Tracking emissions during proton radiotherapy

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First things first
A long history...

‘If a candle was held behind his head, or the sun happened to be behind it, the cranium appeared semi-transparent and this was more or less evident until he attained his fourteenth year.’

Richard Bright, Guy’s Hospital, on a patient with hydrocephalus, 1831.
High attenuation

500 W m\(^{-2}\)

10\(^{-14}\) W m\(^{-2}\)
Optical absorption depends on haemodynamics

Oxygenated Blood

Deoxygenated Blood
Optical tomography

50mW laser. 80 MHz pulses interlaced at 780 nm and 815 nm

Helmet holding 32 sources and detectors onto the head

Microchannel plate photomultiplier tubes

Time-correlated single photon counting electronics
Forward model
Motor evoked responses
UCL optical topography system

32 laser diodes
- 16 at 775 nm
- 16 at 850 nm

16 detectors
Cortical response to heelprick in neonates
Cortical haemodynamics during neonatal seizures

Current research

- Neonatal epilepsy with Addenbrookes
- Psychology research with various collaborators
  - Autism
  - Language development
  - Effects of malnutrition on brain development
  - Adult intensive care
- Modular, wireless, wearable, portable system
Proton therapy
Intensity modulated radiotherapy
Depth dose curves

- 6 MV photons
- 24 MV photons
- 196 MeV protons

Percentage depth dose vs. Depth / cm
Passive scattering delivery

Normalized Dose Rate

BCM signal

Animation produced by Hassan Bentefour
Relative biological effectiveness changes with energy

Ashya King: NHS to fund Prague proton beam therapy

Ashya is undergoing treatment at the Proton Therapy Centre (PTC) in Prague.

The NHS has agreed to fund the care of brain tumour patient Ashya King who is undergoing proton beam treatment at a Czech clinic.

The five-year-old has been receiving post-operative radiotherapy at the Proton Therapy Centre (PTC) in Prague since 15 September.

In a statement, NHS England said it was "clearly best" he continued to be treated "uninterrupted".

His 30-session treatment is due to last six weeks.
1. **Cyclotron**
   Using electric fields, the cyclotron can accelerate the hydrogen protons to two-thirds the speed of light.

2. **Electromagnets**
   The magnets focus and route the proton beams to the gantry.

3. **Gantry**
   Each of the three gantries is three-stories tall and weighs 200,000 lbs.

Sources: University of Florida Proton Therapy Institute

Vu Nguyen / The New York Times
The challenge
Proton therapy requires knowledge of dose distribution relative to tumour and other organs.
Latest techniques use multiple, rapidly changing beams of photons or protons to conform to tumour
Current standard QA gives accurate point dosimetry
Imaging is necessary but not sufficient
The question:

Can we monitor emissions from a proton beam to provide 3D time-varying dosimetry?

Can we monitor emissions from a proton beam to provide 3D time-varying *in vivo* dosimetry?
Interactions of protons with tissue (=water)
Protons lose energy to orbital electrons

\[
\frac{dE}{dR} \propto \frac{1}{(\beta c)^2}
\]

Percentage depth dose

Depth / cm

Energy

Ionisation

Excitation
Protons scatter off nuclei elastically
Protons interact inelastically with nuclei

- Neutrons
- Radioactive decay
- Secondary ionisation
- Characteristic prompt gamma
Prompt gamma emission from excited nuclei

Prompt gamma emission from excited nuclei

Advantages

– Real time verification
– No additional dose
– Range accuracy ~1 mm

• Disadvantages

– Low signal from small, fast-moving beams
– Emissions stop 2-3 mm from Bragg peak
– Background noise from other emissions
Positron emission tomography

Offline PET

(a) Treatment planning dose distribution;
(b) Monte Carlo simulated dose distribution;
(c) Monte Carlo simulated PET distribution;
(d) PET measurement.
Positron emission tomography

Advantages
- Practical with existing equipment (online or offline)
- Range to 1-2 mm accuracy in some regions

• Disadvantages
  - Biological washout
  - Short half lives
  - Depends on elemental composition of tissue
  - Energy threshold for activation means no signal from Bragg peak
Cherenkov imaging

Brian Pogue and team at Dartmouth
http://cancer.dartmouth.edu/focus/Cherenkov_effect_Radiation_Oncology.html
Cherenkov imaging

Fast component.

From ionisations caused by prompt gamma (and neutrons)

Slow component.

From positrons
Particle Induced X-ray Emission
Particle Induced X-ray Emission

Scintillation
Scintillation
Protoacoustics

1. short laser pulse delivered through transparent US sensor
2. scattered photons diffusely illuminate target region
3. photons absorbed by tissue chromophores (e.g., in a tumour) resulting in 3D distribution of absorbed energy
Protoacoustics
BUT range is determined by low energy protons
Informing a model of proton interactions from measurements

Starting properties
- geometry
- physical properties
- beam parameters

Monte Carlo model of dose distribution

Update properties

Predict emissions

Measure emissions

Imaging

Error < threshold?

No

Yes

Dose distribution
It’s worse than that.

Informing a model of proton interactions from measurements

Starting properties
- geometry
- physical properties
- beam parameters

Monte Carlo model of dose distribution

Update properties

Predict emissions

Measure emissions

Imaging

Physical dose distribution

Model radiobiology

Error < threshold?

Biological dose distribution
"Sure he was great, but don't forget that Ginger Rogers did everything Fred Astaire did, ... backwards and in high heels."
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