Radiological Protection in Ion Beam Radiotherapy

A Practical Guidance for Clinical Use of New Technology

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Outline

- Know about ion beam radiotherapy
- Key factors for radiological protection
- Preventing accidental exposure
- Recommendations

This presentation has neither been approved nor endorsed by the Main Commission of ICRP

Introduction

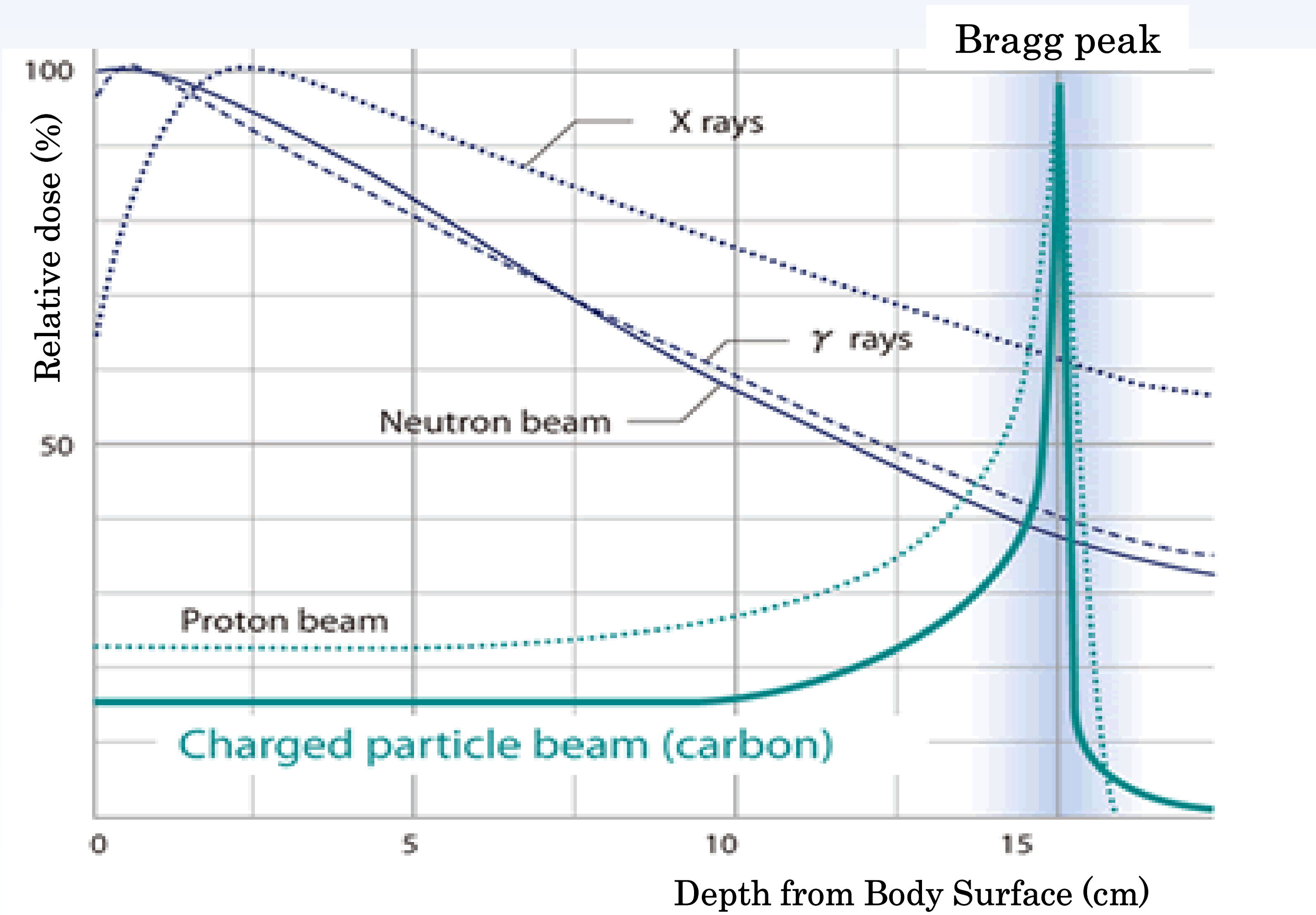
- **Remarkable progress in radiotherapy (RT) in terms of increased applicability and improved outcomes.**
- **Rapid advances in RT require practical guidance for radiological protection in patients and staff.**

