Individual Dose Assessment: the Example of Acute Exposure

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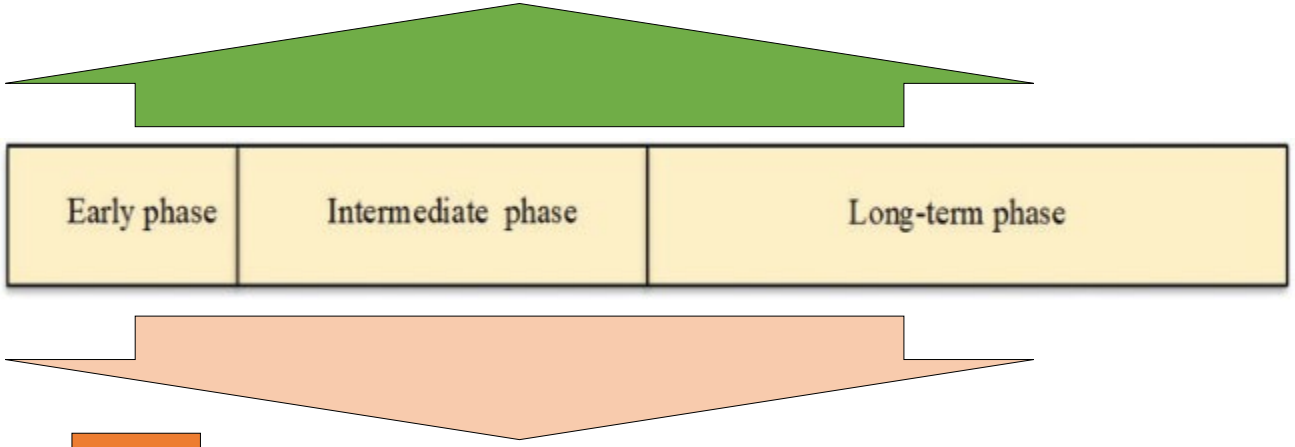
ICRU Meeting, Fukushima, April 2023

Retrospective dosimetry

dose reconstruction for epidemiological studies



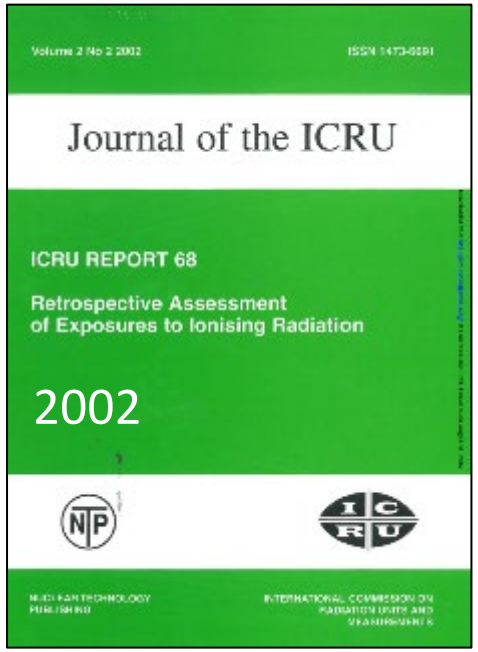
new research in the field has been produced

consistent update of ICRU-68

Dose assessment

early medical information

support and practice of radiological protection



nothing for high doses that cause acute radiation syndrome

expands to estimate potential tissue reactions

Proposed scenarios

Malicious acts

- Dirty bomb
- Improvised nuclear bomb
- Irradiator

Accident

- in a nuclear power plant

Description of the methods

1. Introduction
2. Quantities
3. Biodosimetry
4. Electron Paramagnetic Resonance (EPR) Dosimetry
5. Luminescence Dosimetry
6. Other Individual-Person Radiation Measurements
7. External Dose Assessment Methods Based on Radiation Field Mapping

+ Recommendations on their use for various radiation exposure conditions and dose assessment needs

Quantities

Quantities to be used

Initial phase

Absorbed dose
to a **tissue**
(Gy)

Absorbed dose to
the **dosimeter**
(Gy)

For large-scale, acute exposure events, the quantity to be reported in initial-phase dose assessment for individuals should simply be presented as "**absorbed dose**"

Practical approach
that will enable decision makers to proceed

non-SI units should be avoided in all circumstances

~~**rad, rem**~~

Quantities to be used

Initial phase

Absorbed dose
to a **tissue**
(Gy)

Absorbed dose to
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(Gy)

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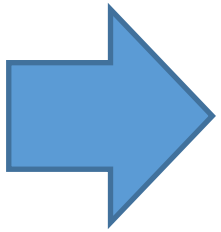
Practical approach
that will enable decision makers to proceed



Individual assessment

RBE-weighted
absorbed dose
(Gy-eq)

Absorbed dose to
an **organ**
$D_{r,T}$ (Gy)

other organs

Absorbed dose to
whole body
$D_{r,WB}$(Gy)

Quantities to be used

Measured absorbed dose
D_r (Gy)

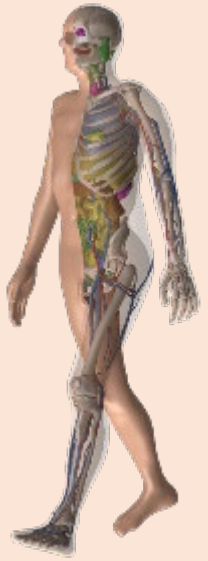
conversion coefficient

$$C_r = \frac{D_{r,WB}}{D_r}$$

Absorbed dose to whole body
$D_{r,WB}$(Gy)

Effective dose
E (Sv)

Monte Carlo simulation



absorbed dose to all organs knowing one measured dose

Proposed methods

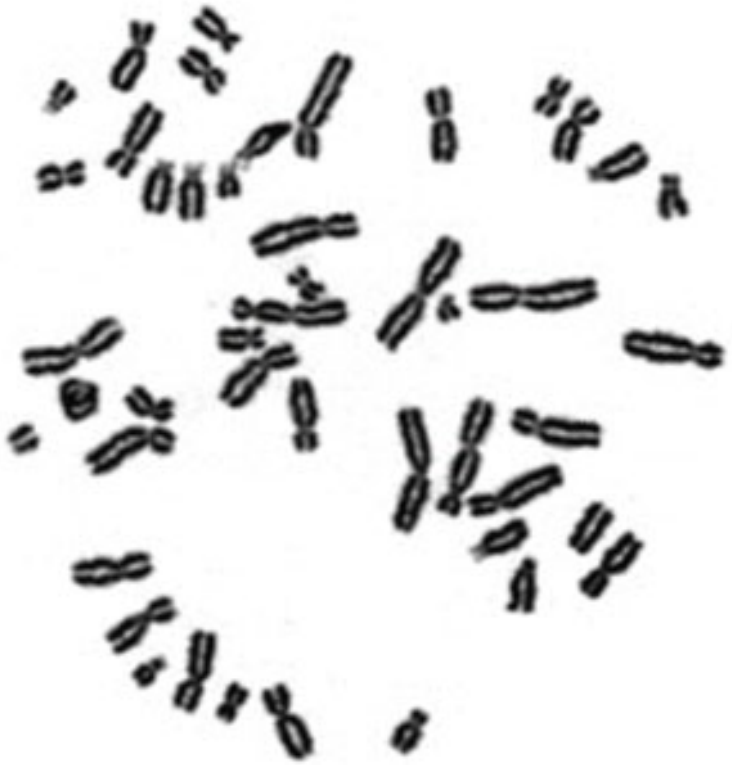
biodosimetry

physical dosimetry

supplementary methods

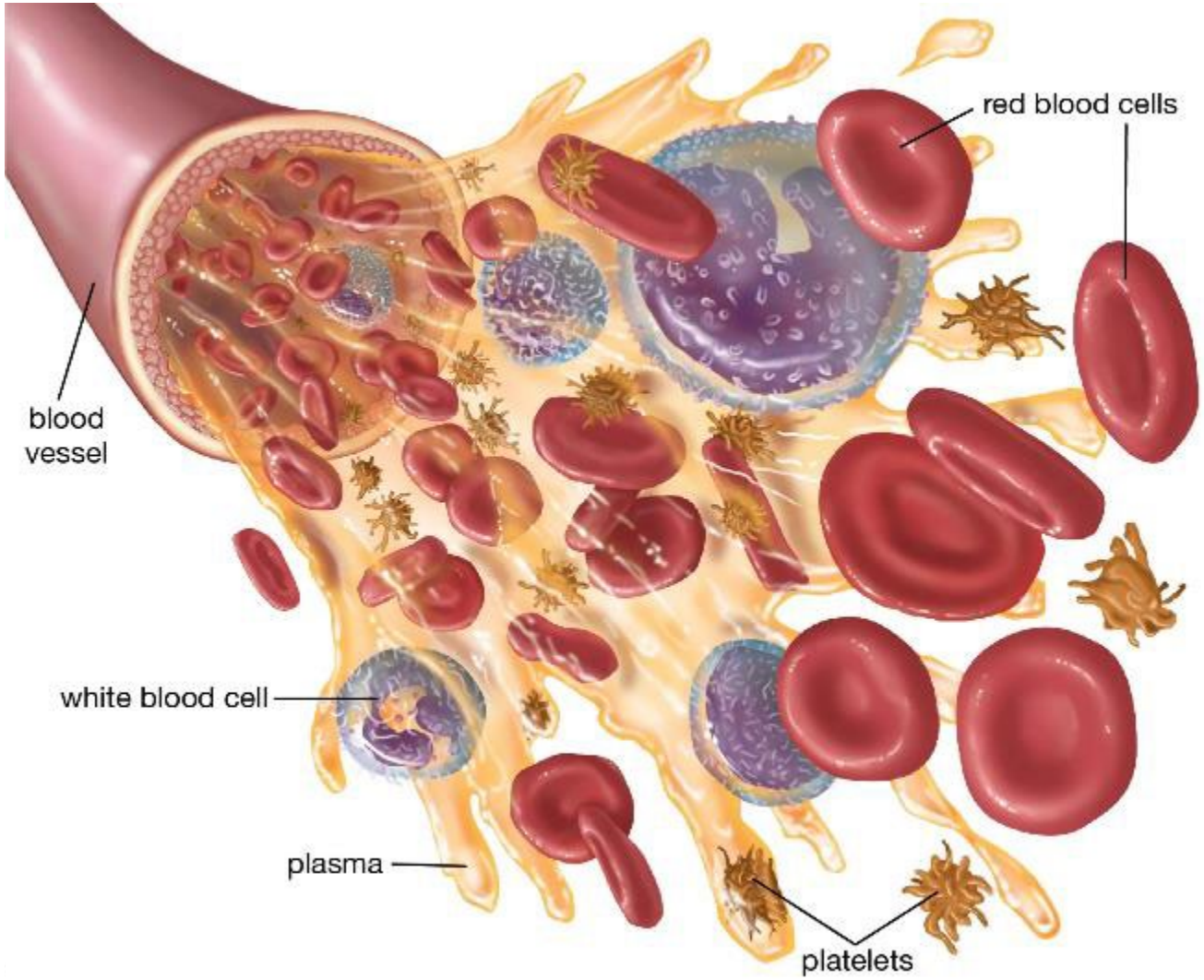
Table 1.2 Primary Dosimetry Topics Described in This Report.

