Assessment of Occupational Exposure due to External Radiation Sources

Accident Dosimetry

Table of content

- Assessment of exposure in emergency situations

- Accident dosimetry: retrospective techniques

- Skin contamination

- Criticality dosimetry

Assessment of exposure in emergency situations

Accident definition

- "Any unintended event, including operating errors, equipment failures or other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety."

- BSS Glossary

Overview radiological accidents

- More than 600 incidents occurred since 1945, resulting in over 200 deaths
  - 41% industrial
  - 19% research
  - 4% military
  - 11% medical
  - 11% nuclear
  - Rest not defined
- 84% external
  - 12% whole body
  - Rest localized
- 10% internal
- Rest mixed
- Chernobyl, Fukushima not included

Accidents: workers vs public

- High levels of exposure of accidentally exposed workers might be associated with nuclear or radiological emergencies
  - Emergency at a nuclear power plant
  - Criticality accident
  - Emergency at an industrial irradiation facility
  - Emergency involving a lost or stolen source
  - Emergency at a medical facility
- dosimeter should be present in normal cases
- Can include workers that are normally not occupationally exposed
  - No dosimeter present!
- Accidents can also involve public and patients: no dosimeter present!

Emergency workers

Four groups of workers may be exposed in an emergency situation:

1. Emergency workers who have specified duties
2. Workers at a facility not involved in response to nuclear or radiological emergency
3. Workers asked to leave site
4. Workers accidentally exposed as result of accident but where exposure is not related to emergency response

Duties of different workers in a nuclear or radiological emergency will differ and appropriate protection strategies should be applied to ensure adequate protection of all workers

Dose limitation for emergency workers

- Emergency workers should be subject to dose limits where possible
- Dose guidance values for specific duties:
  - Life saving
  - Actions to prevent catastrophic conditions
  - Actions to prevent large collective dose
- Guidance value only exceeded if benefit to others clearly outweighs emergency worker's own health risk
- Emergency worker must volunteer and provide informed consent

Exposure assessment for emergency workers

- Response organizations and employers should take all reasonable steps to assess and record exposures received by workers in an emergency
- Exposures of emergency workers monitored on an individual basis (e.g. direct reading, alarm dosimeter)
- Doses received during emergency should be recorded separately from routine work, where possible
- Should be noted on workers' record of occupational exposure
- Information on doses received and associated health risks communicated to emergency worker

Need for dosimetry in accidents

- Dosimetry is needed for medical purposes
- Different kind of accidents
  - Small-scale accidents involving just a few people
  - Large-scale events, either accidental or intentional, that may involve thousands of individuals.
- The numbers of people potentially exposed and requiring dosimetry, including the "worried well", may vary from small to large

Medical questions after accident

- Immediately after the event: What adverse health effects should be expected?
  - The need for initial-phase dose assessment to identify those in need of medical intervention due to deterministic, tissue effects
  - The assessed doses may also later become part of epidemiologic and long-term risk assessment
- Years after the event: What were the actual health consequences?
  - primarily for epidemiology
- Long-time-after-the-event dosimetry: related to stochastic injury for epidemiologic studies
- short-time-after the event dosimetry: related to deterministic, tissue injury (e.g., acute radiation syndrome)
- Good dosimetry is essential to answering these questions.

Biological effects of short term radiation

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Dose Gy	Effect
< 0.2	No detectable effects
0.2-1.0	Measurable transient blood changes. Temporary decrease in white blood cell count.
1.0-2.0	Acute radiation sickness - nausea, vomiting, longer term decrease in white blood cells.
2.0-3.0	Vomiting, diarrhea, loss of appetite, listlessness, death in some cases.
3.0-6.0	Vomiting, diarrhea, hemorrhaging, deaths occurring in 50% of cases at 3.5 Gy or above without medical treatment.
Above 6.0	Eventual death in almost all cases

Radiation effects depend on level

Level of Biological Organization	Important Radiation Effects
Molecular	Damage to enzymes, DNA etc. and interference to biological pathways
Subcellular	Damage to cell membranes, nucleus, chromosomes etc.
Cellular	Inhibition of cell division, cell death, transformation to a malignant state
Tissue, Organ	Disruption to central nervous system, bone marrow, intestinal tract. Induction of cancer
Whole Animal	Death; 'radiation life shortening'
Populations	Changes in the genetic characteristics of individual members

Acute exposure radiation effects

Exposure Health Effect	Organ	Absorbed dose to target organ - Gy
Temporary Sterility	Testes	0.15
Nausea	Whole Body	0.35
Depression of Blood Cell Forming Process	Bone Marrow	0.50
Reversible Skin Effects (e.g., early reddening)	Skin	2.0
Permanent Sterility	Ovaries	2.5-6.0
Vomiting	Gastrointestinal Tract	3.0
Temporary Hair Loss	Skin	3.0-5.0
Permanent Sterility	Testes	3.5
Skin Erythema	Skin	5.0-6.0

Acute exposure - precursor symptoms

- Symptoms arise soon after an exposure
  - Nausea
  - Vomiting
  - Diarrhea
  - Fatigue
  - Disorientation
- The first three symptoms can occur even at moderate, sublethal doses
- Inflammation in the damaged tissues leads to further complications
- Treatment must be initiated within a few hours after exposure
- Intestinal fluid loss and electrolyte imbalance can be detected at an early stage
  - These changes are responsible for the subsequent occurrence of diarrhea