  Publication 86: prevention of accidental exposure of RT.
  Publication 112: focus on new technologies in external RT.
- **Ion beam RT, which can improve dose conformation to target volume with better sparing of normal tissue, requires complex treatment system, and appropriate training and suitable quality assurance programme are recommended in *Publication 127*.**

Ion Beam Radiotherapy

- The clinical use of ion beams, such as protons and carbon ions, provides precise dose distributions due to their finite range in tissue, resulting in significant reduction in radiation exposure to uninvolved normal tissues.
- The clinical advantage of ion beam RT results from the manner in which protons and carbon ions lose their energy in tissue. Much of their energy is lost near the end of their range in tissue. This peak of energy loss or stopping power is called the Bragg peak. This physical phenomenon is exploited in ion beam RT of cancer to achieve a higher absorbed dose within the tumour than in the surrounding healthy tissues.

Physical Characteristics

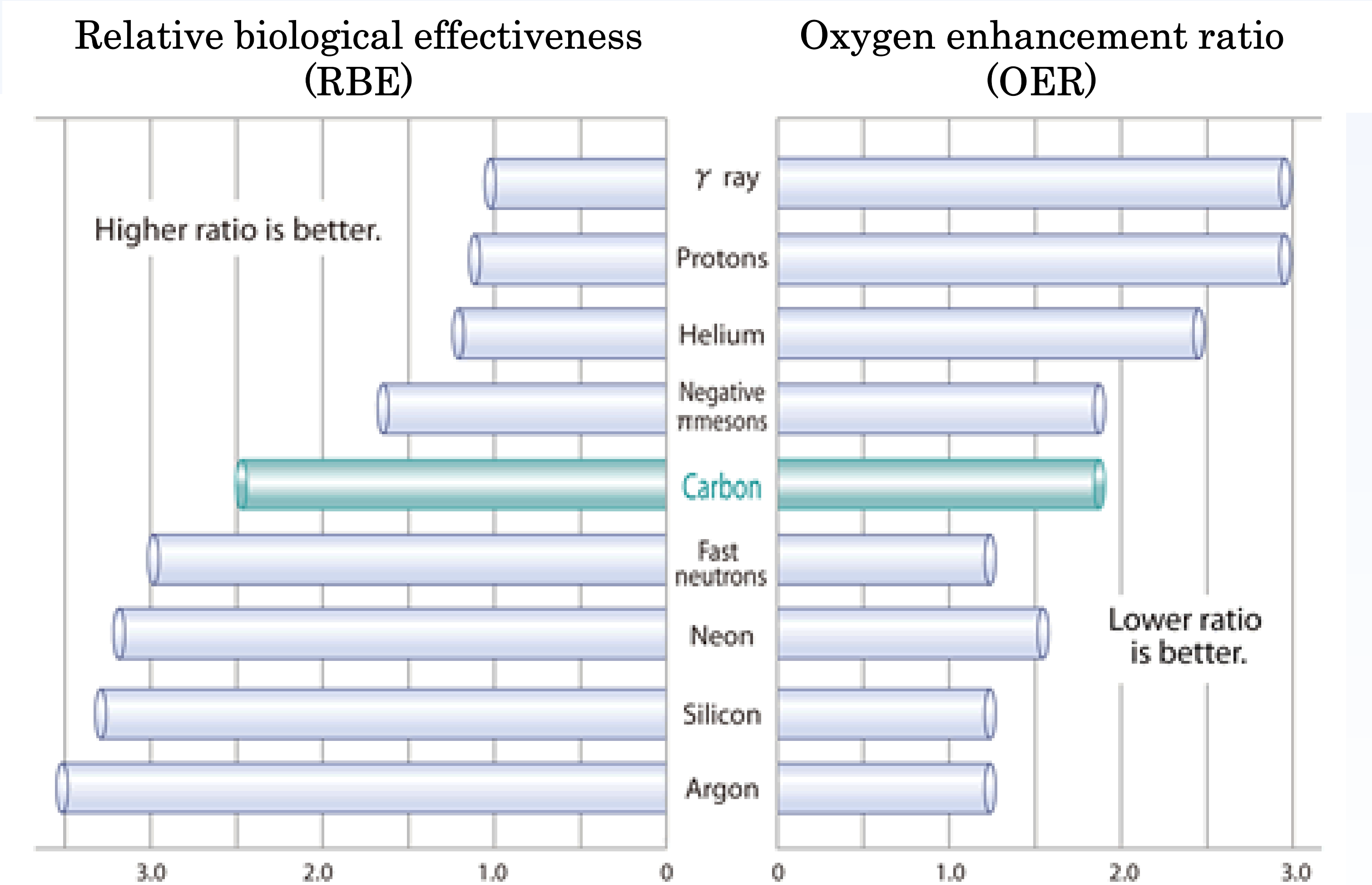


Modified from NIRS web site http://www.nirs.go.jp/ENG/core/cpt/cpt01.shtml

Biological Effects

- The relative biological effectiveness (RBE) values tend to increase with increments of stopping power, linear energy transfer (LET), up to a maximum value before declining.
- Clinically used proton beams are low-LET radiations, hence the RBE values are very close to that of high energy X-rays.
- For a given biological endpoint, carbon ions have higher RBE values than protons and increase with depth and have their maximum near the depth where the Bragg peak occurs.

