CONTRIBUTION OF COMPUTATIONAL DOSIMETRY TO THE MANAGEMENT OF RADIOLOGICAL ACCIDENTS

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Context

**RADIOLOGICAL ACCIDENTS AND MEDICAL MANAGEMENT**

- ~600 radiation overexposure accidents between 1980 and 2013 (from Coeytaux et al., 2015)
  - 2390 overexposed people – 190 died
  - 32% radiation therapy, 31% fluoroscopy, 27% industry
  - Most common type of irradiation: local or partial body irradiation

Medical management of victims of external exposure: priority to diagnosis

- Identification of potential victims
- Diagnosis
- Treatment

Small-scale accidents

Medium to large-scale accidents

Civil nuclear

Industrial applications

Medical use

Defense
MEDICAL MANAGEMENT AND DOSIMETRY

Dose is an indicator of tissue or organ damage that helps clinicians to:

- assess radiation-induced damage
- define the therapeutic strategy

Dosimetry challenge: assessment of the dose and the dose distribution within the body

Dosimetric needs and methods vary depending on the type of accident (whole body versus local irradiation, small versus medium/large scale accidents, ...
How to assess the dose?

CLINICAL DOSIMETRY

BIOLOGICAL DOSIMETRY

PHYSICAL DOSIMETRY

Dicentric chromosomes

FISH

Blood count

Individual dosimetry

Retrospective dosimetry (EPR, OSL, TL)

Dose reconstruction
Numerical dose reconstruction - principle

- numerical phantom
- modelling of the source and of the environment
- Monte Carlo code: particles transport
- absorbed dose assessment
Numerical dose reconstruction – Phantoms
**Diagnosis and definition of the therapeutic strategy – Medical need**

- **Whole body irradiation**
  - Key clinical issue: spontaneous secondary resumption of bone marrow activity?
    - Are there areas of bone marrow underexposed?
  - Support of computational dosimetry: heterogeneity of the dose distribution within the body, in particular at the level of the bone marrow areas

**No need for anatomical precision**

*Use of generic phantoms (stylized, voxel, MESH)*
**Diagnosis and definition of the therapeutic strategy – Medical need**

### Local irradiation

- **Tissue necrosis if dose > 25 Gy**

### Key clinical issue: surgery?

Is there any tissue irradiated at more than 25 Gy that needs to be removed?

### Support of computational dosimetry: to define the dose distribution at the lesion level

#### Need for anatomical precision

**Use of personalized voxel phantoms created from the victim’s images**

<table>
<thead>
<tr>
<th>Skin dose</th>
<th>5 Gy</th>
<th>10 Gy</th>
<th>20 Gy</th>
<th>25 Gy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dose to the skin</strong></td>
<td><strong>ERYTHEMA</strong></td>
<td><strong>DRY DESQUAMATION</strong></td>
<td><strong>MOIST to WET DESQUAMATION</strong></td>
<td><strong>NECROSIS</strong></td>
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Numerical dose reconstruction at IRSN – Timeline of evolution
Localized irradiation– SESAME tool (Simulation of External Sources Accident with MEdical images) (Huet et al., 2009)
Numerical dose reconstruction at IRSN – Timeline of evolution

Lemosquet et al., 2004; Huet et al., 2009; Huet et al., 2019
Dose assessment in case of radiological accidents

Some case studies to be presented in the talk given by JF Bottollier-Depois
Medical management of small scale accidents – contribution of computational dosimetry

To guide the surgery

Surgery + MSC
Courageot et al., 2011

To assess the dose heterogeneity to guide treatments for hematopoietic syndrome

Heterogeneity: no graft and injection of growth factors to stimulate residual hematopoiesis
Huet et al., 2008

Iliac crests: 3.4 Gy
Cranium: 1.5 Gy
Sternum: 2.3 Gy
Dosimetric triage - context

Primary purpose of the initial-phase dose assessment: identify individuals in potential danger of short-term deterministic effects

No example of large-scale-event case studies in which initial-phase dose assessments for large numbers of people were carried out following acute exposure -> conceptual approaches

European consensus concerning the medical management of mass radiation exposure (Vaux de Cernay, 2005):

- time to onset of early phase clinical signs of acute radiation syndrome (first 24h)
- importance and rapidity of the drop of blood lymphocytes (first 48h)
- Non specific