Radiation injury treatment

- Protective treatments can be devised
- Antioxidants scavenge free radicals produced by radiation in the cell, before interaction with critical macromolecules (e.g. DNA)
- Combinations of agents maximize protection
- Post-exposure treatment depends on:
  - Estimate of the dose received
  - Accurate assessment of damage to critical tissues and organs

Selection of exposed persons

- Initial assessment is required to provide:
    - Immediate guidance to medical services in selecting those in need of treatment (triage) and prevent unnecessary overloading of medical facilities by lightly exposed individuals
    - Reassurance to those who have received small or negligible doses
    - Rapid indication to management of the seriousness of the accident

Post accident dose assessment quantities

- Following accidental high doses: absorbed dose in various organs and tissues is needed

- Acute effects are related to absorbed dose in tissue rather than the protection or operational quantities

- Radiation weighting factors are not valid, since they are based on the effects of long-term occupational exposures

- Acute effects depend also on organ/tissue, and the specific RBE for these organs

- The IAEA recommends the use of "torso-averaged" dose, used to "address external exposure to the red marrow, lung, small intestine, gonads, lens of the eye, and thyroid from irradiation in a uniform field of strongly penetrating radiation."

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Quantities to be reported

- Quantity to be reported in initial-phase dose assessment for individuals should be presented as "absorbed dose"
- Use the units of gray in all circumstances in an attempt to avoid the confusion and mistrust that may be generated using multiple or different units in different communication outlets (Gy, Sv, Gy-eq)

Choice of dosimeter

- Depends on the type of radiation
- The following types of dosimeter may be used:
  - Photon dosimeters and neutron dosimeters giving information on the personal dose equivalent $H_p(10)$ for evaluation of D_T in tissues and organs
  - Eye lens dosimeters, giving information on $H_p(3)$ for beta–photon radiation
  - Extremity dosimeters, giving information on the skin dose
- Dose values of general concern range from 250 mGy up to 10 Gy
- Lower limits of interest are about 100 mGy
- Grossly non-uniform irradiations are a special case - dose rates may be up to 10^5 Gy/s

Choice of dosimeter

- To avoid the need for a special additional accident dosimeter, the routine personal dosimeter should be capable to measure to at least 10 Gy
  - Certain dosimeters, such as film dosimeters, may not be capable of achieving this at all energies
- The wearing of warning (alarm) dosimeters (or dose rate meters) can be effective in preventing serious exposures
  - May help in reducing the dose incurred in the accidents
  - Warning dosimeters should be very reliable, especially in high dose rate fields
- Dosimetry in the event of criticality accidents involving fissile materials need criticality neutron dosimeters

Dosimetry system capabilities

- Should permit an initial dose determination within 48 h

- Uncertainty of less than 50%

- Should determine the neutron and gamma-ray components with an uncertainty of less than 25% within one week

- Best accuracy is required for the range for which lethality is possible – whole body irradiation of 2 Gy to 8 Gy

Dosimetry system capabilities for triage

- Some of people require immediate medical attention

- Many persons may have been exposed

- Dosimetry system should provide an exposure indicator for an initial rapid screening to assess doses for all those exposed, to:

  - Identify exposed persons

  - Make rapid assessments of doses

  - Estimate the maximum doses

- Contamination is likely to be a concern

Retrospective dosimetry

- If dosimeters are worn, they should be processed immediately
- Several techniques exist when no dosimeters were worn
  - "retrospective dosimetry": those situations in which conventional dosimeters were unavailable or not sufficient, and yet assessment of doses to exposed individuals is needed or requested

Post accident dose reconstruction

- Dose reconstruction uses multiple input:
    - The assessment of exposures may begin by using data from workplace monitors
    - Position of the source(s) at the time of the accident
    - Positions of exposed individuals relative to the source and any shielding
    - Durations of exposure:
        - Physical characteristics of the radiation field at the locations of exposed persons
        - Orientation of each person
        - Uniformity of irradiation
        - Spectral and dose distribution in the body of each irradiated person
    - Physical methods using body tissues, clothing or samples from the accident scene
    - Biological indicators using the patient's body tissues
    - Accident simulation
    - Mathematical dose reconstruction

Accident dosimetry: retrospective techniques

Physical and biodosimetry

- Physical dosimetry relies on materials that are either biologically derived from the individual (teeth, nails) or are non-biological materials from the personal possessions of the individual (e.g., personal electronics, clothing)
- Biodosimetry (mostly on blood) exploits changes to an organism within the body, either at the molecular level or the cellular level
- Some methods can be used for short-term dose assessment only (e.g., DCA, CBMN, PCC, OSL, TL)
- Others are more stable and can be used either a short time or long time after the event (e.g., FISH, EPR)
- Not all methods are at the same state of maturity

Whole body vs partial body exposure

- Physical dosimetry methods measure the dose to the physical dosimeter material and not to the individual

- It is necessary to use calculation to convert the measured physical dose to an organ dose, or a "whole-body" dose

- Dose estimates to individuals are then based on proximity, mapping of contaminants and/or exposure rates, and information about movements including shielding
  - Not feasible for every individual in the case of a large-scale, mass casualty event

