brachytherapy
The DaVinci system

- Master-slave robot
- Stereo-endoscopy (HD)
- Endowrist

DaVinci for radical prostatectomy

- Cancer to be totally removed
- Critical structures to be spared: neurovascular bundles, urethra
- Potential morbidity: impotency, incontinence
- An alternative to open surgery: laparoscopic surgery
- Benefit as compared to open or laparoscopic procedures (Vattikuti series: 1100 cases [Menon04])
From [Menon et al. 2004]

Table 3
Odds ratio for important outcomes for laparoscopic, robotic, and radical retropubic prostatectomy performed at the Vattikuti Urology Institute

<table>
<thead>
<tr>
<th>Variables</th>
<th>Open radical prostatectomy (reference values)</th>
<th>Laparoscopic radical prostatectomy (odds ratio)</th>
<th>Robotic prostatectomy (odds ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating room time</td>
<td>163 min</td>
<td>1.51&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.91&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Estimated blood loss</td>
<td>910 mL</td>
<td>0.42&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Positive margins</td>
<td>23%</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Complications</td>
<td>15%</td>
<td>0.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.33&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Catheterization time</td>
<td>15.8 d</td>
<td>0.59&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.44&lt;sup&gt;a,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hospital stay &gt; 24 hr</td>
<td>100%</td>
<td>0.35&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.07&lt;sup&gt;a,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Postoperative pain score</td>
<td>7</td>
<td>0.45&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>(0–10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median time to continence</td>
<td>160 d</td>
<td>1</td>
<td>0.29&lt;sup&gt;a,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Medium time to erection</td>
<td>449 d</td>
<td>NA&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.4&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Median time to intercourse</td>
<td>&gt; 700 d</td>
<td>NA&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.5&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Detectable prostate specific antigen</td>
<td>15%</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<sup>a</sup> P < .05 compared with radical retropubic prostatectomy.

<sup>b</sup> P < .05 compared with laparoscopic radical prostatectomy.

<sup>c</sup> Most patients undergoing laparoscopic radical prostatectomy were not sexually active at baseline.

Abbreviation: NA, not available.

The reference values were those from conventional radical prostatectomy; odds ratio was the ratio of the observed to the reference value.

Data from Refs. [24,27].

United States: about 120000 radical prostatectomies per year

### 2005 U.S. Radical Prostatectomy Market
- **79.3%** Open
- **20.3%** Laparoscopy
- **0.7%** DaVinci

### 2006 U.S. Radical Prostatectomy Market (Projected)
- **58.5%** Open
- **41.5%** Laparoscopy
- **0.5%** DaVinci

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**Prostate biopsy**

- Reference examination for cancer diagnosis
- Histopathological analysis of samples
- Sensitivity 60 to 80% - specificity 95%
- False negative leads to repeated biopsies
- Most often: transrectal, US guided
- In France (resp. USA) $10^5$ (resp. $10^6$) biopsy series per year
Transrectal biopsies

- 2D transrectal ultrasound (TRUS) control
- Needle guide on the probe

TRUS probe with needle guide

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Biopsy targets

- McNeal’s 3-zone model: central zone (CZ), transition zone (TZ), peripheral zone (PZ)
- 68% of cancer can be found in peripheral zone
- Prostate cancer is generally not visible
  - systematic targets (12-core protocol)

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A robot what for?

- Increased accuracy in needle and/or ultrasound probe positioning
- Possible physical disconnection of needle and probe
- Aim: improved localization of the sample in the prostate for a better localization of the cancer

US-guided prostate brachytherapy

- Insert radioactive seeds into the prostate through the perineum

US guidance

Insert radioactive seeds into the prostate through the perineum.
Dose planning

- Planned dose: for instance 160Gy
- Dose constraints:
  - Prostate: $160\text{Gy} < D_{90} < 180\text{Gy}$ and $V_{100} > 85\%$
  - Urethra: $D_{30} < 240\text{Gy}$
  - Rectum: less than $1.3\text{cc} > 160 \text{ Gy}$ and $D_{90} < 80\text{Gy}$

A robot what for?

