Medical Applications of Modern Physics

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Medical Physics

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A branch of applied physics concerning the application of physics to medicine

or, in other words

The application of physics techniques to the human health
Introduction to Medical Physics

- Physics discoveries
- Tools for physics applied to medicine
- Medical imaging
- CT
- PET and PET/CT
- Conventional radiation therapy
- Hadron therapy
The beginnings of modern physics and of medical physics

1895
discovery of X rays

Wilhelm Conrad Röntgen

1897
“discovery” of the electron

J.J. Thompson
The beginnings of modern physics and of medical physics

Henri Becquerel (1852-1908)

1896:
Discovery of natural radioactivity

1898
Discovery of polonium and radium

Thesis of Mme. Curie – 1904
α, β, γ in magnetic field

Hundred years ago

Marie Curie Pierre Curie
(1867 – 1934) (1859 – 1906)
Tools for (medical) physics: the cyclotron

1930

Ernest Lawrence invents the cyclotron

M. S. Livingston and E. Lawrence with the 25 inch cyclotron
The beginnings of modern physics and of medical physics

James Chadwick
(1891 – 1974)
The beginnings of modern physics and of medical physics

1932 – C. D. Anderson
Discovery of the positron

Layer of lead
Inserted in a cloud chamber
Tools for (medical) physics: the electron linac

1939

Invention of the klystron

1947

first linac for electrons
4.5 MeV and 3 GHz
Tools for (medical) physics: the synchrotron

1945: E. McMillan and V.J. Veksler

discover the
principle of phase stability

1 GeV electron synchrotron
Frascati - INFN - 1959

6 GeV proton synchrotron
Bevatron - Berkeley - 1954
CERN accelerators

Large Hadron Collider
7 TeV + 7 TeV
Start in 2008

In 1952 the “strong-focusing” method invented at BNL (USA) was chosen for the CERN PS
<table>
<thead>
<tr>
<th>TECHNIQUE</th>
<th>YEAR</th>
<th>ENERGY</th>
<th>PHYSICAL PROPERTY</th>
<th>IMAGING</th>
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<tbody>
<tr>
<td>RADIOLGY X RAYS IMAGING</td>
<td>1895</td>
<td>X RAYS</td>
<td>ABSORPTION</td>
<td></td>
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<tr>
<td>ECHOGRAPHY ULTRASOUND IMAGING</td>
<td>1950</td>
<td>US</td>
<td>REFLECTION TRANSMISSION</td>
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<tr>
<td>NUCLEAR MEDICINE RADIOISOTOPE IMAGING</td>
<td>1950</td>
<td>γ RAYS</td>
<td>RADIATION EMISSION</td>
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## Medical imaging

<table>
<thead>
<tr>
<th>TECHNIQUE</th>
<th>YEAR</th>
<th>ENERGY</th>
<th>PHYSICAL PROPERTY</th>
<th>IMAGING</th>
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<tr>
<td><strong>X RAYS COMPUTERIZED TOMOGRAPHY</strong></td>
<td><strong>CT</strong></td>
<td><strong>1971</strong></td>
<td>X RAYS</td>
<td><strong>MORPHOLOGY</strong></td>
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<td><strong>MAGNETIC RESONANCE IMAGING</strong></td>
<td>MRI</td>
<td>1980</td>
<td>RADIO WAVES</td>
<td><strong>MORPHOLOGY</strong>/FUNCTION</td>
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<tr>
<td><strong>POSITRON EMISSION TOMOGRAPHY</strong></td>
<td>PET</td>
<td>1973</td>
<td>γ RAYS</td>
<td><strong>FUNCTION</strong></td>
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<tr>
<td><strong>COMPUTERIZED TOMOGRAPHY</strong></td>
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<td><strong>POSITRON EMISSION TOMOGRAPHY</strong></td>
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</table>

**PET** 

**CT** 

**MRI** 

**PET**
Medical imaging

Monopol X-ray tubes were available in 1907 and some were modified to Kohler’s specification by 1914. (Courtesy: Siemens AG, Erlangen.)
Medical imaging: x-ray generator and image intensifier

X-ray tube

Image intensifier

[Diagram of an x-ray generator and image intensifier with labels for rotating anode, tungsten target, stator rotor, ball races, 6.3 V ac, 0 V, +100,000 V, electron beam, X-rays, fluorescent screen, X-rays from patient, 25 kV p.d., aluminum, zinc sulfide, lead glass viewing screen, anode, glass tube, light rays to viewer, electrons, focusing plates]
X-ray image versus CT scan

A conventional X-ray image is basically a shadow: you shine a “light” on one side of the body, and a piece of film on the other side registers the silhouette of the bones (to be more precise, organs and tissues of different densities show up differently on the radiographic film).

