Rapid Internal and External Dose Magnitude Estimation

The Radiation Emergency Assistance Center/Training Site

REAC/TS
PO Box 117, MS-39
Oak Ridge, TN 37831
(865)576-3131
www.orise.orau.gov/reacts

prepared by:
Stephen L. (Steve) Sugarman, MS, CHP, CHCM
Health Physics Project Manager, REAC/TS

Internal Dose Magnitude Estimation
Using Annual Limits on Intake (ALI) Comparisons and Derived Reference Levels (DRLs)

Assessing the radiological condition of injured personnel is an important part of the health physicist's job, although hopefully, one that is not done very often. There are many things to be considered. Priorities have to be set, appropriate instrumentation should be selected, proper techniques have to be used, and - many times - a little detective work needs to be done. Also, one should not forget that in many cases medical care providers may not be accustomed to working with radioactive materials. Therefore, they may need attention from the health physicist not only for advice and assistance with radioactive material controls, but for reassurance.

When a person has sustained an injury, there is one over-riding general principle: Medical needs take priority over radiological concerns. Medical evaluation and stabilizing treatment should not be delayed in order to perform a thorough survey or to decontaminate an injured individual. Once the victim has been medically stabilized, radiological surveys and subsequent decontamination may begin. According to an article in *Health Physics News* by Stephanie Carlson, MD, *Ask a Doc? What Do Physicians Know about Radiation Anyway?* (Volume 36, Number 8) there is a suggested general lack of knowledge within the medical community about ionizing radiation and its effects, so it is essential to integrate the health physicist into the radiation emergency medical response team. Establishing a good working relationship between health care providers and health physics personnel in advance of an incident will help the response go much more smoothly and efficiently.

After the normal questions asked by many medical care providers when treating a radioactively contaminated patient, such as "Is it safe for me to treat this patient?" (The answer to which is nearly always, "Yes," with regard to radiological concerns.), the questions often turn to how to treat for intakes of radioactive materials. There is quite a bit of published guidance regarding how to treat, but not much regarding how to rapidly estimate the intake of radioactive materials in a non-occupational setting where there are no routine air samplers, survey histories, or other normally accessible tools to help guide decisions.

Just as medical personnel attempt to determine the history of the patient in order to determine the proper treatment, attempts should also be made to ascertain the generalities of the incident from a radiological point of view. Points of concern may include – but not be limited to – where was the victim at the time of the accident? What was he/she doing? Aside from contamination issues, should exposure be a concern (to the victim and/or care providers)? What radioisotopes were involved? What type of protective clothing or respiratory protection was used? Where are the areas of contamination – wounds? Intact skin? Face?

The key to early medical management of internalized radioactive materials is not necessarily radiation dose calculation and assignment, but radiation dose *magnitude* estimation. An early estimate of the magnitude of the intake and resulting dose can be used to predict potential biological consequences and the corresponding need for medical intervention. All radiation doses should be assigned using proper dosimetry techniques. However, waiting for the results of the formal internal dosimetry process to make treatment decisions often takes time that may delay

treatment. For some radioisotopes, such as many of those in the actinide series (^{241}Am, the plutonium isotopes, etc.), it is especially important to be able to make early assessments of potential intakes so that the decision whether or not to administer appropriate medical countermeasures can promptly be made. For instance, DTPA is most effective when given within a few hours of the occurrence of the intake; therefore a delay in treatment may lead to less dose aversion.

Radiation doses due to internally deposited radionuclides are calculated based on the intake. The intake is the amount of radioactive material taken into the body by inhalation, absorption through the skin, injection, ingestion, or through wounds (*NCRP Report No. 87, Use of Bioassay Procedures for Assessment of Internal Radionuclide Deposition* -1987). Once the intake is determined, the CEDE and/or CDE can then be calculated. Annual Limits on Intake (ALIs) are regulatory limits on how much radioactive material can be taken into the body by radiation workers each working year. U.S. guidance regarding ALIs can be found in *EPA Federal Guidance Report No. 11, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. There, ALIs are provided for both inhalation and ingestion intakes and are based on "whole body" doses (CEDE – committed effective dose equivalent – stochastic risk based) or doses to individual organs (CDE – committed dose equivalent – deterministic risk based), whichever is most restrictive. (The ALIs are listed in uCi or MBq. 1 uCi is 2.22 x 10^6 disintegrations per minute, or dpm, and 1 MBq is 27 uCi.)