Biological Effects



Modified from NIRS web site http://www.nirs.go.jp/ENG/core/cpt/cpt01.shtml

Beam Delivery System

- **Broad beam**

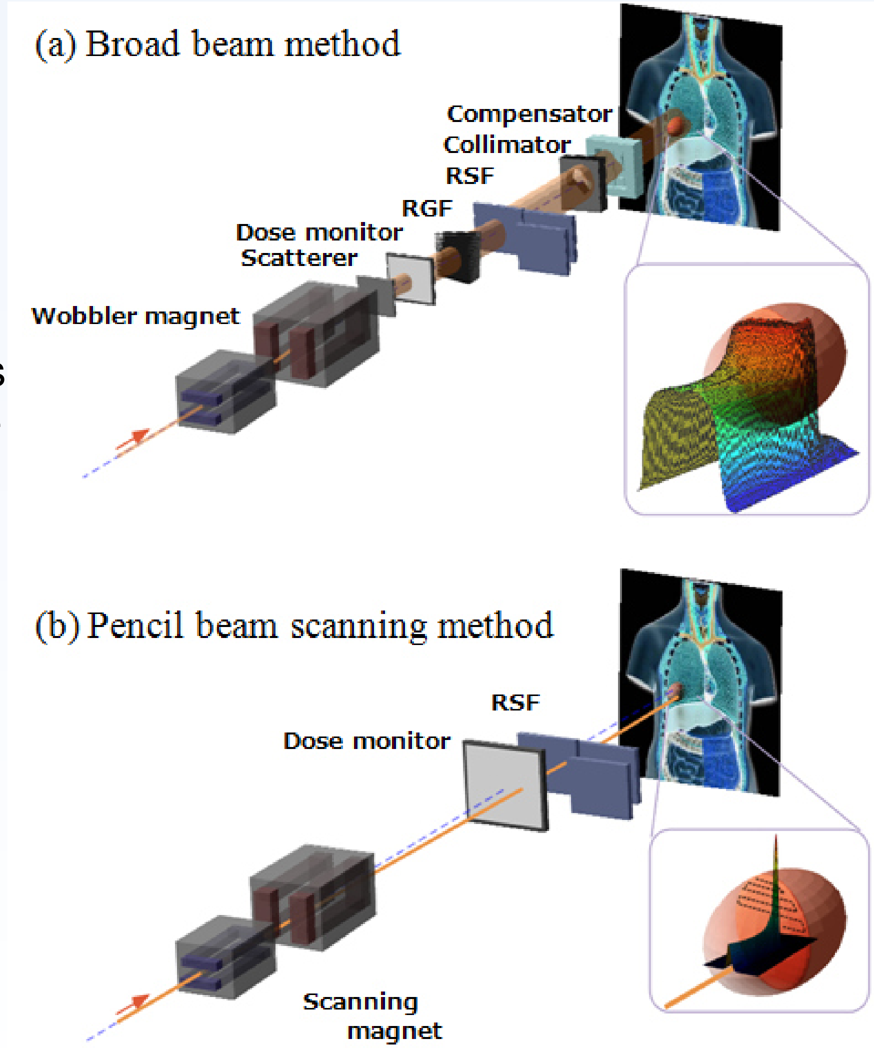
  a narrow pencil beam is broadened uniformly in the lateral and depth directions and part of the expanded uniform beam is clipped to conform to high-dose region to the target tumour volume in a patient's body.

  The beam efficiency is low (30%), and there is a beam loss at every device used to modulate and shape the beam. Those points can be production sources of undesirable radiation such as neutrons.

- **Scanning beam**

  achieve a highly conformal field by three-dimensional scanning of a pencil beam within the target tumour volume.

  The method is characterized by high beam efficiency (almost 100%), and therefore is low production of neutrons.



