Safety issues related to the Synchrotron Stereotactic Radiation Therapy project at the ESRF

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Brain Tumours

• Epidemiology:
  • 10 to 14 new cases/100,000/year
  • 65% are glioma
    High grade tumours - bad prognostic
    6 months life expectancy in 50% of cases

  Radiotherapy (MeV)
  50 Gy at the tumour’s location
  25 fractions @ 5/week
  Limited by tissue tolerance.

  Stupp et al. NEJM 2005

• 9% of adults cancerous diseases
• But high social and economic impact
• Dramatic decrease of life quality
• Third cause of cancerous death in the range 15-35 years old

Is there another means for increasing the dose delivered to the tumour while sparing the surrounding tissue?
CT-Therapy

• History:
  • 1980: Mello, Norman, Solberg, Iwamoto.  
    ‘Radiation dose enhancement with iodine’.
  • 1999: First CT-Therapy with patients using a modified CT scanner.

• Principle:
  • Tumor loaded with a high Z element.  
    (iodine, gadolinium, platinum, gold).
  • Beam size adjusted to the tumor dimensions.
  • Tumor positioned at the center of rotation.
  • Irradiation with kilo-Voltage X-ray beam.
without iodine

**Tomo-irradiation**
- beam height: 2 cm
- beam width: 2 cm

Isodose lines: red = 90%, green = 50%, blue=25%
iodine 10mg/ml

Tomo-irradiation
- beam height: 2 cm
- beam width: 2 cm

Isodose lines: red = 90%, green = 50%, blue=25%

34keV

50keV

85keV

6 MeV, no iodine
Dose distribution with increasing iodine concentration

Tomo-irradiation @ 85keV
- beam thickness: 2 cm
- beam width: 2 cm

Isodose lines: red = 90%, green = 50%, blue=25%

SSRT clinical trials at the ESRF

Monochromatic beam

Stereotactic:
→ rotation of medical chair

Flat X-ray beam:
→ vertical movement of chair
   → Dosimetry
   → Patient safety system
SSRT clinical trials at the ESRF

Clear definition of the responsibilities of ESRF and of the hospital. ESRF is responsible for:

- the characterisation of the irradiation facility in terms of absorbed dose in water (dosimetry protocol, following international standards).
- reproducing the irradiation conditions defined by the treatment planning software.

Fundamental principle adopted by ESRF for radiation therapy projects:

Irradiation facility should be a \textit{static} system, with no variable settings during irradiation.

\rightarrow SSRT done for a limited number of orientations (maximum 10).
\rightarrow For each orientation, treatment planning defines the 2D beam collimation: \rightarrow individual fixed collimators used for each orientation, rather than variable slit settings.
\rightarrow Coincidence” interlock on orientation angle and corresponding 2D collimator.
\rightarrow All motors inhibited (wiggler, slits, monochromators , ...).
SSRT clinical trials at the ESRF

Final configuration

Positioning of patient’s head
Positioning of 2D collimators

Presence switches

Position switches
Fabrication of 2D collimators

**CERROBEND or MCP 69**

Bi 49.4%; Pb 30.9%; Sn 12.1%; Cd 7.6%

Melting point: 69°C

Density 9.7 g/cm³

Mould for the fabrication of 10 collimators.

3-pin keyed
Angular positioning of medical chair

*Rotation arm*
(fixed to the rotation axis of the chair; located below the chair)
Dosimetry and characterisation of the X-ray beam and absorbed dose determination based on IAEA International Code of Practice no. 398 for dosimetry based on standards of absorbed dose to water:

1.3 Types of radiation and range of beam qualities

(b) Medium energy X rays with generating potentials above 80 kV and HVL of 2 mm Al.

80 keV X-rays:

\[
\frac{\ln(2)}{\mu_{\text{photo electric}} + \mu_{\text{compton}}} = 1.4 \text{ cm Al}
\]
Dosimetry and characterisation of the beam

Calibration of ionisation chambers:
Uniform broad radiation fields, with transverse dimensions much larger than the corresponding dimensions of the ionization chamber.

Use of ionisation chamber in a flat beam:
Can we still use the broad beam calibration factors of the ionisation chamber?
Dosimetry and characterisation of the beam

\[ D_{\text{calibration}} \propto D_{\text{beam}} \times \int S(z) \cdot dz \]
active volume

\[ D_{\text{calibration}} = C \times D_{\text{beam}} \times \int S(z) \cdot dz \]
active volume

constant scanning speed of ionisation chamber \( v_z \)

\[ D_{\text{measured}} = C \times D_{\text{beam}} \times \int S(z) \cdot dz \]
active volume

\[ \Delta z = z_{\text{beam}} \]

fixed vertical slits \( z_{\text{beam}} = h_{\text{slits}} \)

uniform radiation field

\[ D_{\text{measured}} = C \times \int \left( S(z) \times \int D_{\text{beam}} \cdot dt \right) \cdot dz \]
active volume

\[ \Delta t = \frac{z_{\text{beam}}}{v_z} \]

relative transverse position of the flat beam (mm)

\[ \phi_{\text{electrode}} = 1 \text{ mm} \]
Dosimetry and characterisation of the beam

