Health Effects, Dosimetry and Radiological Protection of Tritium

Objectives

- Conduct an independent review of scientific literature to assess the adverse health risk to workers and the public from exposures to tritium.
- Assess Canadian and international dosimetry practices for tritium intakes.
- Review the current approaches for limiting exposure to tritium.

To meet these objectives, the report provides:

- An overview of tritium’s physical, chemical and radiological properties
- A detailed analysis of the adverse health effects of tritium radiation, including reviews of laboratory and epidemiological studies
- A review of experimental studies estimating the relative biological effectiveness (RBE) of tritium radiation
- A description of biokinetic models and dosimetry of tritium
- A review of the approach taken by the International Commission on Radiological Protection (ICRP) for protection from tritium and possible modification of the radiation weighting factor ($w_R$)

Overall Study Conclusions

1. The lines of evidence, based on both epidemiological and laboratory studies, reveal that adverse health effects due to tritium exposure at the current exposure levels in Canada are highly unlikely.

2. The results of more than 50 experimental studies related to the determination of a single RBE value for tritium confirm that tritium beta radiation is about 14 times more biologically effective than radiation from 250 kVp x-rays and 2.2 times more biologically effective when compared to gamma rays.

3. Current dosimetry and biokinetic models for assessing dose are acceptable for radiation protection purposes.

4. The current regulatory framework, which uses the linear non-threshold risk model and the principle of ALARA (a practice that aims to keep radiation doses As Low As Reasonably Achievable) is satisfactory for controlling tritium exposures.

This study was peer reviewed by the following subject matter experts:

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Health Effects, Dosimetry and Radiological Protection of Tritium (continued)

Health Effects – Laboratory Studies

Objectives
The health effects of tritium have been studied extensively, perhaps more than any other radioisotope.

This study reviewed scientific literature on:

- **Deterministic effects**: changes in cells and tissues that are certain to occur after an acute dose of radiation (such as teratogenic (foetal) effects, reproductive effects and death).

- **Stochastic effects**: radiation-induced health effects (such as cancer and hereditary effects) where their probability of happening increases proportionally to the radiation dose received.

- **Organically bound tritium**: tritium in molecules such as proteins, fats and starches.

Main Findings

- Tritium behaves much the same as other ionizing radiations in inducing deterministic effects.

- Laboratory studies using animals have demonstrated that tritium exposures, as with other sources of radiation exposure, can interfere with the development of an embryo or foetus, promote cancer, and induce genetic and reproductive effects and cell death.

- The actual quantity of tritium required to induce these effects is very large; in the order of gigabequerels (GBq; billions of tritium atoms decaying and emitting a beta particle per second) per gram of body weight. The dose resulting from these intakes is more than 500 millisieverts (mSv).

- Organically bound tritium is more effective at causing adverse health effects than tritiated water (HTO), primarily due to the length of time spent in the organism.

Table 1 summarizes the studies reviewed in this report, although care needs to be taken in comparing the endpoints and different dose regimes (injection vs. ingestion), especially with respect to the mouse oocyte. Generally, doses above 0.5 GBq and radiation doses of 0.5 Gy are needed to induce an adverse health effect. The exception to this is the mouse reproductive system, whose oocytes are about 100 times more radiosensitive than that of humans.

![Table 1. Overview of studies showing lowest concentration or administered dose of tritium to produce an adverse effect](image-url)
Health Effects, Dosimetry and Radiological Protection of Tritium (continued)

Health Effects – Epidemiology

Epidemiology is the study of the factors affecting the health and illness of populations and how disease is distributed. It serves as the foundation for public health and preventive medicine.

Studies based on good-quality radiation exposure data provide the best source of evidence for estimating human health risks from radiation.