Magnitudes of inhalation intakes can be estimated by applying simple rules of thumb to sample results or direct measurements and comparing your answers to known limits, in this case the ALI for the radioisotope of concern, for a projection of dose magnitude. For suspected inhalation intakes, the nasal swab is a quick and simple sampling method. A cotton swab is lightly rubbed along the anterior nasal passages in order to collect the sample. A separate swab should be used for each naris. The individual performing the swabs should take care not to go too deeply into the nose or to abrade the lining of the nasal cavity.

According to Mansfield (1997), intakes due to particle sizes in the 1 to 5 μm AMAD (Activity Median Aerodynamic Diameter) range can be estimated by assuming that the nasal swab results are about 5%-10%, respectively, of the intake. This is provided they are taken within the first 30 minutes, or so. (1 μm is the particle size used in *Interpretation of Bioassay Measurements NUREG/CR-4884* which uses ICRP 26 and 30 modeling. Newer ICRP models use 5 μm as the default particle size.) Using the ICRP 66 model (ICRP 1994a) and its values for regional depositions of 5 μm AMAD particles, one finds the ratio of deposition between the external nasal passages and the other respiratory tract compartments is 1 to 4.1 (or about 25% deposition in the anterior nares). Additionally, ICRP 66, reports nose-blow values ranging from 1% to 17% in 10 observed individuals.

Since we are interested in dose magnitude, a value of 10% should provide an appropriate estimate of the amount of intake found on nasal swabs taken from the external nasal passages of the general population if the swabs are taken early (separate swabs for each naris, summed). Additionally – and importantly - it is easy to work with powers of ten, making this rule of thumb easily applied by people of different experience levels and backgrounds (medical vs. health physics, for instance).

Example:

> Nasal swabs are taken on an individual that was in the vicinity of a small explosion that occurred in a laboratory fume hood. The swabs are taken from the individual 15 minutes after the explosion. It has been determined that the contamination is from an unknown beta-emitting radionuclide. Individual swabs are taken from each naris. They are counted separately using a pancake GM detector, and the numbers from each swab are then added together for a total of 10,000 counts per minute (cpm). If we then assume a 10% detector efficiency 10,000 cpm will equal 100,000 dpm (1 cpm = 10 dpm). Using the above referenced rule of thumb we know that about 10% of the intake was found on the swabs, so the intake was about 10 times the total swab activity resulting in an intake of 1,000,000 dpm. Since we don't know what the radionuclide is, we use Table 1 (unknown beta-emitter assumes Sr-90) and compare the estimated intake activity to the inhalation ALI. In this case we have 1,000,000 dpm/8,900,000 dpm, or about 11% of one ALI, call it 0.1 ALI. This indicates that the intake isn't likely of immediate medical concern.
>
> > Note: Bioassays should be performed, and stricter internal dosimetry protocols should be followed to verify the magnitude estimation and intake amount.
>
> If the radionuclide is known, we may use Table 2 (A complete list of ALIs can be found in US EPA Federal Guidance Report No. 11.).

One of the keys to proper assessment is to apply common sense to your investigation. Some things to consider are 1) Is the contamination bilateral? Most of us breathe through each nostril fairly uniformly. If elevated contamination levels are found in one naris, but not the other it may be because of cross contamination – check for a contaminated finger! Of course, it may be due to a deviated septum or other reasons. 2) Will the estimate need to be adjusted to take mouth breathing into account? 3) Was there significant facial contamination? It seems reasonable that in most cases where there is enough airborne contamination for a medically significant inhalation intake there would be the presence of facial contamination or significant contamination of the clothing. 4) Particle size will affect the deposition depth and will likely be unknown at the time of an incident. Obviously, there are other things to consider, but, one needs to remember to maintain awareness of what would seem to make sense when assessing contamination for the potential of medically significant internal doses. It is worth stating that the absence of positive results does not necessarily mean that an intake has not occurred, but that the presence of positive results can be used for dose magnitude assessment. Any time an intake is suspected bioassays should be performed for verification purposes.

