Radiation protection issues in practice of pediatric radiotherapy

Ehab M. Attalla; PhD
National Cancer Institute;
Cairo University
Introduction

- Radiation protection, is defined by the International Atomic Energy Agency (IAEA) as "The protection of people from harmful effects of exposure to ionizing radiation, and the means for achieving this". Exposure can be from a source of radiation external to the human body.
BASIC FRAMEWORK OF RADIATION PROTECTION

- Principles of radiation protection and safety upon which the radiation safety standards are based are those developed by the ICRP.

- A practice that entails exposure to radiation should only be adopted if it yields sufficient benefit to the exposed individuals or to society to outweigh the radiation detriment it causes or could cause. This means the practice must be justified.

- Dose limits are not applicable to medical exposures resulting from diagnostic procedures applied in diagnosis of disease or therapeutic procedures applied in treatment of disease.
Radiation protection in radiotherapy…

I. Equipment Design

1. Protection of the patient during treatment
   ▪ Equipment shielding
   ▪ Collimation system
   ▪ Patient comfort & control

2. Protection of others
   ▪ Room shielding

II. Treatment Planning

Treatment planning concepts
   ▪ Planning process overview
   ▪ Patient data required for planning
   ▪ Machine data required for planning
   ▪ Basic dose calculation

Computerized treatment planning
   ▪ Treatment Planning commissioning & QA

Where?

III. Dosimetry

▪ Dose treatment outcome and should be controlled within 5%
▪ Calibration traceability: qualified experts & appropriate Protocols
▪ In vivo dosimetry & external audits

IV. Verification & Reporting

▪ Prescription & reporting
   ▪ Sources of uncertainty
   ▪ Methods to verify dose delivery
     ▪ CBCT / EPID
     ▪ In vivo dosimetry

Recent Advancement in Radiation Medicine, Kuwait; 26-28 Jan., 2020
Optimum radiation energy to use for each treatment site

Megavoltage %DD

<table>
<thead>
<tr>
<th>Energy</th>
<th>Surface</th>
<th>$D_{\text{max}}$</th>
<th>Depth 10 cm</th>
<th>Depth 20 cm</th>
<th>HVL mm</th>
<th>decrement</th>
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<tbody>
<tr>
<td>Cobalt-60</td>
<td>25 %</td>
<td>0.5</td>
<td>55</td>
<td>25</td>
<td>11</td>
<td>4.5% /cm</td>
</tr>
<tr>
<td>4 Mv</td>
<td>22 %</td>
<td>1.0</td>
<td>60</td>
<td>35</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>6 Mv</td>
<td>15 %</td>
<td>1.5</td>
<td>65</td>
<td>40</td>
<td>13</td>
<td>3.5% /cm</td>
</tr>
<tr>
<td>10 Mv</td>
<td></td>
<td>2.5</td>
<td></td>
<td>14.3</td>
<td></td>
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</tr>
<tr>
<td>18 Mv</td>
<td>14%</td>
<td>3.0</td>
<td>80</td>
<td>50</td>
<td></td>
<td>2% / cm</td>
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<tr>
<td>25 Mv</td>
<td>13%</td>
<td>4.0</td>
<td>81</td>
<td>55</td>
<td>13.7</td>
<td></td>
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</table>
## Optimum radiation energy to use for each treatment site

### Optimum energy versus site

<table>
<thead>
<tr>
<th>Site</th>
<th>Co-60</th>
<th>4MV</th>
<th>6MV</th>
<th>10-15MV</th>
<th>18MV</th>
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</thead>
<tbody>
<tr>
<td>Brain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head &amp; Neck</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lung</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lymphoma</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pancreas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole pelvis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pediatrics</td>
<td></td>
<td></td>
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<td></td>
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</table>
## Optimum radiation energy to use for each treatment site