Main Findings

- Many epidemiological studies involving radiation workers, their offspring and members of the public living near nuclear facilities, and several major authoritative reviews of the scientific literature have been reviewed.
- To date, the existing information does not contain enough detail to specifically estimate the health risks of tritium exposure.
- Tritium exposures represent a very small fraction of total radiation exposures from all sources of radiation.
- Based on the lack of excess health risks found from total radiation exposures (which are low) among the populations studied, any health risks to workers and the general population from tritium are expected to be negligible and not distinguishable from the risks of similar health outcomes in the general population.
- To date, no human health studies have demonstrated any tritium-induced cancer or other health effect.

Table 2 is a summary from the study by Zablotska et al (2004), which involved a mortality follow-up of 45,468 Canadian nuclear power industry workers from 1957 to 1994. Overall, there was no indication of any unexpected pattern in the cohort mortality compared with that of the general population.

Studies of populations living near nuclear facilities have major limitations (such as unknown exposure to other carcinogens and unmeasured exposures to tritium) and are unlikely to add to our understanding of the health effects of tritium. An international collaborative study combining tritium worker data from multiple countries would be required to provide the necessary study power to assess tritium risk directly.
Relative biological effectiveness (RBE) is a relative measure of the effectiveness of different radiation types in inducing a specified health effect. It is defined as:

\[
\text{RBE} = \frac{\text{absorbed dose from a given radiation}}{\text{absorbed dose from the reference radiation}}
\]

The RBE contributes to the basis for a universal measurement of dose, the sievert (Sv), for radiation protection purposes. It is also useful for retrospective studies where a more exact dose measurement is needed due to a high exposure requiring medical treatment or for epidemiological studies requiring the best estimate of each individual dose.

The choice of a single value for the RBE of tritium for radiation protection purposes is difficult. There have been more than 50 different estimates of a tritium RBE due to considerable variation and uncertainty in the radiobiological data.

The choice of a reference radiation makes up much of this variability, since the RBE for x-rays and gamma rays—the two types of radiations typically used as the reference radiation—differ by nearly a factor of two. The review of studies to determine a single value for the RBE of tritium radiation indicates that:
- If x-rays are the reference radiation, an RBE value of about 1.4 for tritium would be appropriate.
- If gamma radiation is chosen as the reference, an RBE value closer to 2.2 would be appropriate.
- Gamma radiation appears to be the preferred reference radiation (ICRP, 2003) principally because the atomic bomb survivors were primarily exposed to gamma radiation.

Table 3 provides a statistical summary of the RBE determinations under many different experimental variables.

### Main Findings

- There is no significant difference between in vivo and in vitro studies.
- There are significant differences in RBE values for the reference radiation and if the reference radiation was delivered chronically or acutely.
- The studies with a chronic gamma reference radiation have a mean RBE of about 30% higher than those that used chronic X-ray as the reference radiation.
Dosimetry is a scientific subspecialty in radiation protection and medical physics that focuses on calculating the dose resulting from exposure to ionizing radiation.

- Dose cannot be measured directly with instruments; instead, it must be calculated from measurements of the amount of radiation to which a person has been exposed.
- Dose is proportional to the amount of radiation energy absorbed by the body per kilogram of body weight.
- Doses from tritium are usually determined from bioassay samples (such as urine) of occupationally exposed individuals or through environmental monitoring (e.g., tritium in air).

**ICRP Models**

To calculate the dose resulting from tritium exposure, it is first necessary to know how much tritium is retained in the various organs and tissues of the body over time after exposure to tritium.

The International Commission on Radiological Protection (ICRP) is the international organization that makes recommendations for radiation protection based upon current assessments of health effects caused by radiation exposure. It has recommended two models to calculate the dose from tritiated compounds:

1. The ICRP HTO (tritiated water) model (see Figure 1) is used to calculate the dose resulting from intakes of tritiated water or other tritiated compounds that partially convert to HTO after being taken into the body.

2. The ICRP OBT (organically bound tritium) model (see Figure 2) is used to calculate the dose resulting from intakes of various tritiated organic compounds (such as nutrients). The ICRP OBT model applies to the inhalation and ingestion of organically bound tritiated compounds. This model predicts that for equal amounts of tritium ingested, organically bound tritium yields about twice the dose compared to that from tritiated water.