- The physical dosimeter and the biological dosimeter will not yield the same dose

RBE for biological dosimetry

- RBE: ratio of the dose of the reference radiation to the dose of the particular radiation that produces the same biological effect
  - Biodosimetry determines the accident dose modified by the RBE
  - If the radiation source in the accident is of high linear energy transfer (LET), then RBE values >1 can be expected, whereas RBE ≈ 1 for low-LET sources.
- For physical dosimetry, the concept of RBE does not apply
  - Physical dosimetry has to consider the photon energy response of the dosimetric material

Combining computational and retrospective approaches

- Large-scale events: absorbed dose to the dosimeter material is the recommended dose to use
- Small-scale accidents: calculation of doses to specific organs can be performed
  - MC calculations may be combined with biological and physical dosimetry to assess dose to organs of interest
  - Voxel phantoms can be used elaborated from images of the victim provided by computed tomography or magnetic resonance imaging
  - This approach also permits guidance of surgery in cases of exeresis by defining the tissue volume in which tissue necrosis is expected

Accident dosimetry techniques: ICRU 94 document

- Biodosimetry
  - DCA
  - FISH
  - CBMN
  - PCC
  - RNA expression
  - Protein based assays
  - Metabolomics
- Physical dosimetry
  - EPR
  - TL
  - OSL
- Other
  - Bioassays
  - Neutron activation
  - Mapping and time and motion studies

Biodosimetry: important characteristics

- Stability of marker—the time post-exposure when an assay is informative
- Dose range over which the assay is informative
- Time from sampling to the first result
- Ease of use—for example, degree of automation, requirement for specialized technical skills
- Invasiveness of sample acquisition
- Throughput of sample acquisition and analysis
- Confounding factors on results—for example, age, sex, other exposures, and lifestyle factors
- Accuracy
- Additional characteristics—for example, the ability to detect partial-body exposures, low–dose rate exposures, internal emitters, neutron exposure, or high–LET (linear energy transfer) emitting isotopes

Biodosimetry: introduction

- Mostly based on radiation-induced DNA damage and mis-repair, which can be detected by various cytogenetic assays
- Blood circulates throughout the body: averaging the dose from all parts of the body
- Blood samples should be taken days to a few weeks after exposure.
  - If blood sampling is delayed to several weeks or more, this delay has to be considered by correcting for the half-life of the biological marker
- There is a variety of emerging biodosimetry assays rooted in "omic" approaches.

- It is highly unlikely that there will ever be a single, ideal biodosimetry method. The strongest application will likely come from combined or sequential approaches tailored to specific scenarios

Dicentric Chromosome Assay (DCA)

- Radiation exposure causes DNA strand breaks
- During repair of DNA strand breaks, misrepair of 2 chromosomes and abnormal chromosome replication can lead to dicentric chromosomes

- It is considered the "gold standard" for biodosimetry
- DCA has the disadvantage that it requires 2 d of culture plus scoring time before results become available
- Above 5 Gy, the dicentric chromosomes will deviate from the calibration curve, resulting in an underestimation of the dose

Premature Chromosome Condensation (PCC)

- To overcome the shortcomings on DCA for high exposures, PCC was introduced
- This method forces chromosomes to condense in any stage of the cell cycle, making it possible to distinguish individual chromosomes and therefore chromosomal aberrations such as dicentrics, rings, or translocations
- The method can be used from very low doses up to very high within hours of blood sampling while maintaining a high accuracy over a large dose range (0 Gy to 20 Gy)
- The PCC assay, like the DCA, is well suited for acute exposure, but limited after exposure from internal radionuclides, chronic exposure, or exposures a long time in the past

Cytokinesis-block micronucleus cytome (CBMN) assay

- Micronuclei (MNs) result from the formation of small fragments of chromosome material that lack the ability to interact with the mitotic spindle during anaphase. They form small separate nuclei in the cytoplasm
- Ionizing radiation can induce MNs during cell division in a dose-dependent manner through the process of creating unrepaired DNA DSBs
- MNs are counted only in binucleated cells (BNCs), hence the name CBMN assay
- MNs are not uniquely induced by ionizing radiation exposure

Translocation analysis by FISH

- DCA and CBMN: damage is unstable and disappears with time after exposure
- Translocations, although not all stable, persist for longer times in lymphocytes and can be used as a measure of dose long after the exposure
- The development of fluorescent, whole-chromosome paints has made translocation analysis a viable method for biodosimetry
- FISH: higher cost and longer and more complicated staining protocol
- Limited use in emergency biodosimetry

The γ-H2AX Assay

- DNA DSBs: most biologically significant lesion from ionizing radiation
- One of the early cellular responses to DNA DSBs is the phosphorylation of serine 139 of the H2AX histone, which forms foci at the site of the DSB in a one-to-one correspondence
- Fluorescent markers for this phosphorylated form of H2AX (γ-H2AX) have enabled the visualization of foci at the sites of DSBs
- The dose response in lymphocytes has been shown to be linear up to 10 Gy. Under well-controlled conditions, doses as low as a few mGy can be detected
- Samples can be processed and analyzed immediately
- The background levels of γ-H2AX vary between individuals and are affected by age and lifestyle factors such as smoking