### Optimum energy versus site

<table>
<thead>
<tr>
<th>Site group</th>
<th>Co-60</th>
<th>4-6 MV X-ray</th>
<th>8-12 MV X-ray</th>
<th>&gt;15MV X-ray</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head &amp; Neck</td>
<td>20%</td>
<td>55%</td>
<td></td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td>Gastro-intestinal</td>
<td>15%</td>
<td></td>
<td>20%</td>
<td>80%</td>
<td>5%</td>
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<tr>
<td>Gynecological</td>
<td></td>
<td></td>
<td></td>
<td>75%</td>
<td>5%</td>
</tr>
<tr>
<td>Breast</td>
<td>35%</td>
<td>30%</td>
<td>60%</td>
<td>35%</td>
<td>30%</td>
</tr>
<tr>
<td>Lymphomas</td>
<td>10%</td>
<td>90%</td>
<td></td>
<td>35%</td>
<td></td>
</tr>
<tr>
<td>Lung</td>
<td>10%</td>
<td>70%</td>
<td></td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>CNS</td>
<td>10%</td>
<td>50%</td>
<td></td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Bone</td>
<td></td>
<td></td>
<td>15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin &amp; Eye</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Different Situations: Childhood / Adult Cancers

Childhood Cancer Incidence
(2% of all cancers)

- Leukemia (25-30%)
- Brain
- Hodgkin’s disease (other lymphoid)
- Non-Hodgkin’s Lymphomas
- Bone/Joint
- Connective/soft tissue
- Urinary organs

Adult Cancer Incidence

<table>
<thead>
<tr>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate</td>
<td>Breast</td>
</tr>
<tr>
<td>Lung/Bronchus</td>
<td>Lung/Bronchus</td>
</tr>
<tr>
<td>Colon / Rectum</td>
<td>Colon/Rectum</td>
</tr>
<tr>
<td>Bladder</td>
<td>Uterus</td>
</tr>
<tr>
<td>Lymphomas</td>
<td>Ovary</td>
</tr>
<tr>
<td>Oral cavity</td>
<td>Skin Melanoma</td>
</tr>
<tr>
<td>Skin Melanoma</td>
<td>Cervix</td>
</tr>
<tr>
<td>Leukemia</td>
<td>Leukemia</td>
</tr>
</tbody>
</table>
Anesthesia is a safe and effective method of immobilizing children (uncooperative).
Patient preparation: Immobilisation / Fixation

- Immobilises body in same position every day
- Reduces day to day variation in treatment position (potential source of error)
- Impression of the patient in the optimum treatment position:
  - Baseboard or any immobilization device (vacuum mattress, knee & ankle rests,)
  - Sheet of thermoplastic (Orfit) moulded around body part, fixed onto baseboard

[Image of immobilization devices and a patient lying on a baseboard]
Patient preparation: Immobilisation / Fixation

Vacuum mattress
Treatment-Planning Process

2D/3D patient Image (CT, MRI, PET...)

Target, organ delineation (segmentation)

BEV field design (beam angle, aperture)

Plan optimization (# of beams, beam angle, energy, wedge, weight, intensity distribution)

Dose calculation

Plan evaluation (isodose display, TCP, NTCP)
CT Simulator
CT scans provides the planning system with extremely accurate anatomical information but does not always optimally visualize the tumor.

MRI scans can be used to provide a more detailed view of the tumor area, but requires additional process to be usable for planning.

CT and MRI data sets Aligned/Fused
Delienation I

- Margins are needed to account for uncertainties such as:
  - Motion during treatment
  - Daily variations of motion
  - Volume changes (growth, shrinkage)
  - Heart beating, GI-motion
  - Patient setup errors (3-5 mm)
Treatment-Planning Process: Image Segmentation

Manual segmentation

\{ \text{time-consuming} \}

Auto segmentation

\{ \text{review ??} \}

Contours drawn ......
PTV and PRV

Margins are not problematic

Overlapping margins force complicated tradeoffs in Optimization!
Treatment-Planning Process