Techniques	Primary target materials
Biodosimetry	
● Dicentric chromosome assay (DCA)	Whole blood or lymphocytes
● Translocation analysis by fluorescence *in-situ* hybridization (FISH)	Whole blood or lymphocytes
Cytokinesis block micronucleus (CBMN) assay	Whole blood or lymphocytes
Premature chromosome condensation (PCC)	Whole blood or lymphocytes
● γ-H2AX	Whole blood or lymphocytes
RNA expression	Whole blood or lymphocytes
Protein-based assays	Urine, blood plasma, blood serum, whole blood, lymphocytes
Metabolomics	Urine, blood serum, blood plasma
Physical dosimetry	
● Electron paramagnetic resonance (EPR)	Teeth, bone, nails, glass from personal items, sugars, fabrics, other personal belongings
● Thermoluminescence (TL)	Components of portable electronic devices, glass from personal items, dust on personal items
● Optically stimulated luminescence (OSL)	Components of portable electronic devices, clothing, other personal belongings
Other	
● Bioassays (*ex vivo* and *in vivo*)	Excreta, thyroid, chest, whole body
● Neutron activation	Biological tissue, objects worn by the individual
Mapping and time-and-motion studies	Dose and dose rate measurements



Biodosimetry

https://www.qst.go.jp/site/nirs-english/1369.html



Biodosimetry can be used to **estimate the dose** of radiation an individual has received

https://www.britannica.com/science/blood-biochemistry

Biodosimetric methods

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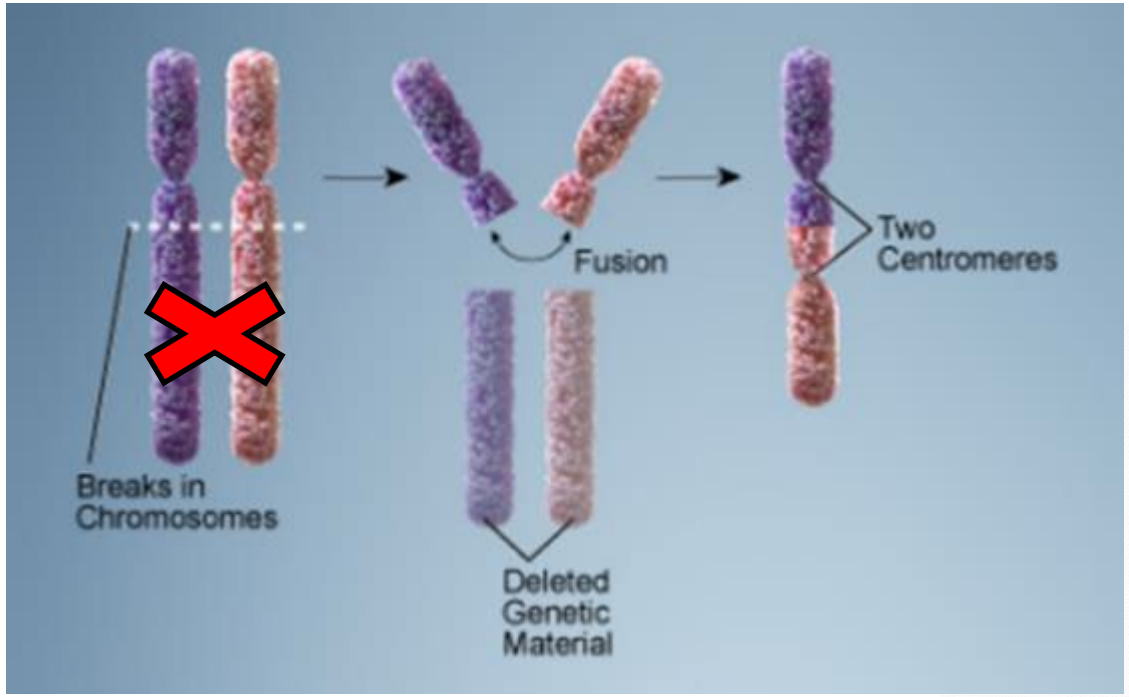
Protein-based assays	Urine, blood plasma, blood serum, whole blood, lymphocytes
Metabolomics	Urine, blood serum, blood plasma

blood cells = circulating dosimeters

they average the dose from all parts of the body

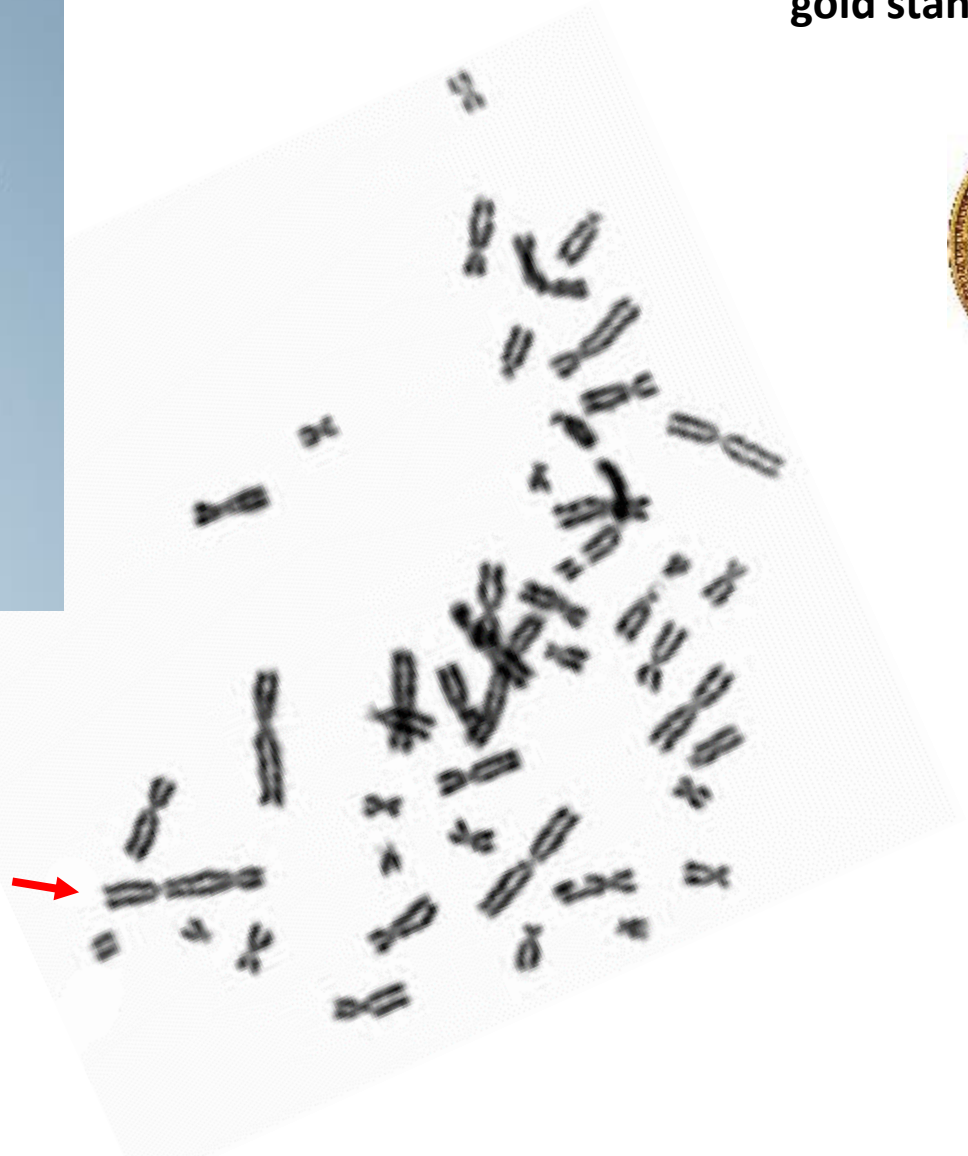
urine can also be used

Dicentric chromosome



very **specific** for ionizing radiation

>50 years old method,
but still considered as the
"**gold standard**" of biodosimetry