Emerging asseys: omics

- Radiation exposure triggers complex cascades of signaling events:
    - Broad changes in the cellular transcriptional program
    - Changes in the levels, localization, and activation status of both signal transduction and effector proteins
    - Changes in cellular, tissue, and organism metabolism
- Biodosimetry assays are being developed to measure changes at the RNA, protein, and small molecule metabolite levels
    - "-omics" technologies: transcriptomics, proteomics, and metabolomics
- These approaches are still under development and not yet standardized
- RNA expression, protein based or metabolomics based assays

EPR: electron paramagnetic resonance

- Spectroscopic technique used to detect and/or identify the sites of unpaired electrons in materials
- Relevant are those radicals induced by ionizing radiation
- Ideally, a material for EPR dosimetry should have a minimum number of properties:
  - Ubiquity, non-invasive sample collection, easy and fast sample preparation, radiation specific, stable in time, clearly distinguishable from non–radiation-induced signals

EPR on tooth enamel (and bone)

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- Considered to be the "gold standard" in retrospective dosimetry, especially for epidemiological studies
- Signals that are stable enough to maintain the information on radiation exposures for decades
- A significant limitation: necessity to have extracted teeth for the dose measurement
- Sufficient time is needed to build a repository of tooth samples
- In-vivo measurement techniques are being developed

- Long-lived radicals can also be detected in irradiated bones by EPR spectroscopy
- Only for very invasive accidents where it is possible to sample bone

EPR on human nails and hair

- Hair, human fingernails and toenails present a radiation- sensitive signal
- Easy and painless collection
- Can be useful for localized irradiation
- Nails
  - Not radiation-specific
  - High uncertainty, not stable
- Hair
  - High intrinsic background
  - Susceptible to UV irradiation and temperature
  - Intensity decreases with time
  - Characteristic of the hair color
- Imperfect and limited-use tools

EPR on sugars / mineral glass

- Sucrose:
  - Almost tissue-equivalent material
  - Stable and dose-dependent EPR signal
  - Linear dose response up to 10 kGy
  - Weak background signal
- Mineral glass, like mobile device touchscreen glasses
  - Properties vary from one type of glass to another
  - Need to destroy the display
  - Confounding signals linked to the light exposure history
  - Highly variable intensity of the background signals
  - Significant decay with time following irradiation

EPR on cotton / plastic

- Textile fibers / cellulose (cotton)
  - Easy collection
  - Allow mapping of the absorbed dose distribution over the body.
  - Pre-irradiation signals
  - Unstable in time
  - Some confounding factors (solar light, detergent, water content,…)
- Plastics
  - Many objects in daily usage (mobile phones, credit cards, buttons, watches, and eyeglasses)
  - Easily collected
  - Rarely used for accident dosimetry due to several important drawbacks
  - Large variety of compositions: each has different properties

Luminescent techniques

- Thermoluminescence (TL) and optically stimulated luminescence (OSL) have long been used in conventional radiation dosimetry
- In emergency dosimetry using fortuitous materials that were on or part of a victim
  - High sensitivity
  - Ease of use
  - High throughput
  - Standardized protocols and accepted uses have not yet emerged

Electronic components

- Chip cards
  - Used on certain credit cards, bank cards, health insurance cards, electronic ID cards, electronic passports, and SIM cards in mobile phones
  - Reverse side, often covered by a plastic laminate, can be used for OSL dosimetry after extraction of the chip from the card
- Surface-mount devices
  - From the circuit board in the form of resistors (and, to a lesser extent, inductors)
  - Mobile phones
  - Destructive
- Integrated circuits
  - Mobile phones
  - Destructive

LCD Display and Touchscreen Glass of Mobile Phones

- Glass has long been known to be a radiation-sensitive material
- TL or PTTL
- The display of mobile phones can be used in emergency dosimetry
- The displays have become increasingly bigger, supplying an ample amount of sample material
- The touchscreen display can be replaced after sampling at lower costs than of replacing the entire phone

Other Personal Items

- Plastic Cards and banknotes
  - High prevalence and low personal value
- Dust on Personal Items and coins
  - Optically stimulated luminescence or TL from dust on herbs, spices, and other foodstuffs
  - OSL on silicate-based dust collected from jewels, watches, keys, coins, and tobacco
- Clothing/fabrics
  - Widespread occurrence
- Knowledge of the dosimetric properties of these materials is, at present, less advanced

Overview on biological methods

Assay	Materials	Period of use since exposure	Partial body exposure	Time (h) from sample receipt to dose estimate	Specificity	Dose Range (Gy)	Automated
DCA	Whole blood, lymphocytes	Days to months	Y	55	IR	0.1-5	Yes
PCC fragments	Whole blood, lymphocytes	Days	Y	2	IR	0.2-20	No
Micronuclei	Whole blood, lymphocytes	Days to months	N	75	IR-BGS	0.2-4	Yes
FISH	Whole blood, lymphocytes	Days to years	N	120	IR-BGS	0.25-4	N
Gamma H2AX	Whole blood, lymphocytes	hours	Y	3	IR/BGS	0.5-10	Y
Gene expression	Whole blood, lymphocytes	Hours to days	Y	4	IR/BGS	0.5-10	N
Small metabolits	Urine, blood, serum, blood plasma	Hours to days	Y	3	IR/BGS	1-10	N
Proteomics	Whole blood, lymphocytes, urine, blood serum, blood plasma	Hours to days	Y	3	IR/BGS	0.5-10	N