Field Multiplicity and Collimation
Treatment-Planning Process: Plan Optimization

Isodose curves

Isodose surface

PTV
cord

eyes
Dose volume histograms (DVHs)

Dose display tools
Treatment-Planning Process: Plan Optimization and Evaluation

- Quantitative plan evaluation, DVH, homogeneity index (HI), conformity index (CI), conformity number (CN). Furthermore, radiobiological indexes like Niemierko’s EUD-based tumor control probability (TCP) and normal tissue complication probability (NTCP). Qualitative plan evaluation.
Effect of planning techniques on the normal tissue
All radiotherapy steps involve risk because even a small error in treatment planning, delivery, or dosimetry can lead to negative consequences.
Conclusions: The comparison between set-up error in EPID and MV-CBCT was not in favour of any of the two modalities. However, the two modalities were strongly correlated but fairly agreed and the differences between the shifts reported were small and hardly influenced the recommended planning target volume margin.

The additional dose to the patient from MV-CBCT study set with 5 MU at the isocenter of the treatment plan was 5 cGy. For EPID verification using two orthogonal images with 2 MU per image the additional dose to the patient was 3.8 cGy. These measured dose values were matched with that calculated by the TPS, where the calculated doses were 5.2 cGy and 3.9 cGy for MVCT and EPID respectively.
This study showed the range of systematic and random set-up errors during the course of radiotherapy treatment for pediatric patients.

The estimated PTV margin was relatively larger in chest, abdomen and pelvis sites compared to head and neck patients owing to the less tight fixation and higher possibility for tilting and rotation in non head and neck sites.
A system that can manage patient treatment schedules, treatment plans, treatment delivery, treatment summaries, and results is assured.

An oncology information system (OIS) can be used to manage these data.
IMRT in Pediatric Oncology- Current status

- 80% of centers adopted IMRT since 2000
- Most international pediatric protocols for CNS and other solid tumors allow the use of IMRT
- Indications, limitations and preliminary results are all with IMRT usage.
Conventional Craniospinal Irradiation Technique (Can be supine or prone)

Historically, CSI has been treated using 3D CRT consisting of opposing whole brain and posterior spinal fields. With the increased use of IMRT techniques in the clinic today, these patients can also be treated step-and-shoot IMRT, sliding window IMRT, volumetric-modulated arc therapy (VMAT).
Pretreatment quality assurance dosimetry film demonstrating a position of the cranial and spinal fields. The film verified the evidence of the lack of overlap between the 2 fields and matching the divergence of spinal field with the inferior border of the half-beam blocked cranial field.
Craniospinal Irradiation Technique
Three techniques: 3D, IMRT & VMAT
Craniospinal Irradiation Technique
Three techniques: 3D, IMRT & VMAT
Total Body Irradiation for Leukemia

Movement couch & Beam Zone Technique

- The TBI technique studied is an AP/PA treatment, patient lies on a table placed directly on the floor with source-to-skin distance (SSD) of 200 cm.
- Treatments are delivered using 6 MV photon beam, field size of 80 cm × 80 cm in extended SSD, with constant speed, constant dose rate 50 cGy/min and velocity.
- The prescribed dose is 12 Gy in five fractions 2.4 Gy per fraction delivered over five days. This technique uses a translating couch, and the velocities are optimized to deliver a uniform dose at patient midline along the craniocaudal midline axis (at the level of the umbilicus).
- The dose variation throughout the body between the measured and calculated dose should maintain within ±10% of the prescribed dose.
• The lungs dose must be reduced by (20 -25) % of the total prescribed dose due to the low lung density and due to scattered radiation from surrounding tissues.

• CT- localization is required in the treatment position for the determination of lung dose.