- Increased accuracy in needle positioning
  - Replaces the template
  - Potentially enables doing more complex trajectories
- Possible automated seed injection
- Faster procedure
- Aim: improved dose delivery for a better control of cancer
Trajectory comparison

- **In today's clinics**
  - Standard transrectal biopsy access
  - Standard transperineal brachy access + possible biopsy access (rare)

- Two other possibilities
  - Rectum
  - Prostate
  - Perineum

Proposed systems

- **US or MRI guided** (one CT-guided)
  - Most often: US guided
  - MRI requires very specific design (very limited space, MR-compatibility) and has more limited availability
- **Most often**: transperineal access
- **Still few systems** clinical trials
- **Some very active groups**
  - Fitchinger et al. (JHU CISST ERC, Queens Univ.)
  - Stoianovici et al. (JHU, URObotics)
Transrectal access – US-guided

2dofs (probe) + 2dofs (sheath) + 2 manual dofs (needle) [Fichtinger – ICRA04]

3dofs RCM passive mech. (probe holder) + 1dof (trans.) [Fenster – SPIE08]

Mainly probe positioners

Transrectal access – MRI-guided

3dofs (sheath rot.+trans. plus needle trans.) [JHU – Fichtinger et al.]

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Transperineal access – US-guided

4dofs (needle) + 1dof (probe) [Davies07]

3dofs (probe) + 6dofs (needle pos. plus insert.) [Phee – ICRA05]

9dofs (gross pos.) + 9dofs (needle) + seed injector [Yu – MICCAI06]

Multi-needle (trans.+rot.) [Podder07]

5dofs (needle prepos.) + 2dofs (needle insert.) [Hungr09]

4dofs [Fichtinger – MedIA08]

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Transperineal access – MRI-guided

4dofs – PEEK, glass, graphite – pneumatic actuation

[Stoianovici – IEEE-TBME07]

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Transperineal access – MRI-guided (2)

5dofs + needle insert. + seed delivery
Pneumatic actuation

[Stoianovici – IEEE-TBME07]

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Robot registration
Transperineal access – CT-guided
[Stoianovici et al.]

A major issue: accuracy

- The prostate moves and gets deformed due to:
  - Bladder or rectal filling
  - Patient leg position
  - Patient breathing
  - Ultrasound probe constraint
  - Needle penetration*
  - Bleeding
- The needles may deflect

*in blue: especially for brachytherapy
Possible approaches

- Improved planning
  - Biomechanical modelling and simulation (tissues, needles, interactions)
- Improved control
  - Real-time image control
  - Active needle steering

Robot for renal puncture

- Objective:
  - To make the access to the kidney under fluoroscopic control easier
  - To increase accuracy, safety and to decrease duration
- Robot PAKY (Percutaneous Access to the KidneY) [Stoianovici et al.] (URObotics, JHU)
- Similar to the manual protocol
PAKY (cont’ed)

- Tests on 23 patients published [Su, Kavoussi et al.]
- Similar performances with/without the robot

Towards automation?

PAKY+RCM [Stoianovici et al.]

- Extra-dofs
CT-based renal puncture
[Stoianovici et al.]

Robot registration
[Taylor et al.]

Endoscope holders

- AESOP (JPL-Nasa + Computer Motion Inc.)
  - 4 active +2 passive DOFs
  - Voice control
  - More than 800 systems installed
- LER-Viky (TIMC + Endocontrol Medical)
  - 3 DOFs, <1kg, autoclavable
  - Several HCI (mini-joystick, voice control, tool tracking)
  - Validation: urologic and digestive surgery
  - EC marked in 2007, FDA approved in 2008
Conclusion

- A real clinical interest and a large potential impact
- Many systems studied and developed
- But still quite few of them clinically used
- Most attention given to the robot mechanical/kinematic design
- Still a lot to do regarding real-time image control