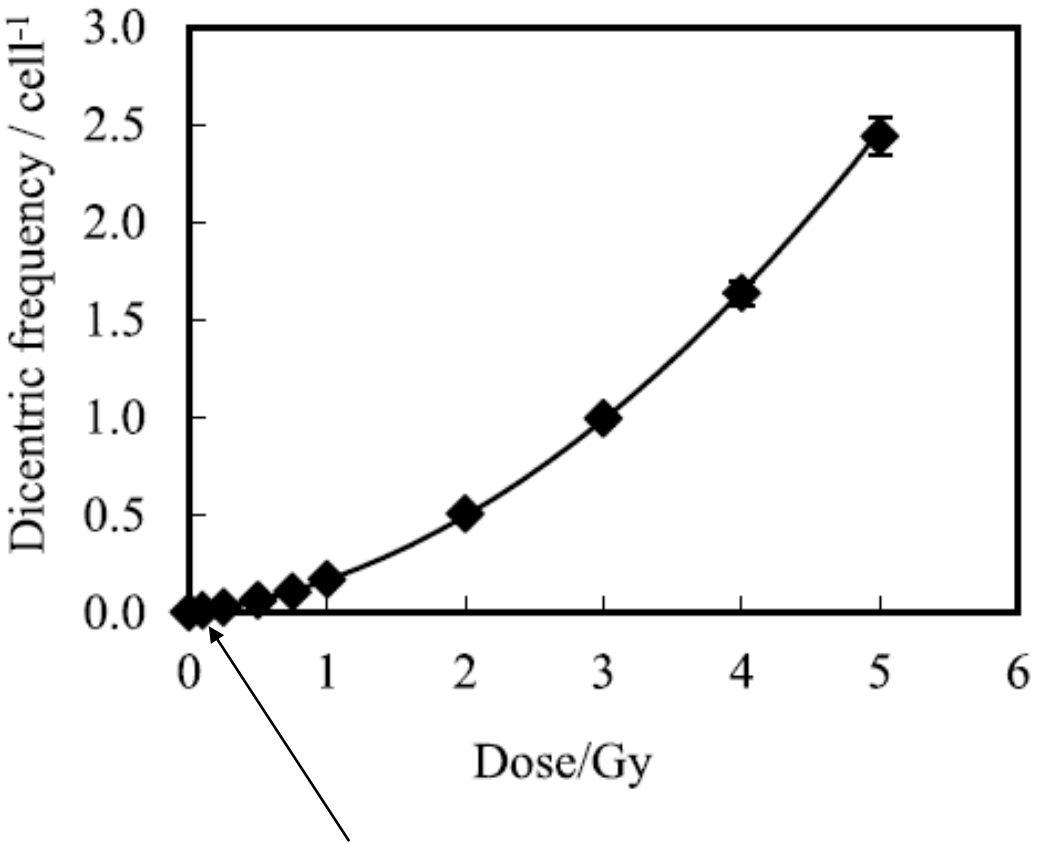


U.S. National Library of Medicine

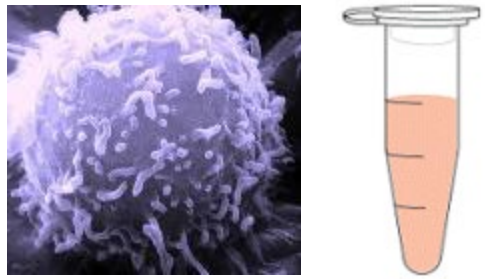
KF Wong et al, Cytogenetic biodosimetry: what it is and how we do it, Hong Kong Med J Vol 19 No 2 (April 2013)

Dicentric chromosome

Typical dose response relationship



minimum detectable dose **MDD ≈ 0.1 Gy**
with a good control group
(low BGD of 0-2 dicentrics/1,000 cells)



REPORT
1.2 Gy

blood sample

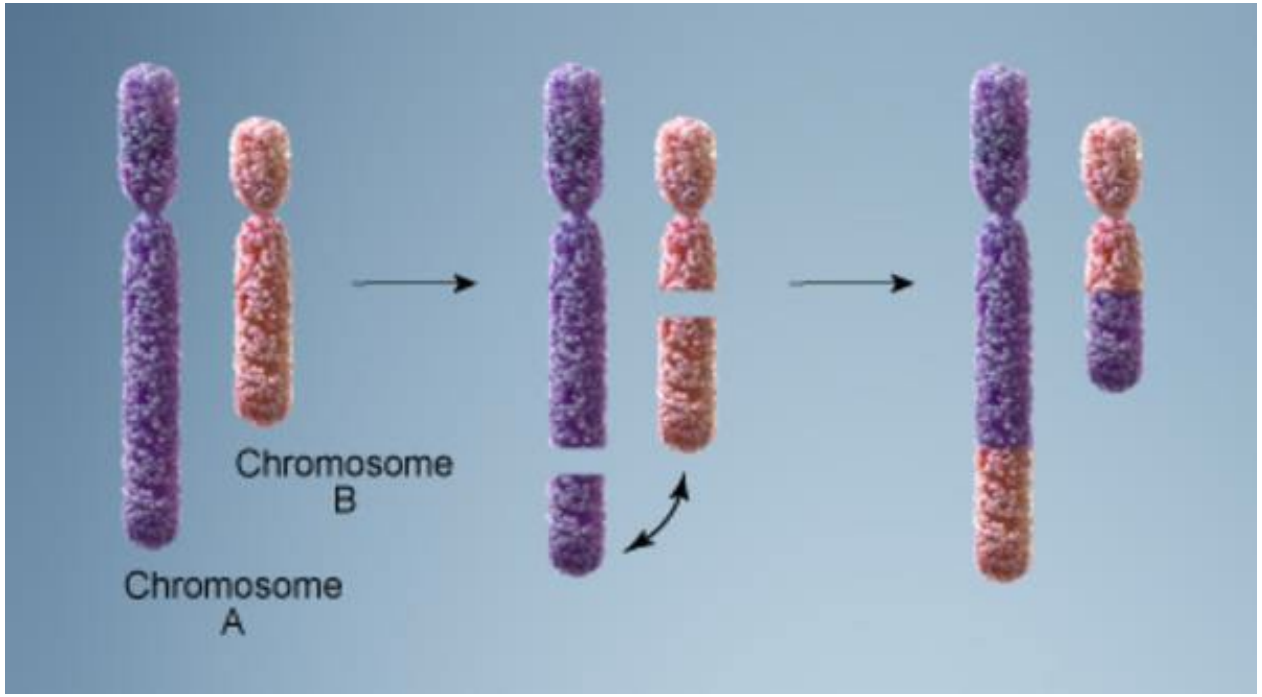
48 h to 72 h culture time
(cytogenetic assays)

If **blood sampling** is **delayed** to several weeks or more, correcting for the **half-life** is necessary

T-lymphocytes **half-lives** *(T)* depend on their immunologic function:

- short-lived (*T* = some weeks/months)
- long-lived (T ≈ 3.5 years or more)

Translocation



measured by
fluorescence in-situ hybridization (**FISH**)

probe stained with
a **fluorochrome**

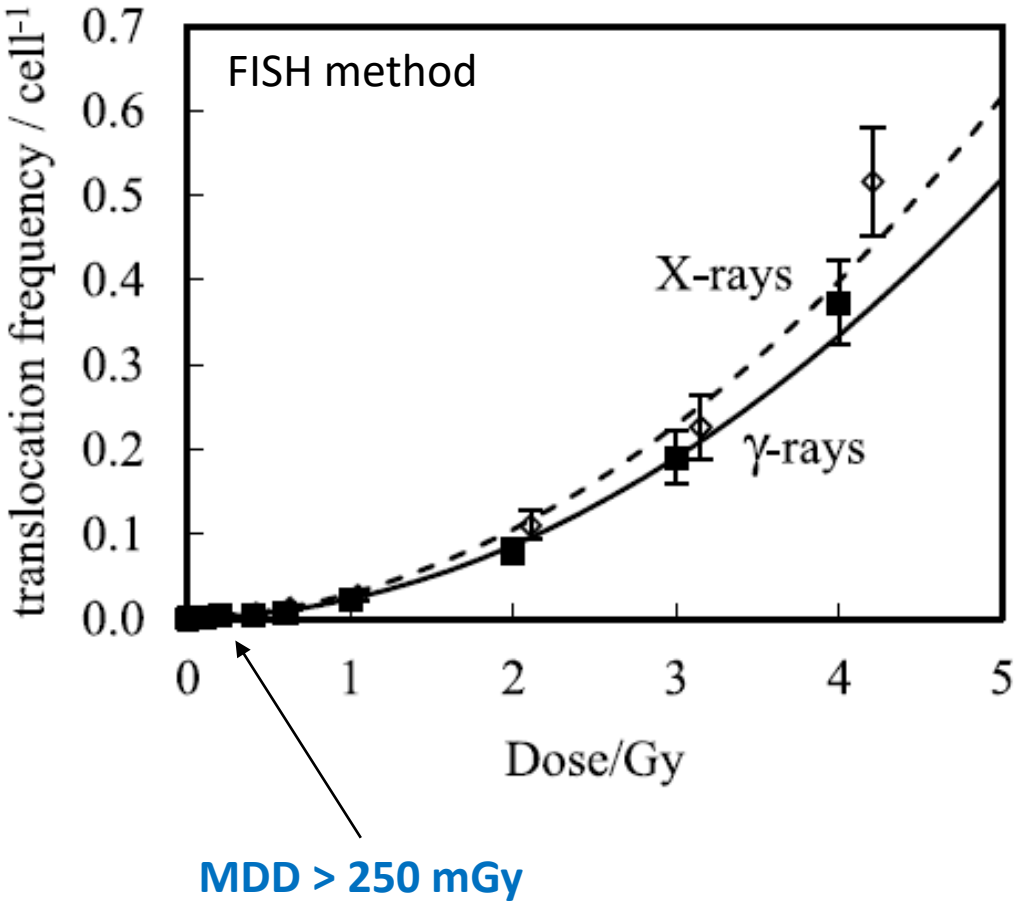
hybridization with
nuclear DNA

appearance with a
microscope

U.S. National Library of Medicine
Par Thomas Ried — National human genome research institute, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2271086