• Absorbed dose calculate d at the patients in (12) different regions ,

• the reference dose is specified as the total dose to mid abdomen dose in the level of the Umbilicus.
Lung shield calculation

- Dose reduction of the lung about (-20 %) of the total prescribed dose.
- Individually shaped partially transmitting shield of calculated thickness are used.
- Thorax wall separation, lung density, and mid lung separation are parameters for the lung shield thickness calculation can be measured from the CT localization.
- Verifying the calculated dose using INVIVO Dosimeter is mandatory.
IMRT- Potential Pitfalls

- Increased risk of “MARGINAL MISS”
- Less homogeneous dose distribution
- Higher total body dose (leakage through the collimator and internal scatter as a result of increased beam-on time)
- Potential increased risk of radiation-induced malignancies (from 1% to 1.75% at 10y)
- Lower biologic effective doses for longer treatment times
**CRITICAL REVIEW**

**INTENSITY-MODULATED RADIATION THERAPY, PROTONS, AND THE RISK OF SECOND CANCERS**

**Eric J. Hall, D.Phil., D.Sc.**

Center for Radiological Research, Columbia University Medical Center, College of Physicians and Surgeons, New York, NY

Intensity-modulated radiation therapy (IMRT) allows dose to be concentrated in the tumor volume while sparing normal tissues. However, the downside to IMRT is the potential to increase the number of radiation-induced second cancers. The reasons for this potential are more monitor units and, therefore, a larger total-body dose because of leakage radiation and, because IMRT involves more fields, a bigger volume of normal tissue is exposed to lower radiation doses. Intensity-modulated radiation therapy may double the incidence of solid cancers in long-term survivors. This outcome may be acceptable in older patients if balanced by an improvement in local tumor control and reduced acute toxicity. On the other hand, the incidence of second cancers is much higher in children, so that doubling it may not be acceptable. IMRT represents a special case for children for three reasons. First, children are more sensitive to radiation-induced cancer than are adults. Second, radiation scattered from the treatment volume is more important in the small body of the child. Third, the question of genetic susceptibility arises because many childhood cancers involve a germline mutation. The levels of leakage radiation in current LINACs are not inevitable. Leakage can be reduced but at substantial cost. An alternative strategy is to replace X-rays with protons. However, this change is only an advantage if the proton machine employs a pencil scanning beam. Many proton facilities use passive modulation to produce a field of sufficient size, but the use of a scattering foil produces neutrons, which results in an effective dose to the patient higher than that characteristic of IMRT. The benefit of protons is only achieved if a scanning beam is used in which the doses are 10 times lower than with IMRT. © 2006 Elsevier Inc.

Intensity-modulated radiation therapy, Passive modulation, Pencil beams, Protons, Second cancers.
Depth dose profiles of photons, protons, and carbon ions. Spread-out Bragg peaks (SOBP): several beams of closely spaced energies are superimposed to create a region of uniform dose over the depth of the target.
THE EFFECT OF INTENSITY-MODULATED RADIOTHERAPY ON RADIATION-INDUCED SECOND MALIGNANCIES


*William Buckland Radiotherapy Centre, Melbourne, Australia; †Monash University, Melbourne, Australia; and ‡Department of Radiation Oncology, Groote Schuur Hospital and University of Cape Town, Cape Town, South Africa

Purpose: To compare intensity-modulated radiotherapy (IMRT) with three-dimensional conformal radiotherapy (3D-CRT) in terms of carcinogenic risk for actual clinical scenarios.

Method and Materials: Clinically equivalent IMRT plans were generated for prostate, breast, and head-and-neck cases treated with 3D-CRT. Two possible dose–response models for radiocarcinogenesis were generated based on A-bomb survivor data corrected for fractionation. Dose–volume histogram analysis was used to determine dose and its distribution to nontargeted tissues within the planning CT scan volume and thermoluminescent dosimetry for the rest of the body. Carcinogenic estimates were calculated with and without a correction factor accounting for cancer patients’ advanced age and reduced longevity.