(ICRP Publication 127, 2014)

Beam Delivery and Radiation

- An ion beam delivery system generally consists of an accelerator, a transport beam line and an irradiation system, where dose is delivered to the patient with either a narrow beam (pencil beam scanning method) or a broadened beam (broad beam method).
- When ion beams pass through or hit these beam line structures, secondary radiations including neutrons are produced, and some of the particles in the structures can become radioactive and form an auto-radioactive component of the beam.

Characteristics of Ion Beam RT

- **Sophisticated procedures**
  a. **Maintenance of high energy accelerator**
  b. **High precision beam delivery**
  c. **Variable RBE (carbon)**
  d. **Treatment planning**
  e. **Immobilization of patient / respiratory gating**

- **New problems**
  a. **Activation of equipment, air, patient (protection)**
  b. **Verification of irradiation (dose)**
  c. **Change of tumor size / shape during treatment (dose)**

Clinical Target

- Selection of the patient based on the benefits of ion beam RT considering possible harmful effects.

- Locally advanced solid tumour with defined border to remove the lesion without surgery.
- Carbon ion RT provides additional advantage for the tumour resistant to photon RT or chemotherapy.

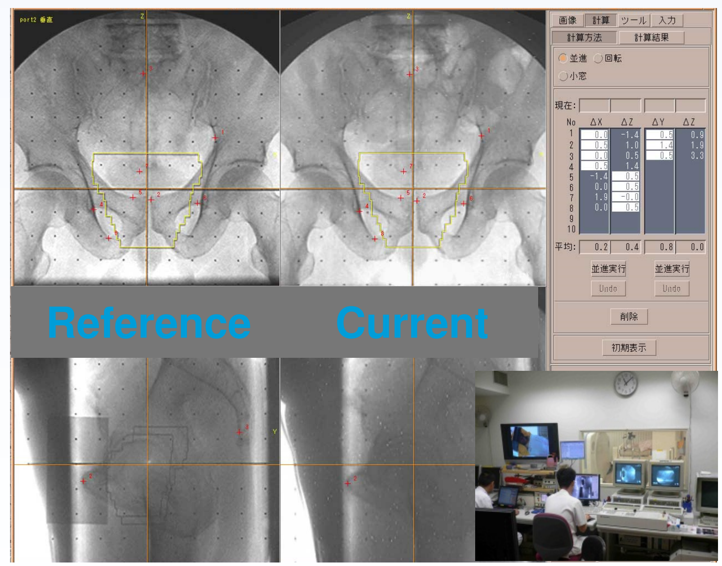
- Not appropriate for tumours in the wall of digestive tracts, such as stomach or colon (except for recurrent colon cancer), due to the unexpected movement and possible perforation of the wall.
- Not advised for patients with extended metastases.