It is worth noting that the ALIs used in the United States differ from those used in many other parts of the world because of the use of different modalities (ICRP 26/30 vs. ICRP 60/66, for instance), tissue weighting factors, and other reasons. Since the ALI is used solely as a reference point based on an "acceptable risk" for radiation workers, it is not as important which set of ALIs (U.S. or international) one uses, but that one understands upon what their benchmark is based. By providing the basis for a quick and simple method for determining the magnitude of the potential dose, the ALI provides us with a comparison point that can be easily obtained and compared to the estimate of the intake, thus allowing medical treatment decisions to be made in a timely fashion.

Open wounds present another route for radioactive contamination to enter the body. NCRP Report No. 156, Development of a Biokinetic Model for Radionuclide-Contaminated Wounds and Procedures for their Assessment, Dosimetry, and Treatment (2006) was consulted to calculate dose conversion factors for various radioisotopes and contaminant/wound types using the Activity and Internal Dose Estimates (AIDE, Bertelli) internal dosimetry software. Dividing the applicable regulatory dose limit by the corresponding dose conversion factor (DCF) results in what can be termed a derived reference level (DRL) – similar to an ALI, which is not defined for wounds (Toohey, et al., *Health Physics* - in press).

DRLs (Table 3, below) can be used as a reference point in much the same way as the ALI is used above. To apply this concept simply obtain an early wound count, convert the count rate to an activity (dpm), and compare it to the appropriate DRL. Remember that just because the contamination levels are higher than the DRL does not necessarily mean there is a significant medical issue, but simply that the contamination levels may result in an internal dose close to the regulatory limit.

Please note that Table 3 is based upon US dose limits, but the dose conversion factors were based on effective dose (international guidance). This should not affect the use of this table for dose magnitude estimation. Remember that the point is to determine a point with which comparisons can be made. These comparisons can then be used to help guide medical decisions. International guidance will use different dose limits resulting in different DRLs (20 mSv – or 2 rem – divided by the appropriate DCF). Refer to NCRP No. 156 or contact REAC/TS for further guidance.

As is usual with rapid field assessments common sense must be used. Confounding factors may include contamination of intact skin immediately surrounding the wound site, the fact that alpha particles being so easily shielded may not be readily detected due to blood or other bodily fluids, or an injection may have occurred at a depth (or of a size) that precludes the contamination from being readily measured by simple handheld instrumentation.

Following is an example of rapidly field assessing a contaminated wound:

> An individual was using a disk grinder to grind welds on contaminated waste containers. He sustained a wound to the thigh when the weld seam was weakened allowing the lid to rapidly break free, bouncing the grinder against his leg. After ensuring he was medically stable, a direct count of the wound with a pancake GM reveals a total count rate of 200,000 cpm. The radionuclide of concern is Cs-137. If we assume a 10% instrument efficiency the activity level is 2,000,000 dpm (or about 1 μCi or 37 kBq). Consulting the table of DRLs above one finds that approximately 200,000,000 (2E8) dpm in the wound would result in an expected committed effective dose equivalent (CEDE) of 5 rem. Therefore, initial magnitude estimates indicate that medical intervention is not immediately necessary.
>
> > Note: Bioassays should be performed, and stricter internal dosimetry protocols should be followed to verify the magnitude estimation and intake amount.
>
> If the radionuclide is unknown, based on the emission we may use Table 1 (A complete list of ALIs can be found in US EPA Federal Guidance Report No. 11.).

It bears repeating that these methods are not intended to specifically quantify the radiation doses associated with potential intakes due to inhalation or contaminated wounds, but to provide a tool the health physicist or physician can use to help guide initial medical management. Doses should be confirmed vis proper dosimetry methods (urinalysis, whole body counting, etc.).