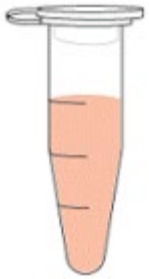
Translocation

Typical dose response relationship



MDD > 250 mGy

100-200 mGy
if pre-exposure sample was acquired



blood sample

longer time than for dicentric

REPORT

1.2 Gy

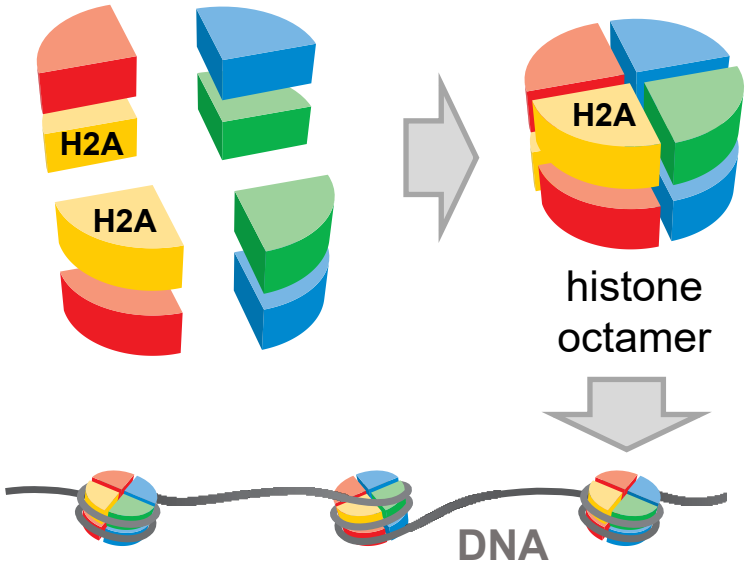
persists over **years** or **decades**

able to **accumulate** during long, chronic exposures

need to have a **baseline**

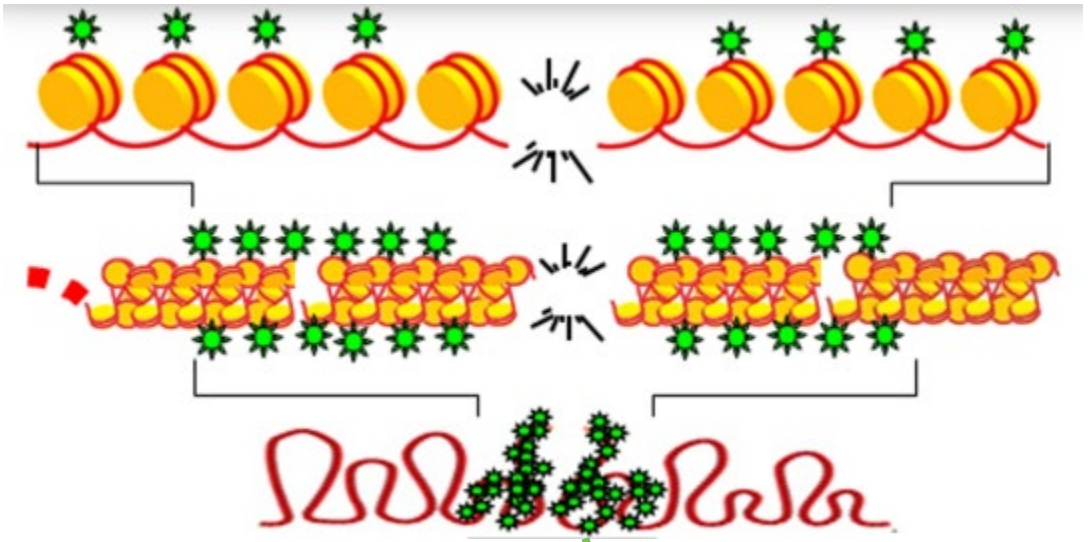
higher cost and longer and **more complicated** staining protocol limit its use in emergency biodosimetry

γ-H2AX

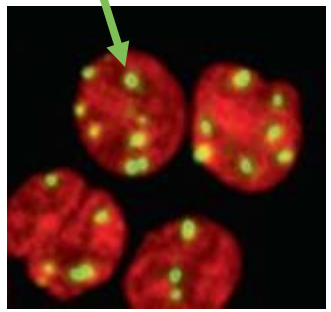


H2AX is one of several genes encoding **histone H2A**

double strand break (**DSB**) induces **phosphorylation** of H2AX → **γ-H2AX**



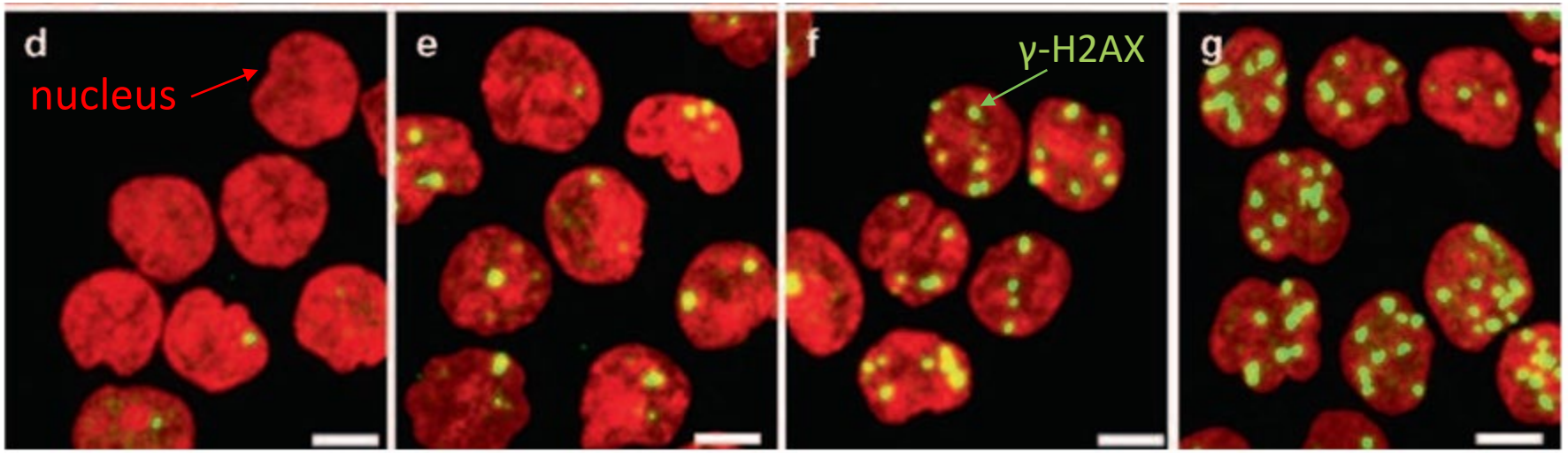
can be visualized with **fluorescent staining**



γ-H2AX

double strand break (DSB)

fluorescence analysis

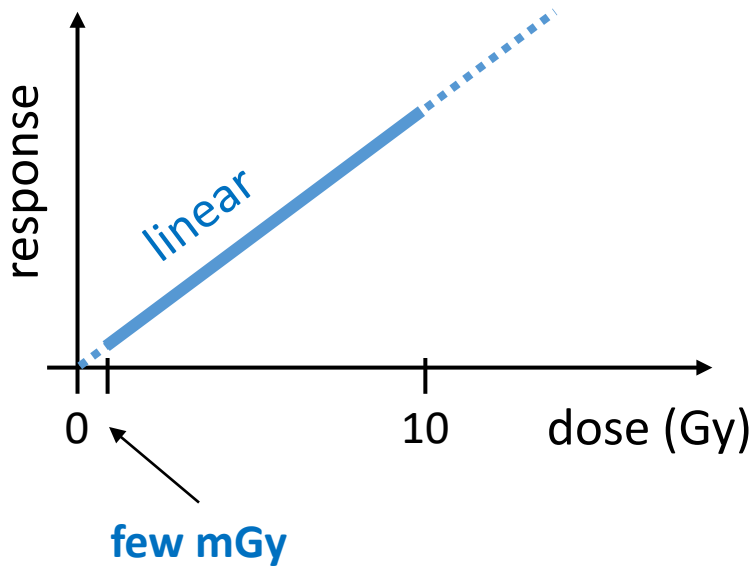


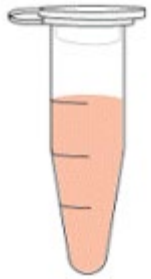
0 Gy **0.1 Gy** **0.4 Gy** **0.6 Gy**

Redon, Nakamura, et al, https://www.dinow.co.jp/en/technology-en/

γ-H2AX

Typical dose response relationship

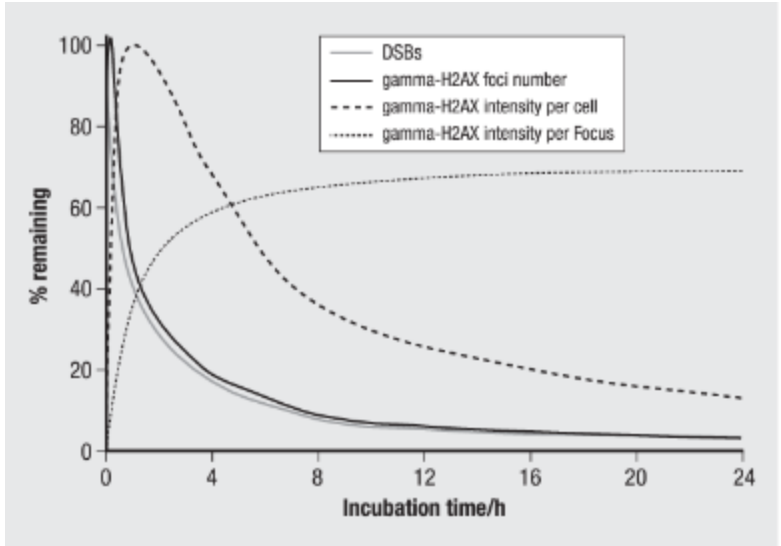




blood sample

processed & analyzed "immediately"