Shadows give an incomplete picture of an object's shape.

Look at the wall, not at the person. If there's a lamp in front of the person, you see the silhouette holding the banana, but not the pineapple as the shadow of the torso blocks the pineapple. If the lamp is to the left, you see the outline of the pineapple, but not the banana.
X-ray computerized tomography (CT)

This is the basic idea of computer aided tomography. In a CAT scan machine, the X-ray beam moves all around the patient, scanning from hundreds of different angles. The computer takes all this information and puts together a 3-D image of the body.
Volumetric CT

< 0.4 sec/rotation
Organ in a sec (17 cm/sec)
Whole body < 10 sec
Cardiac CT

DYNAMIC CT ACQUISITION

ECG

PHASES OF A CARDIAC CYCLE

VOLUME RENDERED IMAGE OF HEART AND VESSELS

FUNCTIONAL PARAMETERS

- EJECTION FRACTION
- CARDIAC OUTPUT
- REGIONAL WALL MOTION
- ...

msec
Positron Emission Tomography (PET)

Cyclotron

Radiochemistry

<table>
<thead>
<tr>
<th>ISOTOPES</th>
<th>Half-Life</th>
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<tbody>
<tr>
<td>11-C</td>
<td>20.4 min, &quot;natural&quot;</td>
</tr>
<tr>
<td>13-N</td>
<td>10.0 min, &quot;natural&quot;</td>
</tr>
<tr>
<td>15-O</td>
<td>2.0 min, &quot;natural&quot;</td>
</tr>
<tr>
<td>18-F</td>
<td>109.8 min, &quot;pseudo-natural&quot;</td>
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J. Long, “The Science Creative Quarterly”, scq.ubc.ca

Pht@CERN2009

M. Silari – Medical Physics
Positron Emission Tomography (PET)

- **Coverage**: ~15-20 cm
- **Spatial Resolution**: ~5 mm
- **Scan Time** to cover an entire organ: ~5 min
- **Contrast Resolution**: depends on the radiotracer
PET functional receptor imaging

Normal Subject

Parkinson's disease

$[^{11}\text{C}] \text{FE-CIT}$

Courtesy HSR MILANO
PET coverage and axial sampling

**FIRST GENERATION PET**

1 SLICE – 2 cm

**CURRENT GENERATION PET**

> 40 SLICES – 6 mm
Axial FOV: 15 –20 cm
PET: total body studies
PET/CT scanner
PET/CT scanner

Courtesy HSR MILANO
PET/CT scanner

CT    PET

CT    PET

Courtesy HSR MILANO
18F-FDG PET/CT
Summary of accelerators running in the world

<table>
<thead>
<tr>
<th>CATEGORY OF ACCELERATORS</th>
<th>NUMBER IN USE (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy acc. (E &gt;1 GeV)</td>
<td>~120</td>
</tr>
<tr>
<td>Synchrotron radiation sources</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Medical radioisotope production</td>
<td>~200</td>
</tr>
<tr>
<td>Radiotherapy accelerators</td>
<td>&gt; 7500</td>
</tr>
<tr>
<td>Research acc. included biomedical research</td>
<td>~1000</td>
</tr>
<tr>
<td>Industrial processing and research</td>
<td>~1500</td>
</tr>
<tr>
<td>Ion implanters, surface modification</td>
<td>&gt;7000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>&gt; 17500</td>
</tr>
</tbody>
</table>

(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004
Three classes of medical accelerators

Electron linacs for conventional radiation therapy, including advanced modalities:

- Cyberknife
- IntraOperative RT (IORT)
- Intensity Modulated RT

Low-energy cyclotrons for production of radionuclides for medical diagnostics

Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u $^{12}\text{C}$-ions)
X-rays in radiation therapy: medical electron linacs

Electron Linac
3 GHz
6-20 MeV
[1000 x Röntgen]
Medical accelerators: electron linac