Overview on physical methods

Assay	Materials	Period of use since exposure	Identify Partial body exposure	Time (h) from sample receipt to dose estimate	Specificity	Dose Range (Gy)
TL or OSL: surface mounted components	Resistors, inductors	Days to weeks	No	1-2	G,X,b	0.1-10
TL or OSL: ICs	Epoxy encapsulation	Days to weeks	No	1-2	G,X,b	0.01-10
TL or PTTL phone glass	Ptotective glass, display glass	Days to weeks	No	1-4	G,X,b, UV, BgS	0.3-20
OSL: other electronic components	Chip cards	Days to weeks	No	1-2	G, X, BGS	0.01-10
OSL clothing	Fabrics, shoes (e.g. polymers such as in cotton, PVC, polyester)	Days to weeks	No	1	G, X, b, bgs	0.1-10
TL or OSL: other	Plastic cards, dust, money	Days to weeks	No	1	G, X, b, bgs	0.1-10
OSL dental materials	Tooth enamel, repair ceramics	Days to weeks	No	1	G,X,b, UV, BgS	0.01-10
EPR teeth	Enamel	Days to years	possible	1	G,X,b, UV, BgS	0.01-10
EPR bone	Hydroxyapatite	Days to years	Possible	Several	G, X, BGS	1-10
EPR nails	Finger or toes	Days	Possible	2-4	G,X,b, UV, BgS	0.1-10
EPR phone glass	Protective glass, display glass	Days to years	No	1	G,X,b, UV, BgS	1-few
EPR, other	Plastic components of clothing	Days to years	No	1	G,X,b, UV, BgS	1-few

Conclusions

- Choice of method depends on the number of affected individuals and the type of radiation exposure

- The choice of method also depends on the goal of the measurement
  - If the goal is rapid screening for triage purposes
  - more detailed follow-up. to assist medical practitioners in determining the most appropriate interventional medical therapy

- Based on laboratory intercomparisons, optically stimulated luminescence (OSL) of electronic components is possibly the closest to real-world application

- Electron paramagnetic resonance (EPR) of biologically derived material (e.g., teeth) is well developed for in-vitro analysis, but not yet for in-vivo analysis

- The available emergency dosimetry methods lead to estimates of the actual absorbed dose with an uncertainty level of ~±20 %

Dose Reconstruction

- Involves
  - techniques for retrospectively estimating radiation dose
  - combinations of theory, modeling, simulation, calculation and measurements.
- Long times after exposure
  - heavily dependent on detailed descriptions of the exposure scenario
  - use various types of exposure-related data (e.g., environmental monitoring data and/or biodosimetry measurements that take days to months to collect).
- Short times after exposure
  - rely on previously developed and benchmarked computer simulation codes
  - computational tools that can be implemented quickly and immediately

Dose Reconstruction

- Numerical approaches are often combined with physical or biodosimetry
  - To normalize the relative dose distribution within the body to the measured dose
  - Numerical phantoms with a high degree of anatomical sophistication
- If the conditions of the accident can be safely reproduced
  - Experimental approach can provide a dose distribution within the body, using a tissue-equivalent phantom filled with appropriate dosimeters
- Future developments
  - 4-dimensional simulation
  - Taking into account the individual's movement during and after the irradiation
  - 3D representation of the accident environment
  - Generate quickly an accurate input file for Monte Carlo codes.

Radiation field mapping

- Radiation doses can be easily estimated based on maps of radiation fields following a radiation incident (if available)
  - E.g. to distinguish locations where the exposure level was sufficient to require medical triage or epidemiologic follow-up
- Radiation field maps can also be used to communicate about the locations of more, or less, health risk
  - Distinguishing areas of "worried well" versus "considerably exposed"

Contamination

Contamination: general

- In an accident, both external and internal contamination is possible for workers and public
- Knowledge of the form of the contamination is needed in deciding the best type of assay and instrumentation to be used.
- The degree of contamination depends on:
  - Situation in which contact with radioactive contamination took place
  - Physical attributes of that part of the body (clothing) that is contaminated
  - Whether internal contamination took place
  - Chemical or physical form of the contaminants

Contamination of public/workers

- Strategies are needed to assess the type and degree of contamination for medical decision making
- Contaminated workers: detailed methods and procedures often exist
- Contamination of the public: much more difficult to manage
  - Population monitoring to evaluate:
    - Required medical treatment
    - Presence of radioactive contamination on the body or clothing (external contamination)
    - Intake of radioactive materials into the body (internal contamination)
    - Removal of external or internal contamination (decontamination)
    - Radiation dose received
    - Resulting health risk from the exposure

Contamination measurements

- Population measurements for external contamination depends on:
    - Number of persons suspected of having been contaminated
    - Number of measurement systems available (and the number of trained personnel available to operate them)
    - Level of contamination of each person
    - Required counting times
    - Complexity of the assay
    - Complexity of the steps necessary to conduct overall data collection. The latter involves interviewing, obtaining informed consent