General Treatment Process

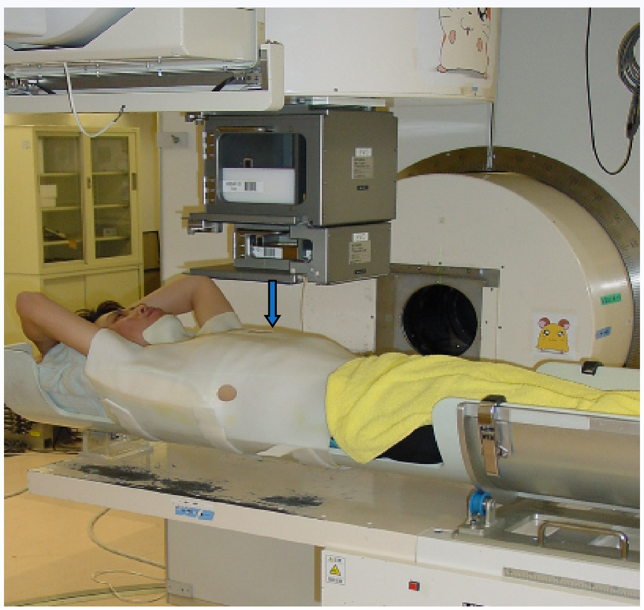
Immobilization

Planning CT

Treatment planning



Patient positioning



Beam delivery

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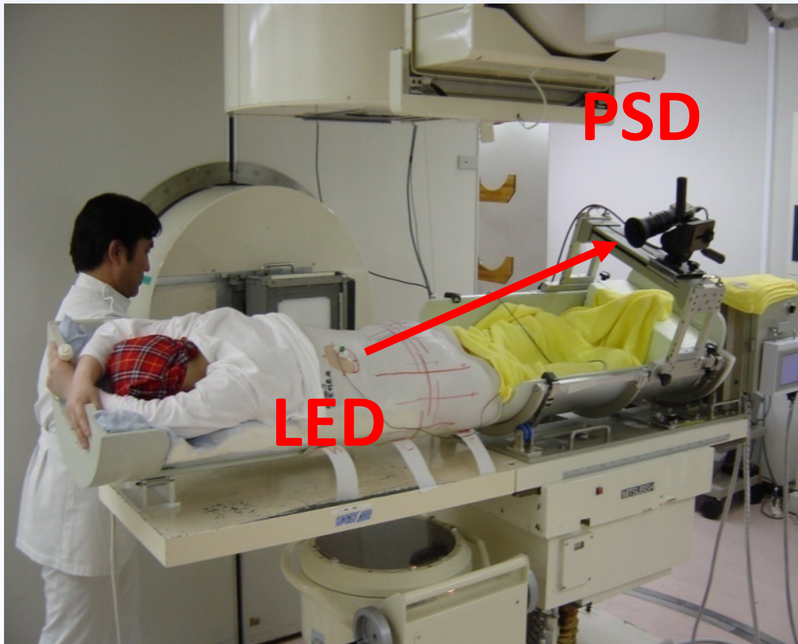
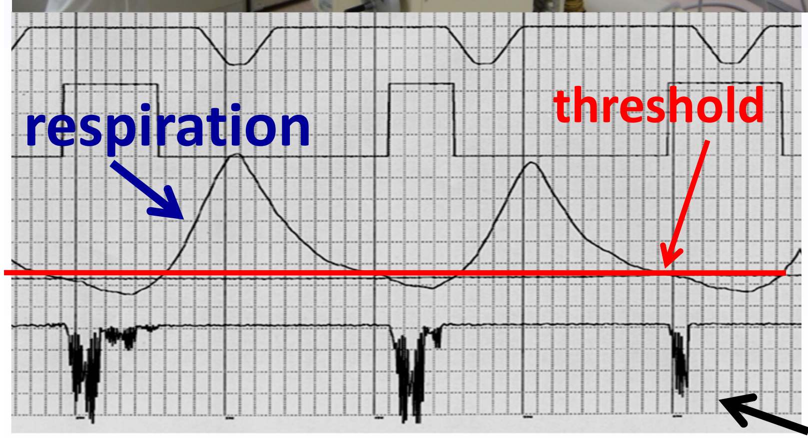
Treatment Planning

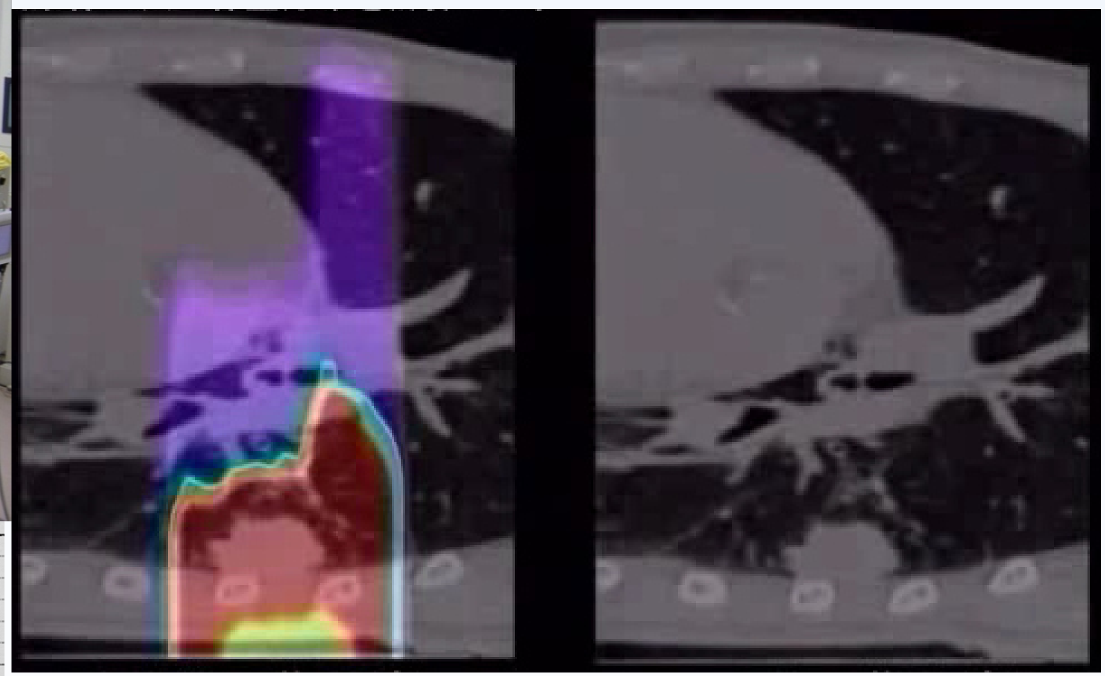
- Careful treatment planning is required for optimisation to maximise the efficiency of treatment and minimise the dose to normal tissues, and depends on the treatment method and the targeted tumour.
- Theoretically, ion beam radiotherapy delivers radiation dose more efficiently to the target volume than conventional radiotherapy while minimising the undesired exposure to normal tissues. Nonetheless, the treatment planning must be sufficiently precise to avoid damaging the critical organs or tissues within or near the target.