Varian Clinac 1800 installed in the S. Anna Hospital in Como (Italy)
CyberKnife (CK) Robotic Surgery System

6 MV Linac mounted on a robotic arm

- No flattening filter
- Uses circular cones of diameter 0.5 to 6 cm
- Non-Isocentric
- Average dose delivered per session is 12.5 Gy
- 6 sessions/day
- Dose rate @ 80 cm = 400 cGy/min

http://www.accuray.com/Products/Cyberknife/index.aspx
Intensity Modulated Radiation Therapy

An example of intensity modulated treatment planning with photons. Through the addition of 9 fields it is possible to construct a highly conformal dose distribution with good dose sparing in the region of the brain stem (courtesy of T. Lomax, PSI).

E. Pedroni, Europhysics News (2000) Vol. 31 No. 6
Intensity Modulated Radiation Therapy

Yet X-rays have a comparatively poor energy deposition

IMRT (Intensity Modulated Radiation Therapy)
with 9 crossing beams

Fraction of dose

Tumour between the eyes
Radiobiological effectiveness (RBE)

\[ \text{RBE} = \frac{D_{\text{x-ray}}}{D_{\text{particle}}} \]

Diagram showing survival vs. dose for particle and x-ray treatments.
Hadrontherapy: n, p and C-ion beams

- Hadrons are made of quarks
- Carbon ion = 6 protons + 6 neutrons
- Proton or neutron
- Quark “u” or “d”
- Electron “e”
Hadrontherapy

Charged hadrons have a much better energy deposition with respect to X-rays

200 MeV protons

4800 MeV carbon ions which control radioresistant tumours

[Dose Distribution Curve]

http://global.mitsubishielectric.com/bu/particlebeam/index_b.html
Proton radiation therapy
A NEW TOOL FOR CONTROLLING CANCER

The Loma Linda University Medical Center Proton Treatment Center is the first in the world to offer proton therapy, designed to treat certain tumors without harming surrounding healthy tissue. The center cost $40 million, took four years to design and build, and contains the world’s smallest synchrotron, built by Fermi National Accelerator Laboratory. It is as large as some hospitals, can serve up to 100 patients a 24-hour day, and is a model for worldwide training and research.

HOW A PROTON BEAM WORKS

The beam strikes the body at a low absorption rate and increases in intensity at a specific point, called the isocenter. As proton beams are focused on the tumor, naturally giving it the highest concentration of radiation, killing the cells of the tumor. Not only is the dose of radiation in normal tissue sharply reduced, compared to conventional radiation therapy, but the energy of the proton beam completely dissipates within the tumor, causing no damage to normal tissues beyond the tumor.

THE GANTRY

Three gagney-like structures can rotate around the patient and direct the proton beam to a precise point. Each gantry weighs about 90 tons and moves three inches at a time. The 35-foot-diameter gantries support the bending and focusing magnets to direct the beam, and have counterweights for extra radiation shielding.

THE INJECTOR

Protons are stripped out of the motion of hydrogen atoms and sent to the synchrotron.

SYNCHROTRON (ACCELERATOR)

The synchrotron is a ring of magnets, about 50 feet in diameter, through which protons circulate in a vacuum tube. As the magnetic field is increased, the energy of the protons is also increased. When the magnetic field reaches the value corresponding to a desired beam energy, the carbon is held constant while protons are slowly extracted from the ring. The beam is accelerated to a maximum energy of 180 million electron volts in one-quarter second and to maximum energy of 210 million electron volts in one-half second.

BEAM TRANSPORT SYSTEM

The beam transport system carries the beam from the synchrotron to the treatment room. This system consists of several bending and focusing magnets which guide the beam around curves and focus it to the desired spot size and location within the vacuum tube. The system maintains the size, position, and intensity of the beam at many points. If deviations from the prescribed parameters are sensed through the computer network, it will adjust the beam to keep track with the automatically shut off.
Acknowledgements

I am indebted to Ugo Amaldi (TERA Foundation and University of Milano Bicocca, Italy) and Maria Carla Gilardi (University of Milano Bicocca, Italy) for providing me with many of the slides that I have shown you today.

I also wish to thank David Bartlett (formerly Health Protection Agency, UK) for pointing me to the very interesting book shown on slide 14.