External Contamination

- External contamination is usually simpler to assess than internal contamination
    - Clothing can be discarded
    - Hair can be washed or cut
    - Skin can be subjected to a range of physical and chemical decontamination agent.
- Body may be very heterogeneously contaminated
    - Difficulty in numerically describing the degree of contamination
- Many types of instrumentation are suitable for detecting contamination
    - Could include emitters of alpha, beta, or gamma radiation
    - Alpha and beta surface contamination measurement instruments, portal monitors, portable gamma spectrometry and gamma dose rate instruments, and personal alarming dosimeters capable of measuring instantaneous dose rate and cumulative dose

External contamination: general measures

- Additionally, corrections of the measured dose might need to be made if a dosimeter is contaminated

- The best way to limit cross-contamination is to frequently measure contamination during and after a manipulation by means of a contamination monitor

- In cases of skin contamination with radioactive substances, immediate and rapid decontamination measures are of higher priority than an exact evaluation of skin activity and dose

Skin contamination

- Contamination of the skin will lead to external exposure and sometimes even to internal exposure, depending on the radionuclide(s) involved, the chemical form(s) present and the activity concentrations

- Principal objectives
  - To ensure the avoidance of deterministic effects
  - In the case of overexposures, to initiate and/or to support any appropriate medical examinations and interventions

Dose limits and skin contamination

- Strongly penetrating radiation
  - For strongly penetrating radiation, the limitation on effective dose generally provides sufficient protection for the skin from stochastic effects

- Weakly penetrating radiation
  - For weakly penetrating radiation, the equivalent dose to the skin is limited to 500 mSv in a year, averaged over 1 cm^2 of the most highly irradiated area. The nominal depth of measurement is 0.07 mm (7 mg/cm^2)

Hot particles

- Situations may arise in which exposure due to 'hot particles' is possible.
  - This can lead to spatially non-uniform exposure from discrete radiation sources with dimensions of up to 1 mm
- Acute ulceration is a particular end point to be prevented
  - This implies that the average dose delivered within a few hours over a skin area of 1 cm^2, should be restricted to 1 Gy
- Detection of hot particles within an ambient radiation field in a workplace can be difficult, because of the very localized nature of the radiation from the particle
  - Emphasis should be given to identifying and controlling those operations that could give rise to such hot particles

Estimation of the dose to the skin from contamination

- Skin contamination in working environment:
  - Unlikely to be recorded by a personal dosimeter
  - Can be detected by the routine use of contamination monitors
- On-site investigation
  - Localize and identify the contamination
  - Quantify its activity
  - Dose assessment
- The dose rates per unit of activity over 1 cm^2 can be calculated:
  - Calculation with the deterministic code like VARSKIN
  - Monte Carlo simulation code of radiation transport

Estimation of dose to the skin from contamination on protective clothing

- The contamination on protective clothing (e.g. gloves) irradiates the skin and contributes to the skin dose. Its contribution to the skin dose should be quantified

- After quantification, if its value is higher than the dosimeter reading, it shall be registered as the skin dose value

- When the contamination is homogenous across the protective clothing or located directly at the dosimeter position, the dosimeter reading already takes into account the contribution

Estimation of dose from exposure to radioactivity in the air

- Radionuclides in the air in the working environment lead to exposure of the personnel. This leads to exposure of the skin

- The directional dose-equivalent rate, H'(0,07) caused by radioactive contamination in room air is to be calculated, if necessary, from the radionuclide composition and "concentration" or should be determined by a measurement

- dosimeters measuring $H_p(0,07)$ provide in most cases the requested dose value

Need to correct estimated doses due to contamination of dosimeters

- If an individual dosimeter is contaminated, the dosimeter reading is larger than the true dose to the respective individual

- If the time the dosimeter has been contaminated, the activity and position of the contamination is known, this excessive reading of the dosimeter can be determined

Accident dosimetry for neutrons: criticality dosimetry

Criticality dosimetry

- *"An unplanned or uncontrolled nuclear excursion resulting from the inadvertent assembly of a quantity of fissile material in a physical geometry such that the configuration is capable of supporting a chain reaction."*

- Possible accumulation of critical fissile material mass or volume
- Could involve fissile material only, or include the fissile material in close proximity to hydrogenous material (e.g, submerged in water)
- Could lead to accident with very high neutron dose in short time
  - Routine neutron dosimeters can not measure this
  - Specific dosimeter types are needed
- Individual monitoring with dedicated criticality dosimeter required

Criticality accident summary

Type	Number	Significant Fatalities	Exposures
Process systems	8	38	2
Fissile solution systems	5	1	0
Bare and reflected metal systems	11	10	2
Moderated metal and metal oxide systems	11	29	2
Miscellaneous systems	6	6	0
TOTAL	41	84	6

- Criticality accidents are rare
- The last 2 occurred in Tokaimura, Japan, in 1997 and in Sarov, Russia, in 1999
  - These 2 accidents led to the death of 3 persons

Neutron criticality accident

- Neutron interactions in matter lead to secondary particles with high LET and significant biological effects
- Specific techniques for emergency dosimetry have to be considered when dealing with neutrons
  - Additional approaches like the measurement of activated radioactivity
- Biological effectiveness of neutrons and gamma are different
  - Determine the gamma and the neutron dose components separately
    - Gamma rays produced in the body, mostly by thermal neutron interactions
    - Direct gamma dose component impinging the body comes from the neutron production process or from neutron scattering outside the body