Respiratory Gating Treatment





Lung cancer



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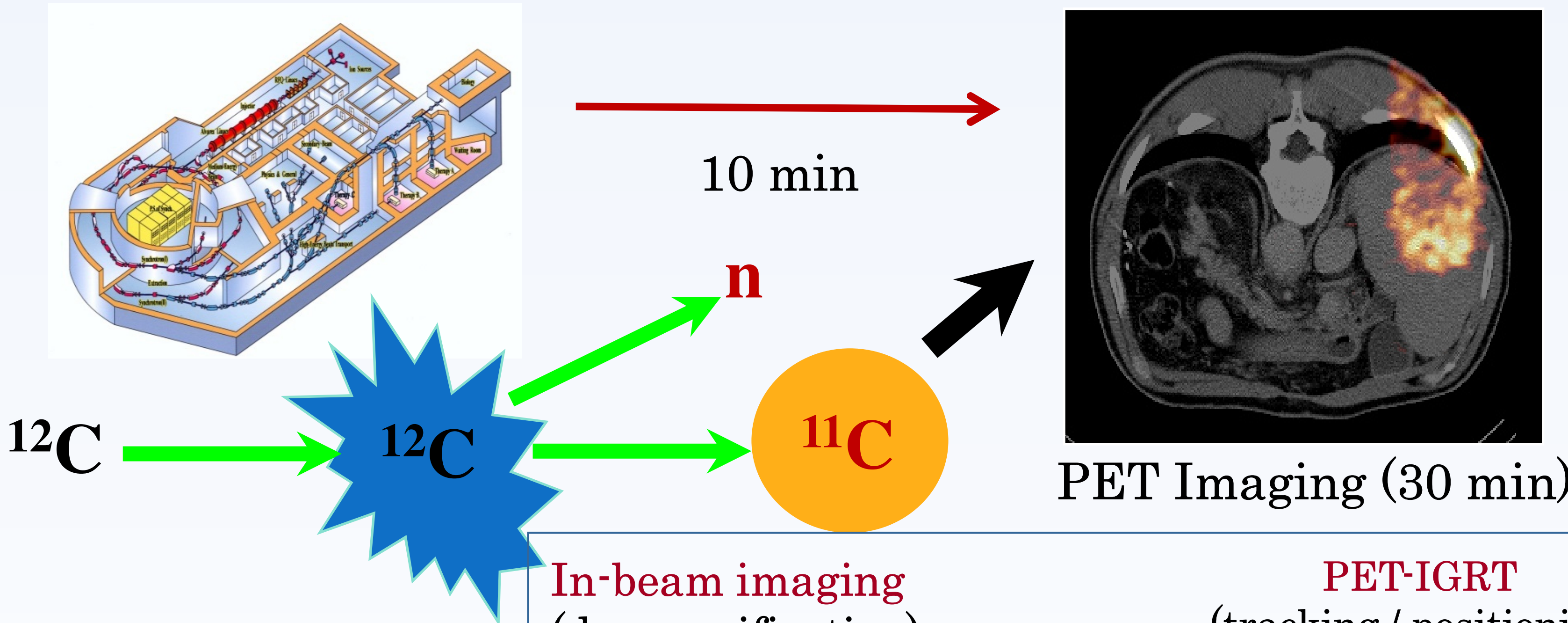
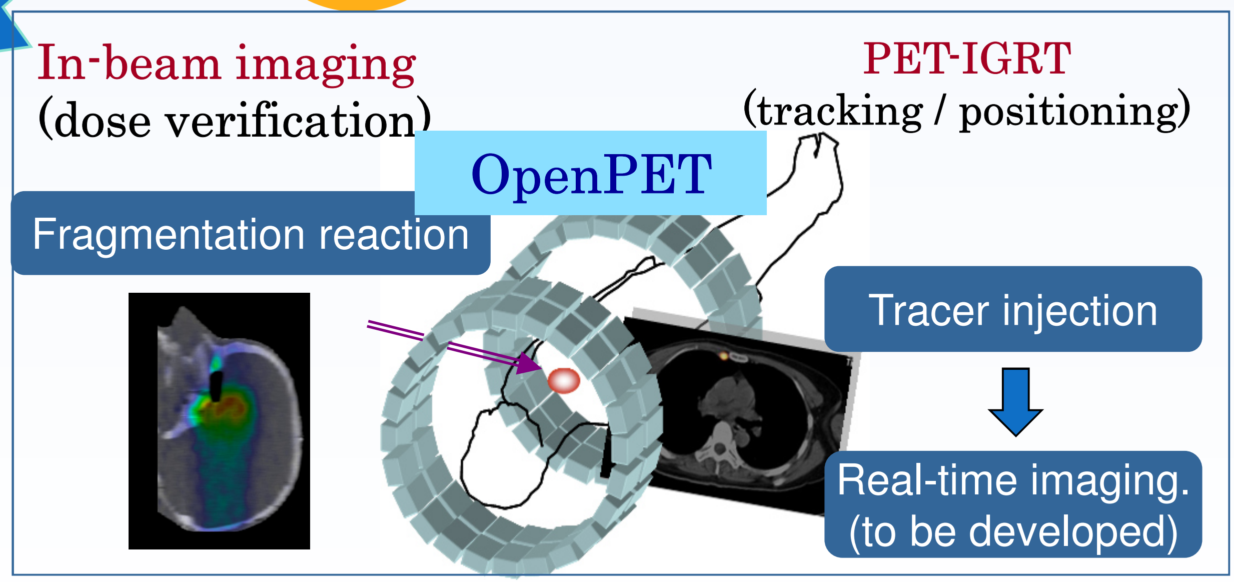
Auto-activation PET for Dose Verification