Pencil-type beam

\[ F_0: \text{uniform differential fluence at } x = 0 \text{ (photons/cm}^2\text{/s)} \]

\[ T_{\text{pencil}}: \text{appropriate conversion factor (Gy}\cdot\text{cm}^2) \]

\[ D(x_0, y_0, 0) = F_0 \times T_{\text{pencil}}(x_0, y_0; y, z) \cdot dy \cdot dz \]

Uniform broad beam

\[ D_{\text{broad}}(x_0, y_0, 0) = F_0 \times \int \int T_{\text{pencil}}(x_0, y_0; y, z) \cdot dy \cdot dz \]

\[ D_{\text{broad}}(x_0, y_0, 0) = F_0 \times \int T_{\text{flat}} \Delta y (x_0, y_0; z) \cdot dz \]

\[ T_{\text{flat}} \Delta y (x_0, y_0; z) \cdot dz = dz \times \int T_{\text{pencil}}(x_0, y_0; y, z) \cdot dy \]
Dosimetry and characterisation of the beam

Scanning object + phantom through beam at constant speed $v_z$

$$D(x_0, y_0, 0, t) = F_0 \times T_{flat} \Delta y (x_0, y_0, z(t)) \times z_{beam}.$$  

$$D(x_0, y_0, 0) = \int_{\Delta t} D(x_0, y_0, 0, t) \cdot dt,$$

$$z(t) = z_0 + v_z \cdot t$$

$$dz = v_z \cdot dt$$

Broad beam field size:
- Horizontal: slits $\rightarrow \Delta y$
- Vertical: height of scan $\rightarrow \Delta z$

Absorbed dose under reference conditions:
- $x_0 \rightarrow$ IAEA: $z_{ref} = 2 \text{ g/cm}^2$
- $y_0 = 0$

Central axis depth dose:
- Different values of $x_0$
- $y_0 = 0$

Horizontal dose profiles:
- $x_0 = 0$
- Different values of $y_0$

Duality between broad beam dose rate and integrated dose from vertical scan through flat beam.
Dosimetry and characterisation of the beam

Example: horizontal dose profiles, measured in water phantom, for different depths and for different field sizes.

Vertical field size = scan interval

Horizontal field size defined by slits

ionisation chamber: PTW semiflex 31002
Dosimetry and characterisation of the beam

Example: horizontal dose profiles, measured in water phantom, for different depths and for different field sizes.

Horizontal field size defined by slits

Vertical field size = scan interval

ionisation chamber: PTW semiflex 31002
Dosimetry and characterisation of the beam

Example: percentage depth profiles measured in water phantom.

Vertical field size = scan interval

Horizontal field size defined by slits

ionisation chamber: PTW semiflex 31002
Dosimetry and characterisation of the beam

Treatment planning software
For each orientation:
- 2D beam profile
- Dose to tumour
  → Corresponding absorbed dose in water at reference depth

\[ D_{2D	ext{ beam}}(x_0, 0, 0) = F_0 \times \int_{z_{\text{min}}}^{z_{\text{max}}} \left( \int_{y_{\text{min}}(z)}^{y_{\text{max}}(z)} T_{\text{pencil}}(x_0, 0; y, z) \cdot dy \right) \cdot dz \]

\[ D(x_0, 0, 0, t) = F_0 \times z_{\text{beam}} \times \int_{y_{\text{min}}(z)}^{y_{\text{max}}(z)} T_{\text{pencil}}(x_0, 0; y, z(t)) \cdot dy \]

\[ D(x_0, 0, 0) = F_0 \times \frac{z_{\text{beam}}}{v_z} \times \int_{z_{\text{min}}}^{z_{\text{max}}} \left( \int_{y_{\text{min}}(z)}^{y_{\text{max}}(z)} T_{\text{pencil}}(x_0, 0; y, z(t)) \cdot dy \right) \cdot dz \]

\[ D(x_0, 0, 0) = \frac{z_{\text{beam}}}{v_z} \times D_{2D	ext{ beam}}(x_0, 0, 0) \]
Dosimetry and characterisation of the beam

Dose measurement with thimble ionisation chamber

\[ D(x_0,0,0) = \frac{\bar{z}_{beam}}{v_z} \times D_{2D beam}(x_0,0,0) \]

Interlock on integrated dose \( \rightarrow \) independent on \( z_{beam} \) and \( v_z \).