very sensitive, but within hours after irradiation



Rothkamm and Horn, Ann Ist Super Sanità 2009 | Vol. 45, no. 3: 265-271

Physical dosimetry

https://www.bruker.com/en/products-and-solutions/mr/epr-instruments.html

Physical dosimetry

Table 1.2 Primary Dosimetry Topics Described in This Report.

Techniques	Primary target materials
Physical dosimetry	
• Electron paramagnetic resonance (EPR)	Teeth, bone, nails, glass from personal items, sugars, fabrics, other personal belongings
• Thermoluminescence (TL)	Components of portable electronic devices, glass from personal items, dust on personal items
• Optically stimulated luminescence (OSL)	Components of portable electronic devices, clothing, other personal belongings

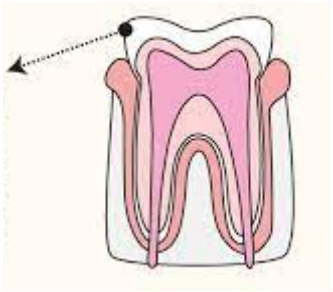
EPR – Electron paramagnetic resonance

EPR can detect and/or identify the sites of **unpaired electrons** in materials

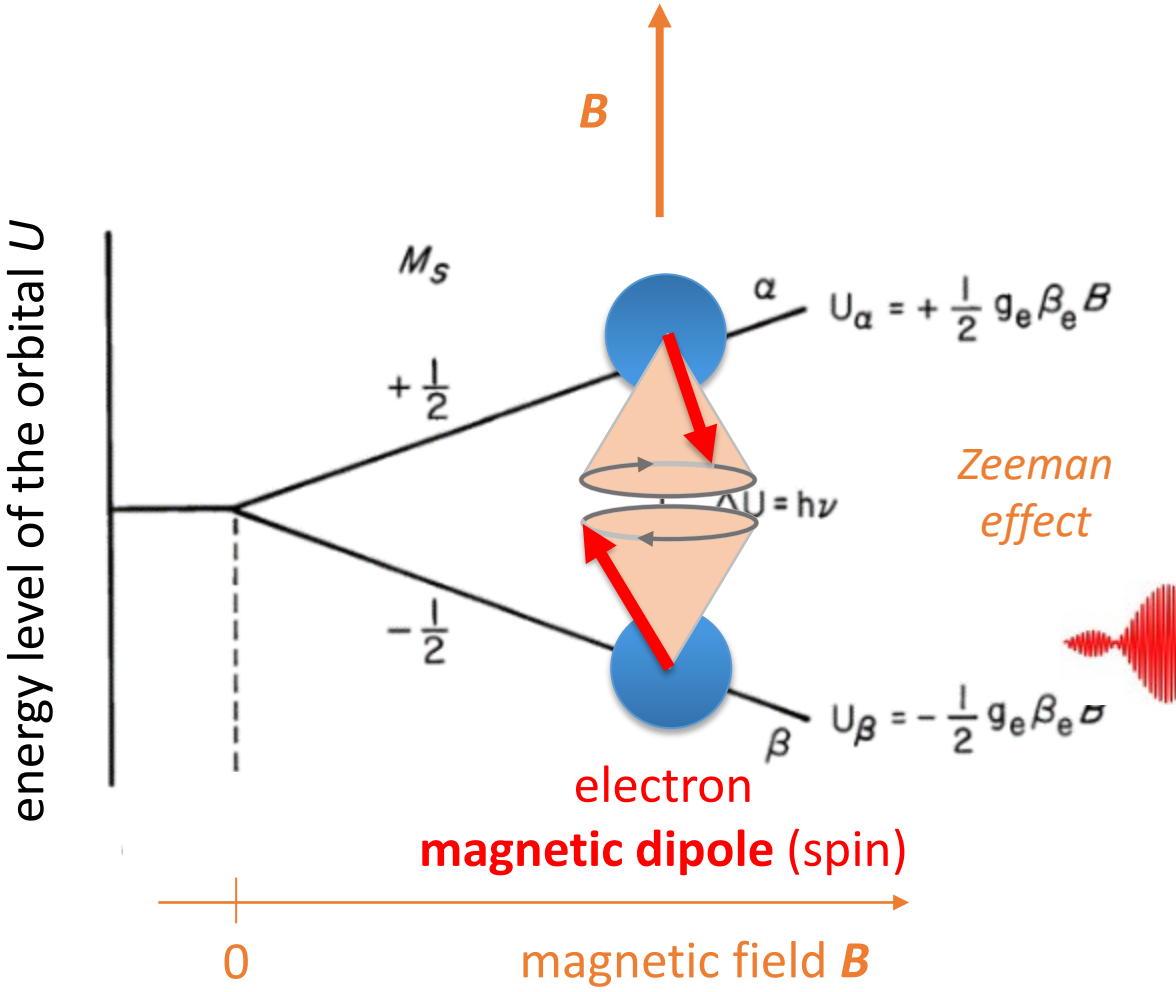
typical example

Carbonate ion CO_2^- is an impurity in hydroxyapatite that can be radiation-induced in tooth enamel

CO_2^- -radicals are **extremely stable** in tooth enamel:



up to **100'000 years** in historical samples

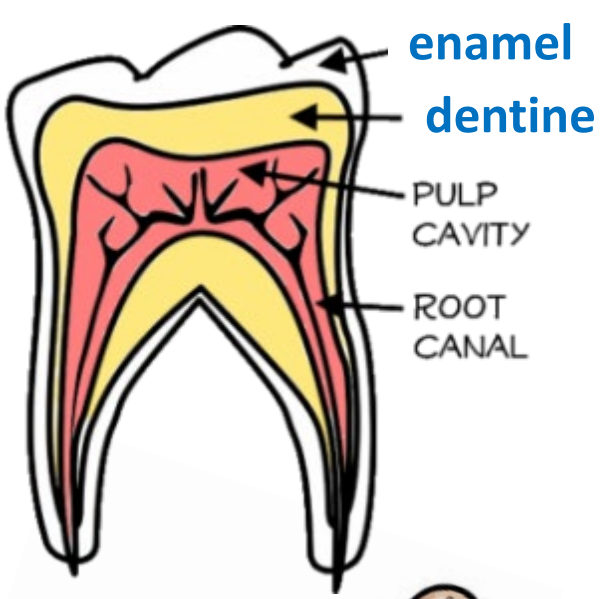


case of a single unpaired electron

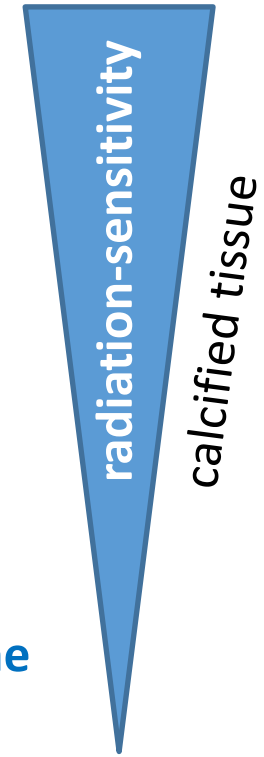
JA Weil and JR Bolton, Electron Paramagnetic Resonance: Elementary Theory and Practical Applications, Wiley, 2007