Table 1 – U.S. ALIs for Assumed Radionuclides

Emission	Assumed Nuclide	Inh. ALI (μCi)	dpm	dps (Bq)
alpha	Am-241	0.006 - W	1.3×10^{4}	7.8×10^{5}
beta	Sr-90	4 - Y	8.9×10^{6}	5.3×10^{8}
gamma	Cs-137	200 - D	4.4×10^{8}	2.6×10^{10}

Most restrictive ALI values in FGR-11 are listed (solubility class also listed).

Table 2 – U.S. ALIs for Specific Radionuclides

Nuclide	Inh. ALI (μCi)	dpm	dps (Bq)
H-3	80,000 (H_20 Vapor)	1.8×10^{11}	1.1×10^{13}
Co-60	30 - Y	6.7×10^{7}	4.0×10^{9}
U-235, 238	0.04 - Y	8.9×10^{4}	5.3×10^{6}
Pu-238	0.007 - W	1.6×10^{4}	9.6×10^{5}
Pu-239	0.006 - W	1.3×10^{4}	7.9×10^{5}
Cf-252	0.02 - W	4.4×10^{4}	2.6×10^{6}

Most restrictive ALI values in FGR-11 are listed (solubility class also listed).

Table 3 - Selected DRLs for Defined Solubility Class (dpm)

Isotope	**Based on***	**Weak**	**Moderate**	**Strong**	**Avid**
Co-60	ED	1.54E+08	1.54E+08	1.65E+08	2.01E+08
Sr-90	BS	2.20E+07	2.20E+07	2.25E+07	2.38E+07
Tc-99m	ED	2.00E+11	2.56E+11	9.33E+11	8.78E+11
I-131	Thy	7.06E+07	8.01E+07	1.26E+08	3.46E+08
Cs-137	ED	2.20E+08	2.20E+08	2.23E+08	2.34E+08
Ir-192	ED	4.49E+08	4.66E+08	6.21E+08	1.69E+09
U-235	BS	8.23E+05	8.23E+05	8.29E+05	8.46E+05
U-238	BS	8.55E+05	8.55E+05	8.63E+05	8.78E+05
Pu-239	BS	1.81E+03	1.81E+03	1.85E+03	1.92E+03
Am-241	BS	1.65E+03	1.65E+03	1.68E+03	1.74E+03
Cf-252	BS	5.14E+03	5.15E+03	5.75E+03	7.96E+03

ED reference point = 5 rem (committed)
Organ dose reference point = 50 rem (committed)
** ED = Effective Dose, BS = Bone Surface, Thy = Thyroid*

Information for Internal Dose Magnitude Estimation Using Annual Limits on Intake (ALI) Comparisons and Derived Reference Levels (DRLs) was taken from the following sources not specifically mentioned in the text:

Sugarman, S; Toohey, R; Goans, R; Christensen, D; Wiley, A. *Rapid Internal Dose Magnitude Estimation in Emergency Situations Using Annual Limits on Intake (ALI) Comparisons*. Health Physics, 96.6 (June, 2010): 815-818.

Toohey, R; Bertelli, L; Sugarman, S; Wiley, A; Christensen, D. Dose *Coeffecients for Intakes of Radionuclides Via Contaminated Wounds*. Health Physics, 100.5 (May, 2011): 508-514.

Sugarman, S; Goans, R; Garrett, S; Livingston, G. *The Medical Aspects of Radiation Incidents*. QuickSeries Publishing (2010).

Mansfield, G. *Nuclear Emergency and Radiological Decision Handbook* (Draft). Lawrence Livermore National Laboratory (May, 1997).

Various NCRP, ICRP, and EPA documents were also mentioned as describing various models or listing US regulatory limits.

Early External Dose Estimation

Medical care to an irradiated patient is greatly influenced by the initial dose estimates. It is, therefore, important to be able to quickly and accurately determine the magnitude of the radiation dose. This, however, is not always an easy task. There are many variables that come into play when doing initial dose estimation. Among the things to consider are time of exposure, distance from the source, source activity, potential shielding, and isotope. Some of these items are usually fairly straight forward, source activity and isotope, for instance. It is oftentimes much more difficult to be able to pinpoint the distance the affected area was from the source or the time of exposure. Due to distance vs. dose rate relationships and the extremely high dose rates often encountered, these inconsistencies can have tremendous impacts on the dose estimates.