Need for complementary and alternative methods
Dosimetric triage

**Multibiodose project**
- 7 dosimetric assays tested
- Dosimetric triage categorisation in three different categories

**Current R&D in biological and physical dosimetry worldwide**
- To reduce the time of analysis and to lower the detection limits of the techniques used for diagnosis
- To investigate less invasive methods, new materials and new biomarkers
- To develop tools deployable on site

**Increase triage capacity and harmonize practice**
- Laboratory network
- Intercomparisons
- Training

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*Table 9.1 Radiation Dose Triage Levels for Symptoms and Medical Care Suggested by the Multibiodose Project in the European Union (Jaworska et al., 2014).*

<table>
<thead>
<tr>
<th>Category</th>
<th>Triage dose Symptoms and care</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt; 1 Gy. Unlikely to develop symptoms of acute radiation syndrome (ARS); no immediate care required</td>
</tr>
<tr>
<td>Medium</td>
<td>1 to 2 Gy. May experience mild or delayed ARS symptoms; follow-up care may be necessary</td>
</tr>
<tr>
<td>High</td>
<td>&gt; 2 Gy. Moderate-to-urgent care may be required</td>
</tr>
</tbody>
</table>
Objective: convert the measured physical dose of a sample into an organ dose or a “whole-body” dose

Method
- Modelling of one or several locations of the sample
- Modelling of several geometries of exposure
- Calculation of predetermined conversion coefficients with a Monte Carlo code
Dosimetric triage - Derivation of dose conversion coefficients (2)

- Whole body and organ dose conversion coefficients from EPR fortuitous dosimeter (Hervé et al., 2007)
  - Exposure: standard exposures (AP, PA, RLAT, LLAT), source at 1 m, in a pocket, a hand and contaminated ground
  - Sources: monoenergetic photons and neutrons, $^{60}$Co, $^{137}$Cs, $^{192}$Ir, $^{252}$Cf and AmBe
  - Type of samples / location: teeth, bones, sample in a pocket (sugar for instance)
  - MCNPX 2.4 code and MIRD phantom with modified head
Dosimetric triage - Derivation of dose conversion coefficients (3)

Whole body dose conversion coefficients from mobile phone samples (Eakins and Kouroukla, 2015)

- Exposure: standard exposures (AP, PA, RLAT, LLAT, ISO), rotational and contaminated ground
- Sources: $^{60}$Co, $^{137}$Cs, $^{192}$Ir
- Type of samples / location: resistors (aluminium oxide) / chest, leg, back and hip
- MCNPX code, ICRP 110 reference male phantom, modelling of the mobile phone
Whole body dose conversion coefficients from mobile phone samples (Kim et al., 2019)

- Exposure: standard exposures (AP, PA, RLAT, LLAT, ISO) and rotational
- Sources: $^{60}$Co, $^{137}$Cs, $^{192}$Ir
- Type of samples / location: display glass / chest, hip, thigh and hand
- Three different postures: standing, kneeling, squatting
- Geant4 code, ICRP 145 mesh reference male phantom, modelling of the mobile phone
Numerical dose reconstruction at IRSN – Timeline of evolution
Dosimetric triage – SEED tool (Simulation of External Exposures and Dosimetry)

- Collaboration SPRA/IRSN
- Powerful mobile and autonomous computer (72 cores) deployable on site
- Developed in C++, Geant4 / GATE Monte-Carlo code

Collection of input data  Scene modelling  Results display
Dosimetric triage – SEED tool (Simulation of External Exposures and Dosimetry)
Numerical dose reconstruction at IRSN – Timeline of evolution
Dosimetric triage – SEED tool

**VALIDATION STEPS**

- **2018**
  - Comparison with another Monte-Carlo code
    (Entine et al., 2022)

- **2019**
  - Comparison with experiments
    (Entine et al., 2022)

- **2022**
  - Deployment of the tool on site
**Dosimetric triage – SEED tool**

**ONGOING AND FUTURE DEVELOPMENT**

- Improvement of ergonomics and ease of use
  - Libraries (anthropomorphic phantoms, furniture, sources, ...)
  - Modeling aids (copy/paste, ...)