Neutrons accident quantities

- Specific dose quantities have been proposed in the case of criticality accidents
  - To estimate the maximum dose in the body
  - Estimated by considering "the dose deposited in a volume element 2 cm thick, located at the mid-point of the frontal surface of a cylindrical phantom with a radius of 15 cm and height of 60 cm"
  - This particular element volume is defined as element 57 of the phantom
- The fluence-dose conversion coefficients for element 57 have been calculated
- Takes into account dose due to albedo neutrons

Criticality dosimeters – activation foils

- Traditionally, most common criticality accident dosimeter
- Detectors chosen for their cross sections and half-lives
- Half-life long enough to allow post-accident recovery and counting, usually > 1 hour
- Cross sections to cover thermal to > 10 MeV
    - Thermal
    - Intermediate – n,γ, w/ cadmium covers.
    - Fast – n,n', n,p or n,α
  - Not sensitive to gamma's: can be determined separately

Slow neutron fluence determination

- Lower-energy neutrons usually provide a relatively unimportant fraction of tissue dose
- Usually use n,γ reactions
- Employ paired foils, w/ and w/o Cd covers
- Thermal neutron fluences vary appreciably close to the surface of the body and differ from those at the same point in free air
  - Because neutrons incident upon the body backscatter and re-emerge from it with the same or lower energies
  - For thermal neutrons about 80% of the incident neutrons are backscattered

Intermediate neutron detectors

- Usually n,γ detector with Cd cover

- Should have an high sensitivity in the range 10^2 -10^5 eV

- Not easy to achieve, so information in this energy region is often lacking

- Correlation between the incident and reflected fluences is influenced by many factors, e.g. neutron spectrum, angle of incidence and body-detector separation

Thermal and intermediate detector materials

| Foil material	Reaction	Half life	Principle radiations emitted - MeV
Gold	^{197}Au(n,γ)^{198}Au	2.7d	γ (0.412) β (0.961)
Copper	^{63}Cu(n,γ)^{64}Cu	12.8 h	Photon (0.511) β (0.578)
Indium	^{115}In(n,γ)^{116m}In	54.3 m	γ (0.417, 1.097, 1.294) β (0.873, 1.011)

Fast neutron detectors

- Several factors influence the choice of nuclear reactions for measurement of fast neutrons:
  - Low neutron energy threshold
  - Well-established cross-section
  - Sufficiently long half-life (activation detectors)
  - High sensitivity to fast neutrons
  - No reactions with thermal neutrons that mask the measured reaction product
- No fast neutron detectors that satisfy all requirements
- Combination of several activation foils

Fast neutron detector materials

Foil material	Reaction	Effective neutron threshold (MeV)	Product half-life	Principal radiations Emitted (Mev)
Rhodium	$^{103}Rh(n,n')^{103m}Rh$	0.8	56.1 min	X-ray (0.020)
Indium	$^{115}In(n,n')^{115m}In$	1.2	4.5 h	γ (0.335)
Phosphorus	$^{31}P(n,p)^{31}S$	2.8	2.62 h	β (1.49)
Sulfur	$^{32}S(n,p)\ ^{32}P$	3.3	14.3 d	β (1.711)
Magnesium	$^{24}Mg(n,p)^{24}Na$	7.5	15.0 h	γ (1.37, 2.75)

Some relevant cross sections
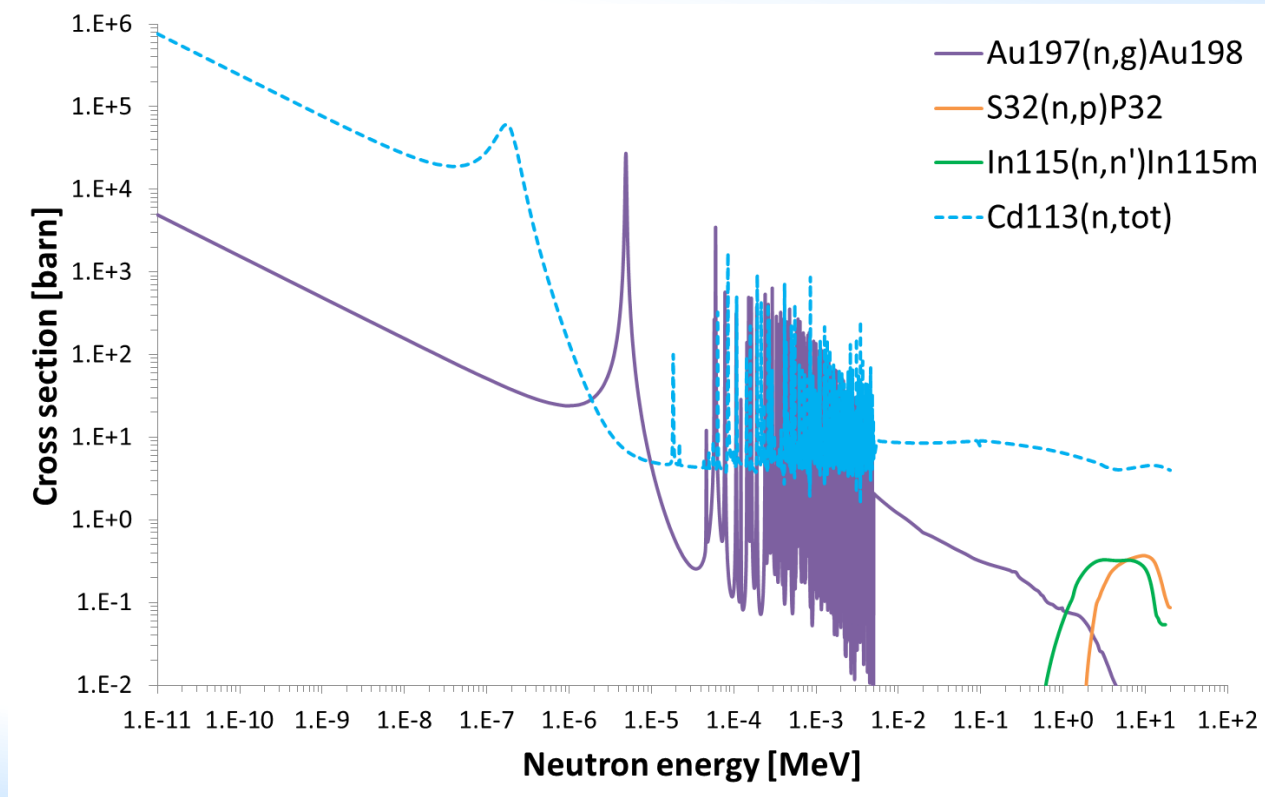
Some foils can be used for immediate on-site triage