For point sources, the inverse square law can be used to calculate gamma dose and dose rate. The inverse square law says that the dose or dose rate falls off with the inverse square of the distance ($1/R^2$). Another way to state this is "double the distance, quarter the dose." It can also be written as:

$$\textit{Equation 1: } (D_1) \times (R_1)^2 = (D_2) \times (R_2)^2$$

Where:
D_1 is the original distance
D_2 is the distance of interest
R_1 is the initial dose or dose rate
R_2 is the dose/dose rate of interest

Note: Knowing any three parameters allows for solving for the fourth.

The generally accepted rule of thumb used to determine whether, or not, the inverse square law can be used says that the distance from the source must be at least three times the longest dimension of the source. For small sources such as industrial radiography sources the distance required is a centimeter, or slightly less.

Other useful rules of thumb for estimating gamma radiation doses include:

Line source: The dose rate falls off proportionally with the distance (1/R where R = distance).
Disk/cylindrical source: The dose rate falls off somewhere between 1/R and $1/R^2$.

More accurate equations can be found in Section 3 of *The Health Physics and Radiological Health Handbook, 3rd Edition.*

To estimate gamma dose rates for exposures not in direct contact with the source one can use the information found in third column of Table 1 or Table 2 in conjunction with the following equation:

$$\textit{Equation 2:}\quad D = \frac{\Gamma A t}{d^2}$$

Where:
*D is the absorbed dose**
A is the source activity
t is the exposure time
d is the distance
Γ is the gamma-ray constant (R-cm^2/hr-mCi or Sv-cm^2/hr-MBq)

*Assumes 1 R in air produces 1 rad (0.01 Gy) in tissue.

For exposure in direct contact with the source, information from the fourth or fifth columns of Table 1 or Table 2 can be used in conjunction with the following equation:

$$\textit{Equation 3:}\quad D = SAt$$

Where:
D is the absorbed dose
A is the source activity
t is the exposure time (min)
S is the surface dose rate constant (Rad/min-Ci or Gy/min-TBq)

It is often the case that one is concerned with dose at various depths in tissue. Table 3 can be utilized by using the formula above and substituting the information from the second or third columns for S (Rad/min-Ci, Gy/min-37GBq, or mGy/min-37GBq).

Early dose estimations should always be compared to physical dosimetry, if available, and to the onset of medical signs/symptoms (or lack thereof). In many cases, the true dose will be elusive and medical management will require ongoing teamwork between medical care personnel and health physics personnel in order to provide the proper response to the situation. Oftentimes, the best that one can hope for is determination of the magnitude of the radiation dose. Keep in mind that observable injuries/illnesses due to acute radiation exposure are related to threshold doses and usually take time to fully develop. If the initial dose estimates do not jibe with observed effects the physician must weigh what he/she is seeing versus what was calculated by the health physicist.

The health physicist must also be mindful of potential pitfalls associated with dose estimation in accident situations in order to provide good support to the medical staff. Mock-ups, multiple in-depth interviews, or other means of reconstructing the accident scenario may provide additional information to fine-tune the dose estimates being used to help guide medical care.

Table 1: Approximate Hand Doses from Common Gamma Emitters (U.S. Units)

Radionuclide/ Half-Life	Energy (MeV) Beta(s)/Gamma(s)	Distance R-cm^2/hr- mCi	Surface* Rad/min-Ci	Surface** Rad/min-Ci
Co-60/5.26y	0.31/1.17, 1.33	13.0	2075	3100
Cs-137/30.17y	0.51,1.2/0.662	3.26	513	770
Ir-192/74d	0.67/0.468	4.80	813	1200
Ra-226/1620y	0.4-3.2/0.047-2.4	8.25	1310	1950

*Uncorrected for electron production in metal capsule wall.
**Assumes approximately 50% dose increase due to electron production in the capsule

Notes:
1. Assumes point source geometry.
2. Sources are cylinders approximately 3mm (diameter) x 3 mm.
3. Metal (usually stainless steel) source capsules are approximately 6 mm (diameter).