EPR – Electron paramagnetic resonance

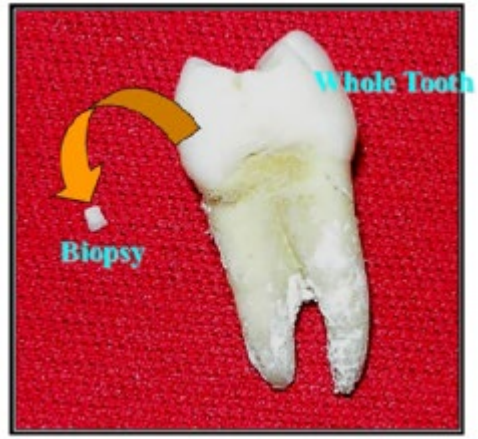
biologically derived materials



bone



minimum detectable dose (MDD)
for bone in X-band ≈ 5 Gy



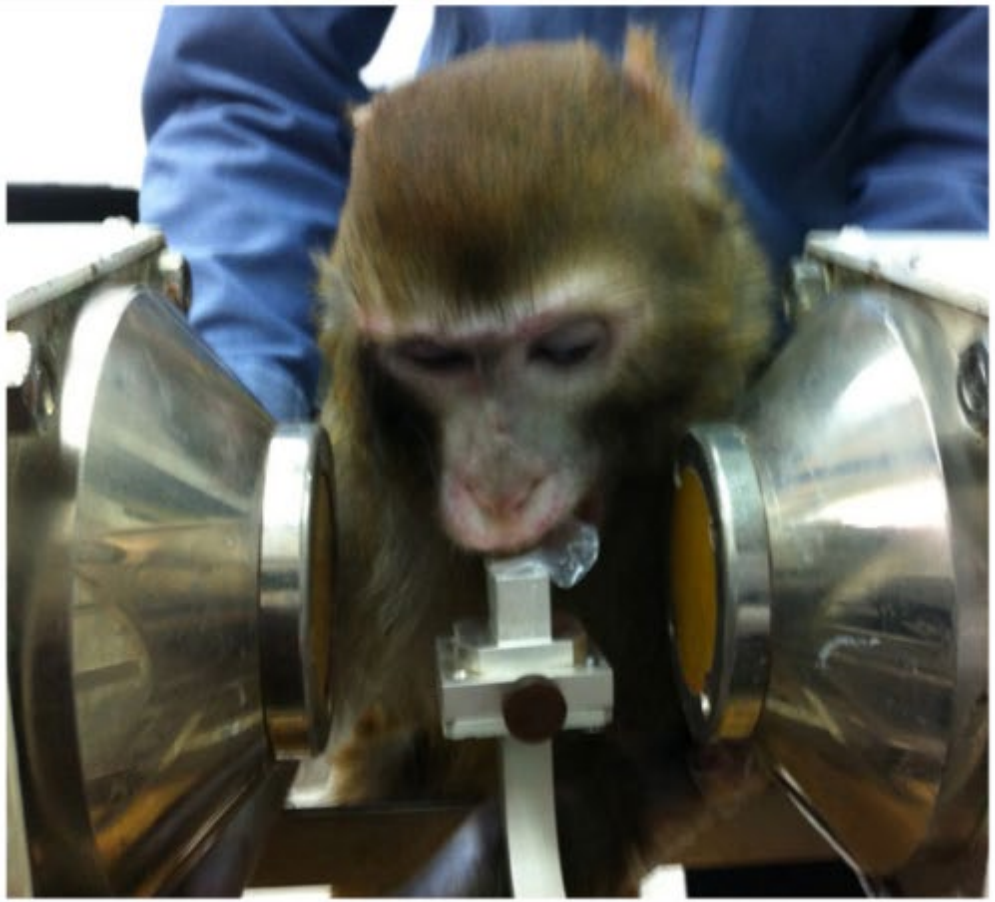
in vitro measurement

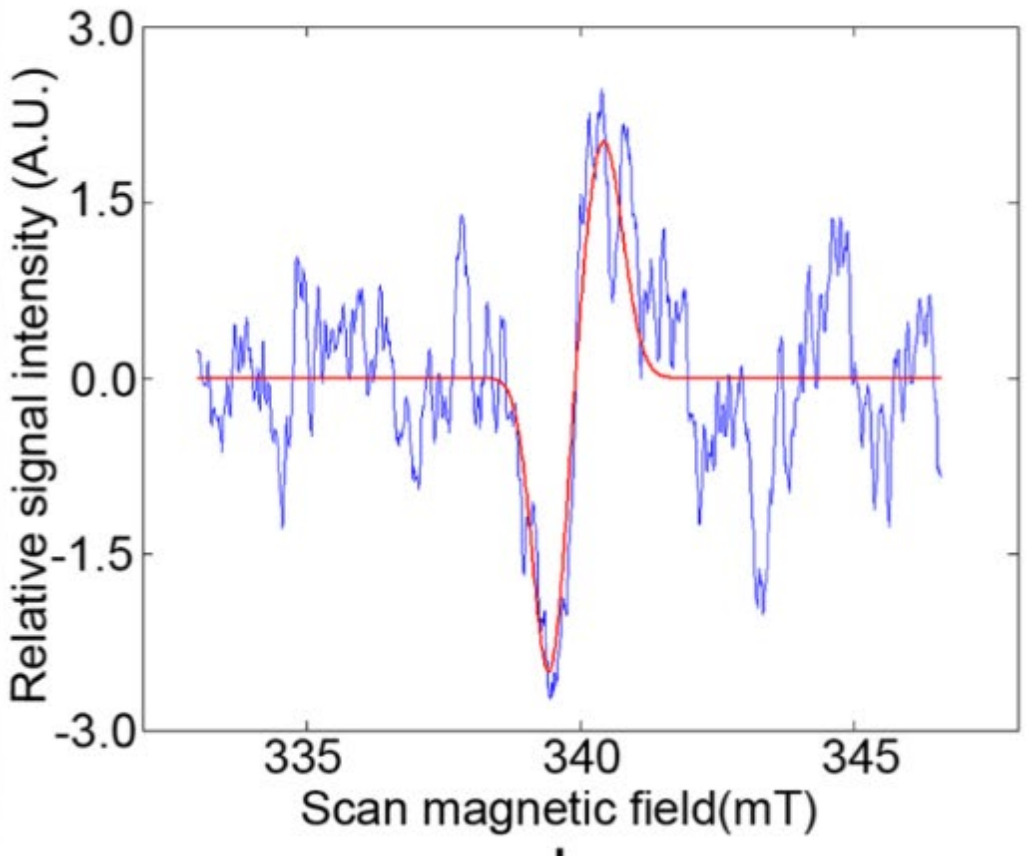
typical sample size
≤ 5 mg

https://www.thesmartclinics.co.uk/understanding-tooth-anatomy-for-better-dental-health/

EPR – Electron paramagnetic resonance

in vivo measurement

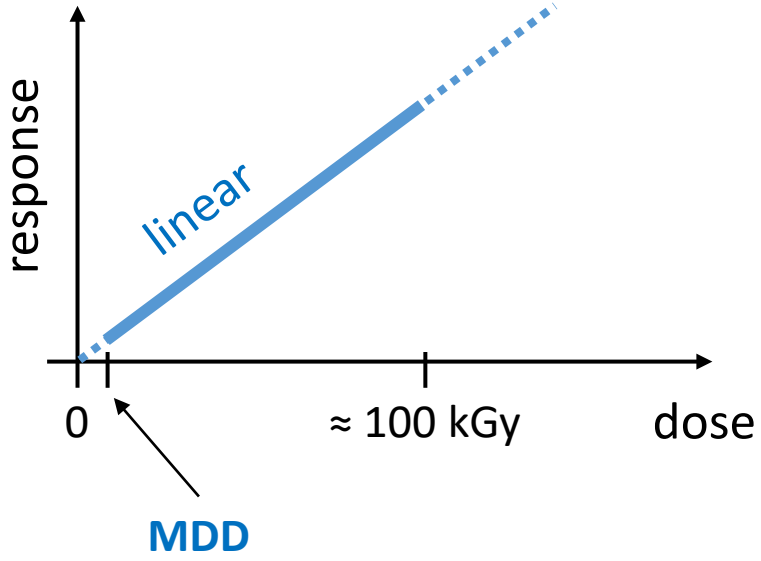




Junwang G *et al.* (2014) New Developed Cylindrical TM010 Mode EPR Cavity for X-Band In Vivo Tooth Dosimetry. PLOS ONE 9(9): e106587. https://doi.org/10.1371/journal.pone.010658

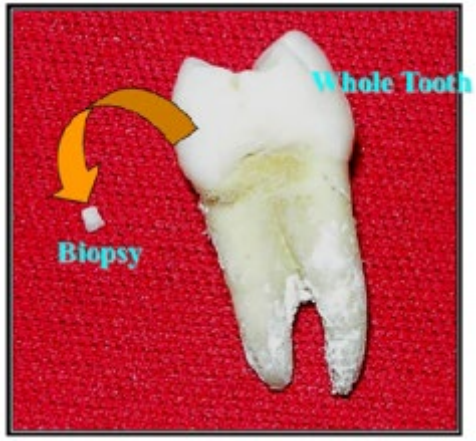
EPR – Electron paramagnetic resonance

Typical dose response relationship



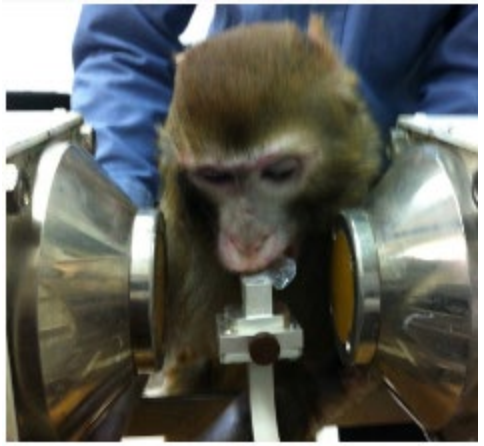
EPR in **tooth enamel**
"**gold standard**"
of retrospective dosimetry