- Place of the tool in the dosimetric arsenal
  - Integration of other dosimetric information (dose rate measurement, dose from a sample, ...)
  - In field exercises
Conclusion

- Valuable contribution of computational dosimetry to the management of radiological accidents for small scale accident
  - for diagnostic purposes
  - alone or in combination with other dosimetric techniques

- Initial-phase dose assessments for large numbers of people (medium/large scale accidents)
  - conceptual approaches but computational dosimetry may have a valuable contribution
  - Gap: individual dose assessment with confidence
Goals, research questions and directions of research of computational modeling  
(Fattibene et al., 2023)

<table>
<thead>
<tr>
<th>Research questions</th>
<th>End goal</th>
<th>Possible directions of research</th>
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</thead>
<tbody>
<tr>
<td>How to ease and improve the dose reconstruction?</td>
<td>Dose assessment and dose mapping for small-scale events</td>
<td>Develop libraries of phantoms, sources, shielding, etc.</td>
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<td>Develop implementable computational tools [131]</td>
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<td>Develop means to perform calculations ‘on the fly’, to generate conversion coefficients immediately after events rather than relying on pre-tabulated databases</td>
</tr>
<tr>
<td>How to harmonize? Which dose quantity is needed?</td>
<td>Dose assessment for large-scale and small-scale events and dose mapping for small-scale events</td>
<td>Train modellers in computational techniques</td>
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<tr>
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<td>Support the benchmarking of application through the setup of intercomparison exercises</td>
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<td>Support collaboration between different experts in RD, and between experts in RD, crisis management units and clinical staff</td>
</tr>
</tbody>
</table>

- In which circumstances are the exposure conditions known with sufficient detail to allow dose conversion coefficients to be accurately computed and applied in large-scale scenarios?
- Under what sets of situations might the dose to the fortuitous dosimeter be a sufficiently reliable indicator of the dose to the individual?

- Dose assessment for large- and small-scale events
- Analyze the types of situations in which ignorance of the precise exposure conditions may either be minimized or have minimal impact, within an acceptable level of agreement also to be established.
- Develop consensus on what level of discrepancy and/or conservatism is acceptable for triage dosimetry seeking collaboration among involved figures, such as experts in RD, crisis management units and medical experts.
- Generate a database of such conditions and the associated limitations/uncertainties of reporting dosimeter doses ‘as is’.

- How best to provide dose harmonization from multiple materials (fortuitous dosimeters, radiation monitors, …), either co-located or spatially distributed?
- Dose assessment for large- and small-scale events
- Develop methods to interrelate such doses, both to each other and to the individual.
Thank you for your attention
The first 48 hours: Primary scoring

**Score 1**
- Average delay before symptoms appear
- Cutaneous erythema
- Ascites
- Vomiting per 24 hrs
- Diarrhea/number of stools per 24 hrs
- Abdominal pain
- Headache
- Temperature
- Blood pressure
- Temporary loss of consciousness

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Score 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 12 hrs</td>
<td>0</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
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<tr>
<td>Maximum 1</td>
<td>+</td>
</tr>
<tr>
<td>Maximum 2 - 3; bulky</td>
<td>++</td>
</tr>
<tr>
<td>Minimal</td>
<td>++</td>
</tr>
<tr>
<td>Less than 38°C</td>
<td>++</td>
</tr>
<tr>
<td>Normal</td>
<td>++</td>
</tr>
</tbody>
</table>

**Score 2**
- Less than 5 hrs
- +/-
- ++
- +++
- Intense
- **
- 38° 40°C
- Normal
- Possible temporary decrease

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Score 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 5 hrs</td>
<td>+/ -</td>
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<tr>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>+++</td>
<td>Intense</td>
</tr>
<tr>
<td>**</td>
<td>38° 40°C</td>
</tr>
<tr>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Possible temporary decrease</td>
<td>0</td>
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</tbody>
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**Score 3**
- Less than 30 min
- ++++; before 3 hrs
- +++
- +++
- Above 10; intractable
- Above 10; watery
- Excruciating
- Excruciating; signs of intra-axial HT
- Above 40°C
- Systolic below 80
- + / coma

**Depletion of blood lymphocytes**

- Outpatient monitoring
- Hospitalisation for curative treatment
- Hospitalisation (MOF predicted)
Whole body and organ dose conversion coefficients for industrial sources (Kim et al., 2018; Han et al., 2019)

- Exposure: three distances (0.5, 10, and 30 cm) in four directions (front, back, right, and left) at five levels (ground, mid thigh, lower torso, mid torso, and upper torso)
- Sources: $^{60}$Co and $^{192}$Ir point sources
- Calculation of source self-shielding factors
- Geant4 code, MRCP phantoms (ICRP 145) and 10th and 90th percentile MESH phantoms