Results: For the model assuming a plateau in risk above 2-Gy single-fraction-equivalent (SFE), IMRT and 3D-CRT produced risks of 1.7% and 2.1%, respectively, for prostate; 1.9% and 1.8%, respectively, for nasopharynx; 1% each for tonsil; and 1.4–2.2% and 1.5–1.6%, respectively, depending on technique, for breast. Assuming a reduction in risk above 2-Gy SFE, risks for IMRT and 3D-CRT were 1.1% and 1.5%, respectively, for prostate; 1.4% and 1.2%, respectively, for nasopharynx; 1% each for tonsil; and 1.3–1.8% vs. 1.3–1.6%, respectively, for breast. Applying a correction factor of 0.5 for cancer patients halved these risks and their relative differences.

Conclusions: Carcinogenic risks were comparable in absolute terms between modalities. Risks are dependant on technique used. Risks with IMRT are influenced by monitor unit demand and are therefore software/hardware dependant. The dose–response model accounting for cell killing at higher doses fitted best with actual observed risks. © 2008 Elsevier Inc.

IMRT, Carcinogenesis, Late effects, 3D conformal radiotherapy, Second malignancy.
### Particle therapy facilities in a planning stage

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>WHO, WHERE</th>
<th>PARTICLE</th>
<th>MAX. ENERGY (MeV), ACCELERATOR TYPE, (VENDOR)</th>
<th>BEAM DIRECTION(S)</th>
<th>NO. OF TREATMENT ROOMS</th>
<th>START OF TREATMENT PLANNED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Australian Bragg Centre for Proton Therapy and Research (SA-HMRI), Adelaide</td>
<td>p</td>
<td>230, synchrotron, (?)</td>
<td>2 gantries, 1 fixed beam</td>
<td>3</td>
<td>2020</td>
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<tr>
<td>Argentina</td>
<td>Instituto de Oncologia Angel Rumo Hospital, Rosario, Buenos Aires</td>
<td>p</td>
<td>230, cyclotron, (IBA)</td>
<td>1 gantry</td>
<td>1</td>
<td>2010</td>
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<tr>
<td>Belgium</td>
<td>University Hospitals Wallonia, Charleroi</td>
<td>p</td>
<td>230, cyclotron, (IBA)</td>
<td>1 gantry</td>
<td>1</td>
<td>2020</td>
</tr>
<tr>
<td>China</td>
<td>Hong Kong Sanatorium and Hospital PTC, Shau Kei, Wan, Hong Kong</td>
<td>p</td>
<td>230 ? cyclotron, (?)</td>
<td>2? gantries</td>
<td>2?</td>
<td>2018?</td>
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<tr>
<td>China</td>
<td>Tianjin Taishan Cancer Hospital, Sino-US proton treatment &amp; research center, Tianjin</td>
<td>p</td>
<td>230, cyclotron, (?)</td>
<td>3 gantries</td>
<td>3</td>
<td>2018</td>
</tr>
<tr>
<td>China</td>
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<td>250, SC cyclotron, (Varian)</td>
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<tr>
<td>Egypt</td>
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<td>p</td>
<td>230, cyclotron, (IBA)</td>
<td>1 gantry</td>
<td>1</td>
<td>2020</td>
</tr>
</tbody>
</table>
COMMENTARY

Consensus Report From the Stockholm Pediatric Proton Therapy Conference

Daniel J. Indelicato, MD,* Thomas Merchant, DO, PhD,† Normand Laperriere, MD, FRCPC,‡ Yasmin Lassen, MD, PhD,§ Sabina Vennarini, MD,|| Suzanne Wolden, MD, FACR,¶ William Hartsell, MD,## Mark Pankuch, PhD,### Petter Brandal, MD, PhD,#### Chi-Ching K. Law, MD,## Roger Taylor, MD,### Siddhartha Laskar, MD,#### Mehmet Fatih Okcu, MD, MPH,||| Eric Bouffet, MD,&& Henry Mandeville, MBChB, MRCP, FRCR, MD,## Thomas Björk-Eriksson, MD, PhD,*** Kristina Nilsson, MD, PhD,*** Hakan Nyström, PhD,*** Louis Sandy Constine, MD,**** Michael Story, PhD,**** Beate Timmermann, MD,***** Kenneth Roberts, MD,****** and Rolf-Dieter Kortmann, MD*******