Studies have shown that these ICRP models are reasonably consistent with experimental results. The following are a graphic description of the current ICRP models.

**Figure 1. ICRP model for the biokinetics of tritiated water**

<table>
<thead>
<tr>
<th>Blood</th>
<th>HTO</th>
<th>OBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>97%</td>
<td>( T_{1/2} = 10 ) days</td>
<td>3%</td>
</tr>
</tbody>
</table>

- Urine (47%)
- Feces (3%)
- Other (50%)

**Figure 2. ICRP model for the biokinetics of organically bound tritium**

<table>
<thead>
<tr>
<th>Blood</th>
<th>GI Tract</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

- HTO
  - \( T_{1/2} = 10 \) days
- OBT
  - \( T_{1/2} = 40 \) days

- Urine (47%)
- Feces (3%)
- Other (50%)

It is important to note that there are ongoing studies looking at improving the accuracy of these models, based upon differences in retention time (or biological half-life).

Because tritiated water largely has the same chemical and physical properties as normal water, it will be distributed evenly throughout the body as would any water molecule. Its retention in the body is also the same as any other water molecule.

However, in most OBT compounds, tritium that is bound to oxygen, nitrogen, phosphorus or sulphur will exchange freely with hydrogen in water. Therefore, it has the same metabolism and distribution in the body as HTO and is called the exchangeable bound tritium fraction. Tritium bound to carbon will not exchange with hydrogen in water and is known as non-exchangeable bound tritium. Biokinetic models under consideration attempt to better estimate the differences in retention time for the exchangeable and non-exchangeable OBT compounds.
Health Effects, Dosimetry and Radiological Protection of Tritium \textit{(continued)}

Options for Assessing and Controlling Risks Associated with Tritium Exposures

Nationally and internationally, the approach taken to protect radiation workers and members of the public from radiation is to adopt the principles and recommendations of the International Commission on Radiological Protection (ICRP).

The ICRP has designated the sievert (Sv) as the unit to give a measure of dose for all ionizing radiations. It does this by applying weighting factors ($w_R$) for the different types of radiation (alpha, beta and gamma) and for the radiation sensitivities of different organs and tissues.

- The sievert is strictly a unit for radiation protection purposes.
- It provides a single unit for dose from all ionizing radiations for optimization and to compare against the dose limit.
- Due to simplifications, the $w_R$ loosely reflects the biological effectiveness of the type of radiation and is therefore only an approximate indicator of risk.
- All electrons (beta radiation) and photons have a weighting factor of 1.
- The $w_R$ is not based upon the source of the radiation (for example, x-ray machines or specific radioisotopes).
- Doses are gender neutral; equivalent and effective doses are calculated for a ‘representative person’ based on a population of males and females, ethnicity and age.
- The sievert should not be used to assess doses when individual risk assessments are required, such as cases where large intakes are suspected or in epidemiological studies. In those cases, tissue-weighted absorbed doses with appropriate relative biological effectiveness (RBE) values should be used. As well, characteristics specific to the individual should be taken into account.

The ICRP does not believe that practical radiation protection would be improved by having radioisotope-specific radiation weighting factors or separate dose estimates for males and females. But for its recommendation to be effective, doses must be kept As Low As Reasonably Achievable (ALARA).

Using a different $w_R$ for tritium to reflect the RBE value would best reflect the radiation risk from tritium. However, the following considerations must be taken into account with this approach:

- The apparent improvement in correlation with risk may be misleading given the existence of many other uncertainties due to other significant variables (sex, age, weight, metabolic rates, genetic susceptibilities, etc.). Occupational and public doses are already low and there is a continuous effort to reduce these further.
- It would be inconsistent with the ICRP system of radiological protection which is currently the international standard approach. Specifically:
  a) There are no other isotope-specific $w_R$ values.
  b) It would be difficult to compare radiation protection practices nationally and internationally.