stable for
decades



great for epidemiology
where time is not an issue

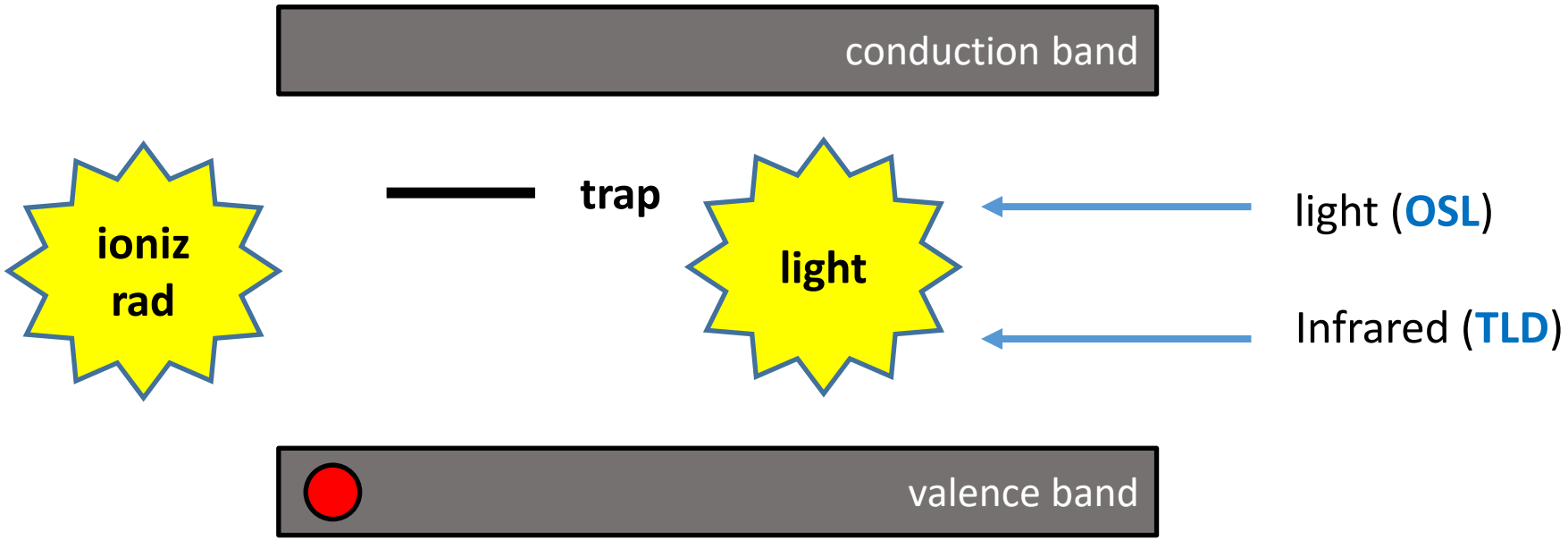
MDD ≈ **100 mGy**



fast enough to be
used in emergency

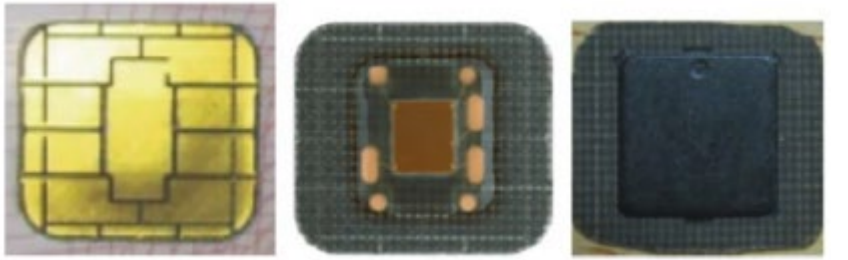
MDD ≈ **500 mGy**

Luminescence – TLD OSL



Luminescence – TLD OSL

non-biological samples



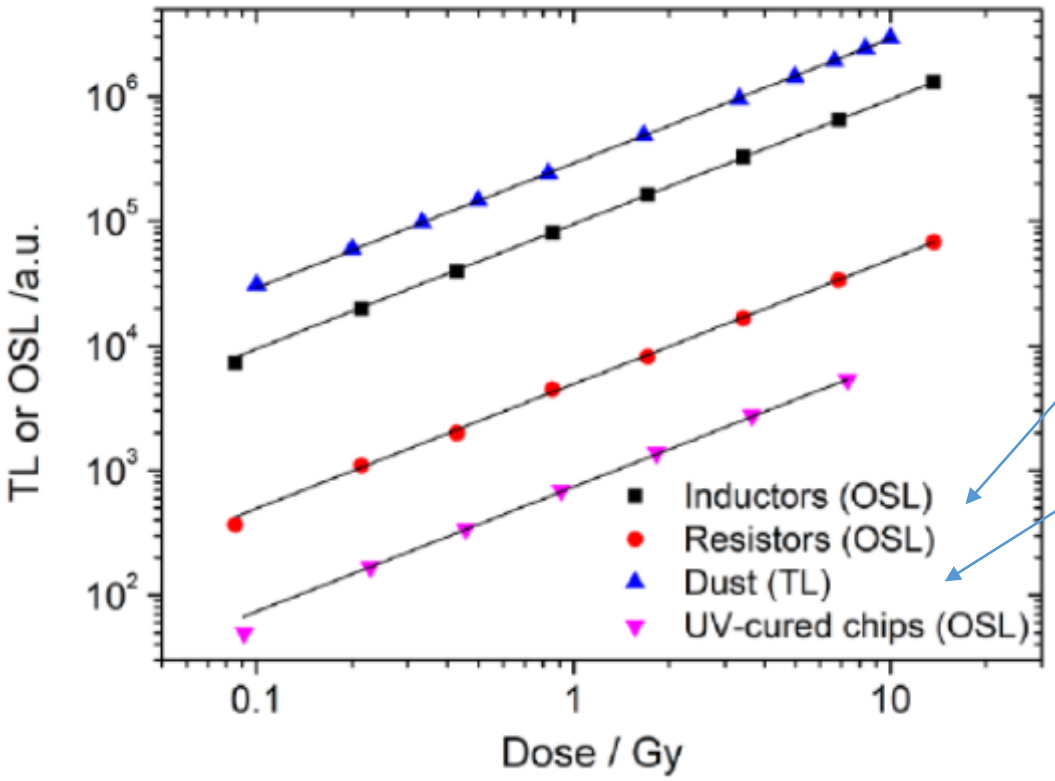
personal electronics, plastic cards, fabrics

biological samples

teeth, dental repair ceramics, clothing

Luminescence – TLD OSL

Typical dose response relationship



MDD

	UV-cured transparent encapsulations	intact contact-based molded encapsulation	chemically prepared molded encapsulation
immediate	2-7 mGy	40-60 mGy	3 mGy
10 days	20-40 mGy	130 mGy	5 mGy

Supplementary methods

https://www.qst.go.jp/site/nirs-english/1369.html

Supplementary methods

Table 1.2 Primary Dosimetry Topics Described in This Report.

Techniques	Primary target materials
Other	
Bioassays (*ex vivo* and *in vivo*)	Excreta, thyroid, chest, whole body
Neutron activation	Biological tissue, objects worn by the individual
Mapping and time-and-motion studies	Dose and dose rate measurements

Bioassay

Biodosimetry and physical dosimetry cannot distinguish between **external** and **internal** exposures

in-vivo

- whole-body counting (WBC)
- thyroid counting
- chest counting

ex-vivo

- excretion analysis

http://www.advancetechcontrols.com/radiation/in-vivo-and-health-safety/

Neutron activation

Example of Na activation in blood

$^{23}Na(n,\gamma)^{24}Na$	$T_{1/2}$ = 14.96 h	E_γ = 1.36 MeV (100 %) and 2.75 MeV (99.85 %)

do not wait for more than a few days

easy to measure

e.g with a gamma-survey instrument positioned against the abdomen

beware of the main Cl activation in blood (from NaCl)

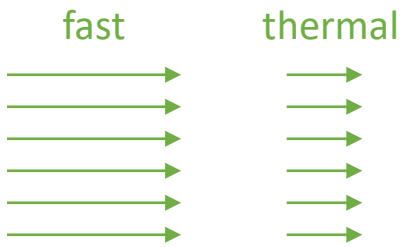
$^{37}Cl(n,\gamma)^{38}Cl$	$T_{1/2}$ = 33 min	E_γ = 1.64 MeV (31 %) and 2.17 MeV (47 %)

Neutron activation

Example of Na activation in blood

$^{23}Na(n,\gamma)^{24}Na$ $T_{1/2}$ = 14.96 h E_γ = 1.36 MeV (100 %) and 2.75 MeV (99.85 %)

essentially from
thermal neutrons



more activation

Activated Na depends on the

- neutron **energy** distribution
- **surface** of the body
- **mass** of the body

more activation

on average, 1.4 g of ^{23}Na
per kilogram of body weight

Neutron activation

Example of Na activation in blood

$^{23}Na(n,\gamma)^{24}Na$ $T_{1/2}$ = 14.96 h E_γ = 1.36 MeV (100 %) and 2.75 MeV (99.85 %)