Transmission ionisation chamber

active part of ionisation chamber

beam
Treatment planning software (DOSISOFT)
- Orientation
- 2D beam profile
- Dose to tumour

Corresponding absorbed dose in water at reference depth

Dose measurement with thimble ionisation chamber

Online dose interlock from transmission ionisation chamber

Relative calibration of transmission ionisation chamber
Patient Safety System

The patient safety system is based on the patient safety system that was developed for the angiography clinical trials, which was approved by the French authorities:

- Redundant, relay based system, based on standard ESRF personnel safety systems;
- Use of fast relays for critical interlocks;
- Direct interlock to storage ring RF transmitters.

The existing system has been modified to take into account:

- The different irradiation orientations;
- The individual 2D collimator for each orientation;
- More precise integrated dose interlock:
  - Precision measurement of the vertical chair position;
  - Precision measurement of the vertical chair speed.
Patient Safety System

The only part of the patient safety system managed by software:

The integrated dose, predefined for each orientation, is obtained by adjusting the vertical speed of the chair, as a function of the exact intensity of the stored electron beam.

- Beam intensity read prior to start of irradiation:
  → Vertical speed of chair calculated and limits set;
  → Limits set for transmission ionisation chambers.

- “Confirm stable beam” in the patient safety system freezes these limits.

- If irradiation not started within 1 minute, irradiation is aborted.
Patient Safety System

Key
Safety Group
24 V

Key
ID17

Patient Mode

Not
Key
Safety Group

Not
Key
ID17

Test Mode

Patient mode

not
Test mode

SSRT hutch
interlock no. 1

SSRT hutch
interlock no. 2

Ionisation
chamber

Confirm
Stable beam

Scan ready

Scan
button

holding volts:
Hutch search
Scan emergency stop
Not scan completed

Scan ready

Scan slow safety

Not
Key
ID17

ID17

v

z

Vz
Patient Safety System

24 V

Test mode

Not Patient mode

Slow scan safety

Dose Monitor

Mode

Irradiation

Not
Imaging mode

Y' centred

Vertical speed chair

Collimators high position

Collimators coincidence interlock

Safety belt

Vertical chair position

Imaging mode

Not
Irradiation mode

Y' off-centred

Rotation speed chair

Collimators Low position

Fast interlock

storage ring RF

0 V

Rotary shutter closed

Guillotine shutter no. 1 closed

Guillotine shutter no. 2 closed

Patient Safety System

vz
Patient Safety System

24 V

Test mode

Patient mode

Slow scan safety

Dose Monitor

Mode

Not

Imaging mode

Y' centred

Vertical speed chair

Collimators high position

Collimators coincidence interlock

Safety belt

Vertical chair position

Imaging mode

Not

Irradiation mode

Y' off-centred

Rotation speed chair

Collimators Low position

Permit guillotine shutter

Test mode

Not

Patient mode

Slow scan safety

Dose Monitor

Mode

Imaging mode

Y' centred

Vertical speed chair

Collimators high position

Collimators coincidence interlock

Safety belt

Vertical chair position

Imaging mode

Not

Irradiation mode

Y' off-centred

Rotation speed chair

Collimators Low position

Permit Rotary shutter

0 V

0 V
Patient Safety system

Central cubicle of SSRT patient safety system during initial testing

Fast relays
Evaluation of the radiological risk

Energy of X-rays: around 80 keV, quasi-monochromatic spectrum.

Measured dose rate: 2.6 mGy/s/mA.

→ Dose rate at 200 mA: 520 mGy/s.
→ Dose rate at 300 mA: 780 mGy/s.

Reaction time in case of problem (e.g. sudden stop of chair): 5 ms.

• 5 ms: already achieved during angiography clinical trials;
• Development on safety systems foreseen to reduce this reaction time down to 2 ms.

5 ms:
- 520 mGy/s → 2.6 mGy over-dose on max. surface of 30 x 1 mm².
- 780 mGy/s → 3.9 mGy over-dose on max. surface of 30 x 1 mm².

Annual limit for equivalent dose to skin for the public: 50 mSv
→ 5 ms delay: accidental dose <1/10 annual limit.

For comparison:
Dose rate during angiography clinical trials: 12.5 Gy/s (at 200 mA).
Planning

Approval of medical protocol by ethical committee

- Submission June 2009
- Approval expected before summer 2009

Approval from French Nuclear Authorities

- Simultaneous submission to
  - ASN (Autorité de Sûreté Nucléaire)
  - AFSSAPS (Agence Française de Sécurité Sanitaire des Produits de Santé)
- First contacts in 2008 (ASN) and 2009 (AFSSAPS)
- Submission August 2009
- Approval expected end 2009

Treatment planning software

- Commissioning from July 2009 onwards

Patient Safety System

- Installation August 2009
People involved

Medical Investigators

- Pr Jacques BALOSSO, oncology radiotherapy
- Pr Jean François LE BAS, radiology
- Pr François ESTEVE, biophysics
- Pr Emmanuel GAY, neurosurgery
- Pr François BERGER, neuro-oncology
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