*University of Florida Health Proton Therapy Institute, Jacksonville, Florida; †St. Jude Children’s Research Hospital, Memphis, Tennessee; ‡Princess Margaret Cancer Centre/University Health Network, Toronto, Ontario, Canada; §Aarhus University Hospital, Aarhus, Denmark; ¶Agenzia Provinciale per la Protonterapia, Trento, Italy; ‡Memorial Sloan-Kettering Cancer Center, New York, New York; ‡Northwestern Medicine Chicago Proton Center, Chicago, Illinois; ***Oslo Universitetssykehus, Oslo, Norway; §§Queen Elizabeth Hospital, Hong Kong, China; ††Swansea University South West Wales Cancer Centre, London, United Kingdom; †††Tata Memorial Hospital, Mumbai, India; †††Texas Children’s Hospital, Houston, Texas; ‡‡The Hospital for Sick Children, Toronto, Ontario, Canada; ‡‡‡The Royal Marsden NHS Foundation Trust, London, United Kingdom; ***The Scandion Clinic, Uppsala, Sweden; ††††University of Rochester Medical Center, Rochester, New York; ‡‡‡‡University of Texas Southwestern Medical Center, Dallas, Texas; ‡‡‡‡‡Westdeutsche Protonentherapiezentrum, Essen, Germany; ‡‡‡‡‡‡Universitätsklinikum Leipzig, Leipzig, Germany

Received Apr 8, 2016, and in revised form May 26, 2016. Accepted for publication Jun 14, 2016.

According to the American Society for Radiation Oncology’s Model Policy published in 2014 (1), solid tumors in children are considered among the highest priority for proton therapy. Worldwide, there are currently 54 facilities offering proton therapy and 61 more under construction (2).

As the number of institutions proliferates, expert opinion is important in guiding safe and rational adoption and use of this technology in young patients. In June 2015, 24 international leaders in pediatric radiation oncology, pediatric oncology, medical physics, and radiobiology convened in
Conclusions

• RT is effective in increasing local control in several pediatric tumors, but it is often associated with severe late effects, including secondary tumors.
• The physical advantages of protons, which decrease the dose to healthy tissues, are promising in achieving significant clinical benefits.
• Dosimetric comparison studies pointed out the superiority of protons over photons in several tumor locations.
Children are more sensitive to radiation compared to adults. This shows that children have a 10% - 15% lifetime risk from radiation exposure while individuals above the age of 60 have minimal to no risk (due to the latency period for cancer and the person’s life expectancy).
The risk of secondary cancers attributable to verification imaging dose using MV-CBCT is very small compared to therapeutic dose using IMRT. Therefore, it is important to focus on the risk of secondary cancers attributable to therapeutic dose especially when using IMRT, where the produced leakage radiation is considerably high compared to some other techniques (such as conformal radiotherapy).
Challenges In Radiation Therapy

Dose of radiation is limited by Normal Tissues Tolerance
QUANTEC provided a comprehensive overview of dose volume-response relationships for adverse effects of radiation therapy in adults. Special attention for data on children treated with radiation therapy is needed, because of growth and development during radiation exposure as well as in the attained life span, the much longer life-expectancy for children.
A group of physicians (radiation and pediatric oncologists, subspecialists), physicists (clinical and modelers), epidemiologists who intend to critically synthesize existing data to:

• Develop quantitative evidence-based dose/volume guidelines to inform RT planning and improve outcomes
• Describe relevant physics issues specific to pediatric radiotherapy
• Propose dose-volume-outcome reporting standards to inform future RT guidelines.

IAEA
Challenges in RP issues in pediatric RT

- Normal tissue tolerance differences between children and adults
- Secondary Cancer Risk
- Dose from Verification: add/ subtract
- Concept about the Cancer patient with imaging modalities
Thank you