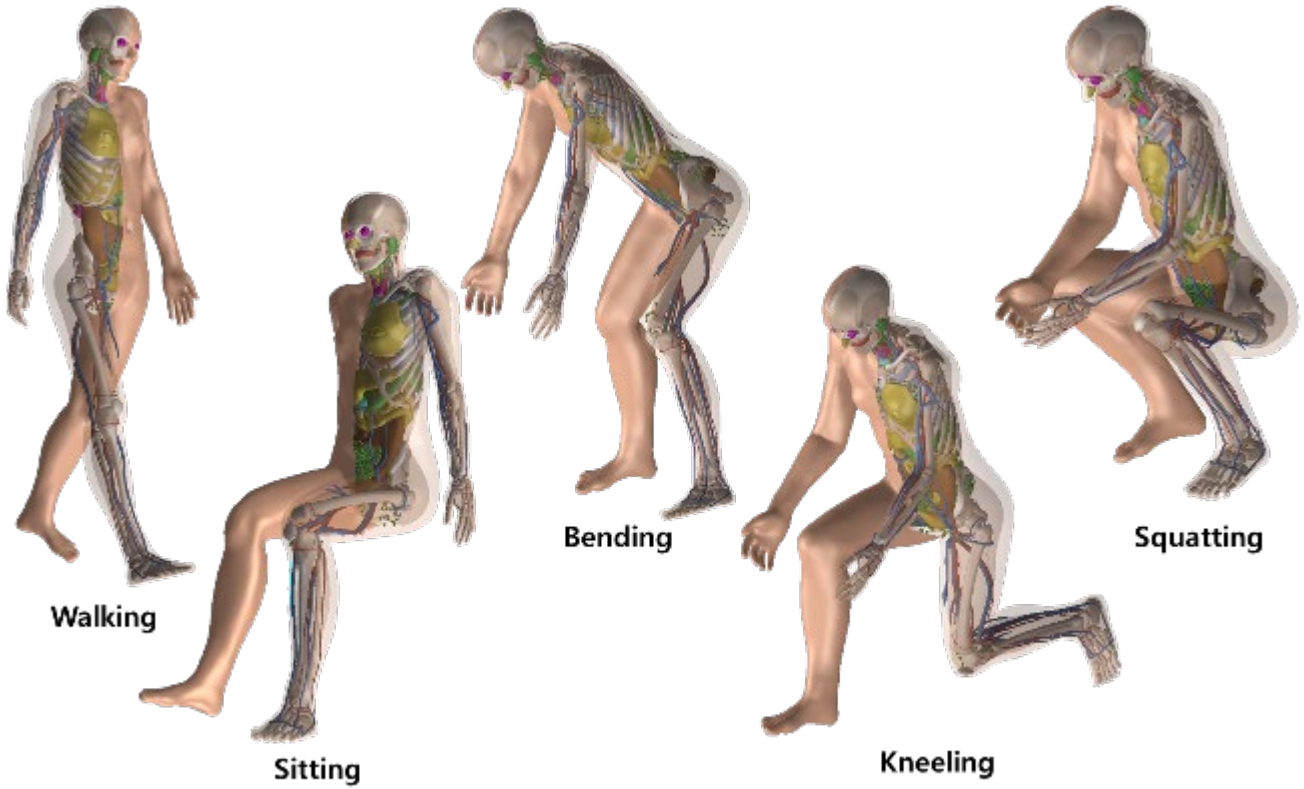
More precise measurements

MDD

few **10s µGy** (thermal neutrons)
a bit higher (fast neutrons)

http://www.advancetechcontrols.com/radiation/in-vivo-and-health-safety/
https://bsi.lv/en/products/hpge-detectors-spectrometers/hpge-spectrometer-lead-shield/

Monte Carlo (MC) simulation mixed with biodosimetry



memory should not be fully trusted,
but the **scenario** of an accident **can be simulated** with 3D phantoms

biodosimetry
or official dosimeters

can be used to **normalize MC calculations**

Radiation field mapping

Dose assessment

"time-and-motion" dose analysis

Where were you?

When were you there?

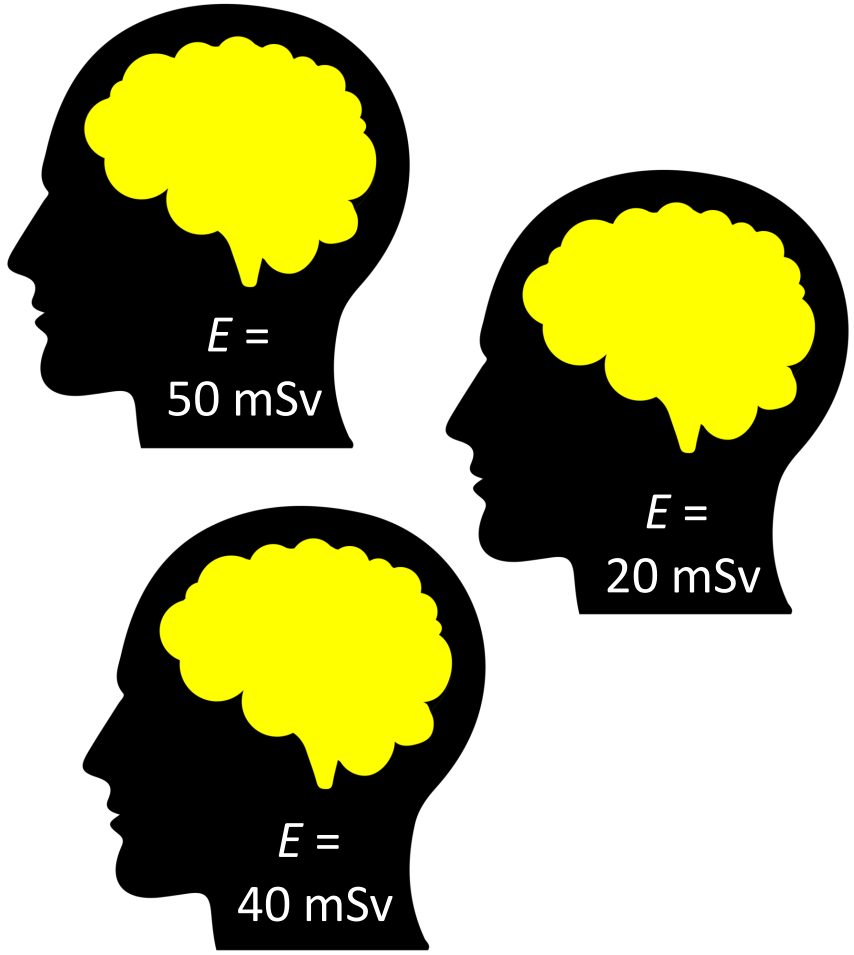
How long were you there?

What was the **shielding** of your locations?

Time evolution of the dose rate?

dose rate *time* *shielding* *location*

$$\text{Dose} = \sum_{i=1}^{n} \dot{d}\left[x(t_i), y(t_i)\right] \Delta t_i S_i,$$



Radiation field mapping

Dose assessment

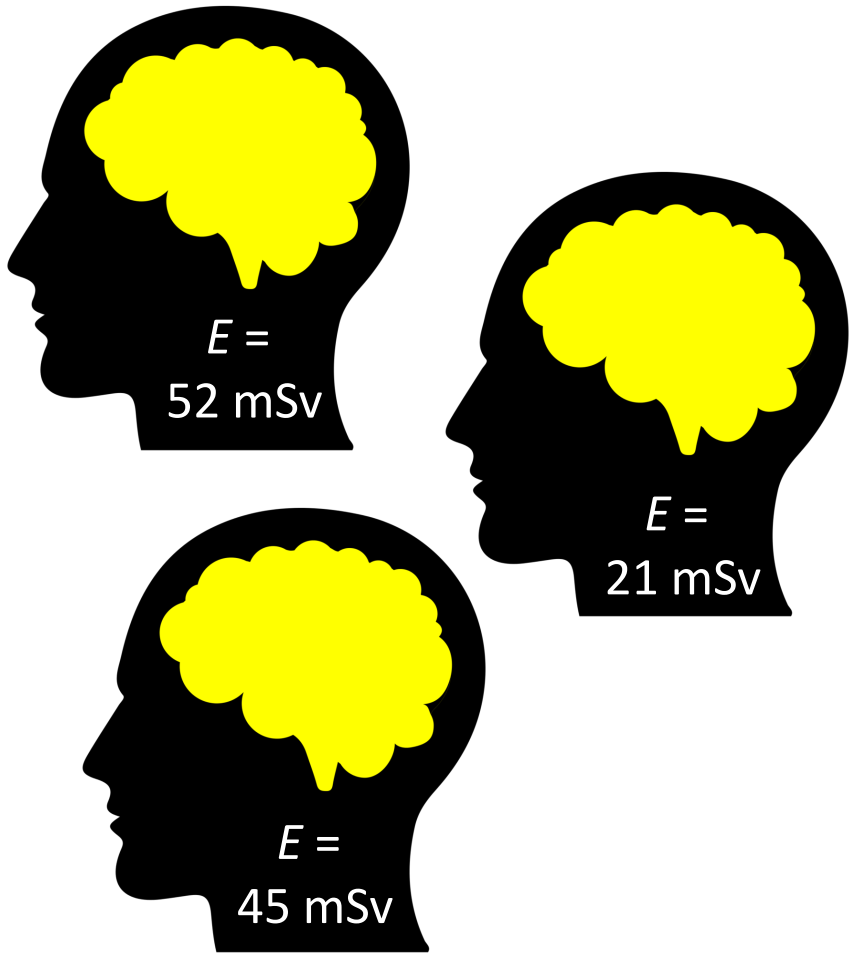
"time-and-motion" dose analysis

more precise

$$\text{Dose} = \sum_{i=1}^{n} \left[\int_{t=start}^{t=stop} \dot{d}_{0i}(x,y)\, e^{-\lambda t} S_i \, \mathrm{d}t \right],$$

dose rate *time* *shielding* *location*

$$\text{Dose} = \sum_{i=1}^{n} \dot{d}\left[x(t_i), y(t_i)\right] \Delta t_i S_i,$$



Conclusions

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- In case of an event, important to **act quickly**
  - first results in **absorbed dose** (Gy)
  - many methods available
  - ICRU Report 94 provides guidance

- Essential to **be prepared well in advance**
  - these techniques take time to master