The OpenPET geometry:
original idea to visualize physically open field-of-view.
[Yamaya et al, PMB 2008].

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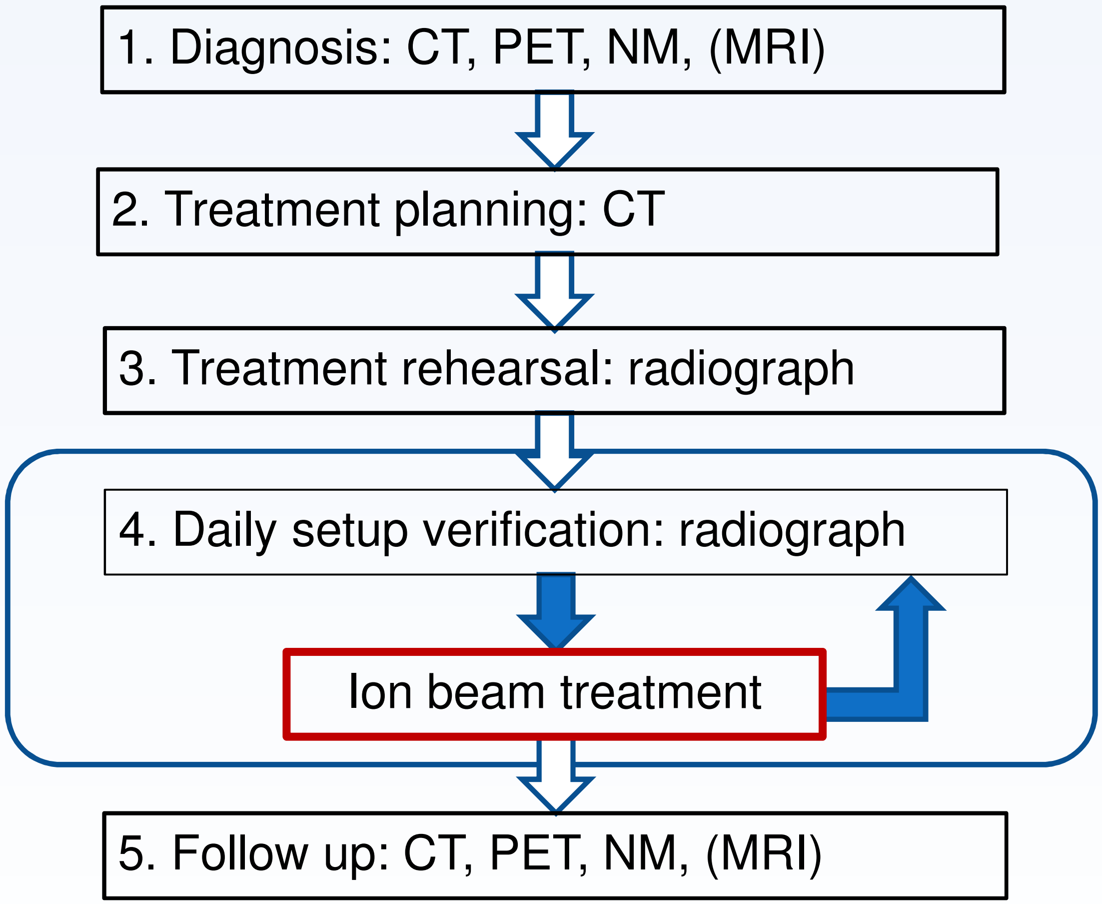
Dose in Out-of-field