- $^{115}In(n,\gamma)\,^{116m}In$
  - $^{116m}In(54min) \rightarrow \beta^-(880keV) + {}^{116}Sn^* \rightarrow \gamma(1293keV) + {}^{116}Sn$

- Immediate triaging with gamma survey meter

- About $60\ \dfrac{\mu Sv/h}{Gy}$, depending strongly on the energy spectrum
  - Only the order of magnitude of the dose can be estimated

Relation between activity and fluence

- $A = f_{ss} f_{con} \dfrac{N_A}{\mathcal{M}} \lambda \int_0^{+\infty} \sigma(E) \varphi(E) dE$

  - A = Activity
  - f_{ss} = Self-shielding correction factor
  - f_{con} = Isotopic abundance correction factor
  - N_A = Avogadro constant
  - $\mathcal{M}$ = Molar mass
  - λ = Decay constant
  - $\sigma(E)$ = Energy dependent neutron cross section
  - $\varphi(E)$ = Neutron fluence energy spectrum

Deconvolution of the neutron spectra

- Combination of different activation foils: deconvolution of neutron spectra
    - To give correct dose quantity
- Underdetermined mathematical problem
- Iterative algorithm
    - Starting from an intelligent guess for the energy spectrum:
        - If real spectrum is not known: start from fission spectrum + thermal component

    - Binning of the energy range: $\ln(E_j) = \ln(E_0) + j \dfrac{\ln(E_{n_E-1}) - \ln(E_0)}{n_E}$

    - $\varphi_{n+1}(E_j) = \varphi_n(E_j) \dfrac{\sum_i \frac{\sigma_i(E_j)}{R_{calc,i}}}{\sum_i \frac{\sigma_i(E_j)}{R_{meas,i}}}$

IAEA recommendations for criticality dosimeters

- Dose range from 0.25 up to 10 Gy

- Dose rates up to 10^5 Gy/s

- Estimation of neutron energy spectrum

- Immediate separation of exposed and non-exposed individuals

- Dose reconstruction with < 50% uncertainty within 2 days

- Dose reconstruction with < 25% uncertainty within 6 days

Neutron Activation in the body

- When there is an accident, not always are the victims wearing a dosimeter, nor criticality dosimeters
- Even if they do wear a dosimeter, extra information is always useful
- Radiological accidents with a neutron component
  - Leads to induced radioactivity in body tissues, metal objects and clothing
  - No perturbations from the direct gamma-ray components
- Neutron activation products with short half-lives require short delays in measurements

Neutron Activation in the body

- Activation of sodium in blood
  - $^{23}Na(n,\gamma)^{24}Na$, t ½ = 14.96 h, E_γ = 1.36 MeV (100 %) and 2.75 MeV (99.85 %)
  - Can be used for triage
  - Induced activity from ^{24}Na is mainly due to thermal neutrons
  - Fast neutrons compared with thermal neutrons will generate a lower level of activated sodium but a much higher level of dose
  - The total sodium activity is dependent on the surface of the body exposed
  - The sodium activity also depends on the mass of the body

Neutron Activation

- Other activation options
  - Activated sulfur in hair, nails, and wool
  - $^{32}S(n,p)^{32}P$, $t_{1/2}$=14.28 d, $E_{\beta max}$=1.710 MeV (100 %)
  - Threshold for the reaction is about 3 MeV
  - Cross section of this reaction almost constant between 3 MeV and 20 MeV
  - Sulfur activity approximately proportional to the neutron kerma in tissue
  - Hair can be collected from different parts of the victim's body, and thus useful information on the dose distribution can be derived