- Doses in the out-of-field volumes arise from the secondary neutrons and photons, particle fragments, and photons from activated materials.
- These undesired but unavoidable doses should be considered from the standpoint of radiological protection.
- Secondary neutrons are the major contributor to absorbed dose in the areas distant from the treatment volume.
- The pencil beam scanning method can minimise this type of radiation exposure.

Medical Exposure from Imaging



Management of Equipment and Air

- Appropriate management is required for the therapy equipment and also for the air in the treatment room which is activated.
- Management should always be in conformity with criteria of the regulatory agency.
- The current regulations for occupational exposures in photon radiotherapy are applicable to ion beam radiotherapy with protons or carbon ions.

Patients and Family

- After the treatment with ion beams, the patient will be slightly radioactive for a short time. However, radiation exposure to family members of the patients and caretakers as well as to the public due to this activation is negligible, and no specific protection procedures are required.
- Thus the methods of radiological protection for public exposures in photon radiotherapy facilities are applicable to and adequate for ion beam radiotherapy facilities.

Strategy for Radiological Protection

- **Optimize the treatment**
  - Provide sufficient dose to the target tumor.
  - Minimize the effects in surrounding normal tissues.
- **Safety culture to avoid accidental exposure**
  - New methods are associated with complicated procedures.
  - Biological effects appear in the later period.
- **Need for long term follow up of the late effects**
  - Longer survival of the patients increases the risk of second malignancy.
  - "Low dose" exposure in large area of normal tissues
- **Protection of personnel**
  - Activation of equipment, air, and patient.

Radiation Safety Management

- **Radiation safety management for the facilities**
- **Management of exposure due to activation of devices**
- **Management of radioactivity due to activated nuclides**
  - Monitoring air concentration
  - Discharge of air from the radiotherapy facilities
  - Management of solid waste
  - Patient
- **Monitoring system for management of radiological protection**
- **Quality assurance in management of radiological protection of the facilities**

Preventing Accident

- New technologies in RT brought highly conformal dose distribution, but even subtle errors during the treatment process would easily bring severe consequences.
- In order to avoid such accidental exposures, there is a need for prospective, structured and systematic approaches to the identification of system weakness and the anticipation of failure modes.
- Since ion beam RT requires large accelerator and more complex treatment system, appropriate training of the staff and suitable quality assurance programmes are essential to avoid possible accidental exposure to the patient.

Conclusion and Recommendations

- Ion beam radiotherapy provides excellent dose distribution to the targeted tumour, and the proper selection of the patient should be the first step for justification of the treatment to provide the optimal benefit to the patient.
- Careful treatment planning is required for optimisation to maximise the efficiency of treatment and to minimise the dose to normal tissues. The treatment planning must be sufficiently precise to avoid damaging critical organs or tissues within or near the target volume.
- Ion beam delivery system consists of accelerator, high energy beam transporter and irradiation system. When ion beams pass through or hit these beam line structures, secondary neutrons and photons can be produced, as well as particle fragments and photons from the activated materials. These doses should be considered from the standpoint of radiological protection.

Conclusion and Recommendations

- Appropriate management is required for the therapy equipment and also for the air in the treatment room which is activated. After the treatment, the patient is also a radioactive source for a short period. However, radiation exposure to family members or public is small, and no specific care is required.
- Ion beam radiotherapy requires complicated treatment system, and extensive training of the staff and adequate quality assurance programme are recommended to avoid possible accidental exposure to the patient.
- Incorporating lessons from past accidental exposures into training is crucial to prevent reoccurrence. A number of generic lessons in photon radiotherapy may be applicable to ion beam radiotherapy. This retrospective approach should be complemented with prospective methods for identification of system weaknesses and their prevention.

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