Table 2: Approximate Hand Doses from Common Gamma Emitters (SI Units)

Radionuclide/ Half-Life	Energy (MeV) Beta(s)/Gamma(s)	Distance mSv-cm^2/hr-MBq	Surface* Gy/min-TBq	Surface** Gy/min-TBq
Co-60/5.26y	0.31/1.17, 1.33	3.51	$5.6X10^2$	$8.4X10^2$
Cs-137/30.17y	0.51,1.2/0.662	0.89	$1.4X10^2$	$2.1X10^2$
Ir-192/74d	0.67/0.468	1.30	$2.2X10^2$	$3.3X10^2$
Ra-226/1620y	0.4-3.2/0.047-2.4	2.23	$3.6X10^2$	$5.4X10^2$

*Uncorrected for electron production in metal capsule wall.
**Assumes approximately 50% dose increase due to electron production in the capsule

Notes:
1. Assumes point source geometry.
2. Sources are cylinders approximately 3mm (diameter) x 3 mm.
3. Metal (usually stainless steel) source capsules are approximately 6 mm (diameter).

Table 3: Approximate Dose Rate at 1 and 3 cm Tissue Depth Due to a 1 Ci (37GBq) Source

Radionuclide	Dose Rate at 1 cm Tissue Depth	Dose Rate at 3 cm Tissue Depth
Cobalt-60	114 rads/min (1.14 Gy/min)	16 rads/min (0.16 Gy/min)
Cesium-137	28 rads/min (0.28 Gy/min)	3.7 rads/min (37 mGy/min)
Iridium-192	43 rads/min (0.43 Gy/min)	5.5 rads/min (55 mGy/min)
Radium-226	72 rads/min (0.72 Gy/min)	9.7 rads/min (97 mGy/min)

Notes:

1. Assumes point source geometry.
2. Sources are cylinders approximately 3mm (diameter) x 3 mm.
3. Metal (usually stainless steel) source capsules are approximately 6 mm (diameter).

Table 4: Skin Injury Thresholds vs. Acute Doses

Dose	Effect	Timing* (time post exposure)
300 rads, 3 Gy	Epilation	14-21 days
600 rads, 6 Gy	Erythema	Early, then 14-21 days later
1000-1500 rads, 10-15 Gy	Dry Desquamation	2-3 Weeks
1500-2500 rads, 15-25 Gy	Wet Desquamation	2-3 Weeks
> 2500 (> 25 Gy)	Deep Ulceration/Necrosis	Dependent upon dose

* At higher doses the time to onset of signs/symptoms may be compressed.

Table 5: Thresholds for Acute Radiation Syndromes

Dose	Syndrome	Signs/Symptoms*
0-100 rads, 0-1 Gy	NA	Generally asymptomatic, potential slight drop in lymphocytes later (near 1 Gy)
> 100 rads, > 1Gy	Hematopoietic	Anorexia, nausea, vomiting, initial granulocytosis and lymphocytopenia
> 6-800 rads, > 6-8 Gy	Gastrointestinal	Early severe nausea, vomiting, watery diarrhea, pancytopenia
> 2000 rads, > 20 Gy	Cardiovascular/ CNS	Nausea/vomiting within first hour, prostration, ataxia, confusion

* At higher doses the time to onset of signs/symptoms may be compressed.

Example Problem

An individual enters an area where industrial radiography was previously performed. The radiographer left for another job where he noticed that the source wasn't in the camera. He returns to retrieve the source and finds it lying underneath the boiler where he was taking pictures. Your investigation into the incident reveals that there was only one person in the area where the source was left, a maintenance worker working on the piece of equipment adjacent to where the source was found. The worker was only 3 feet away from the source. He was in the area for a total of 1 hour. The source strength was reported to be 50 Ci; the isotope being Ir-192. What is his potential whole-body dose? About 3 weeks later the maintenance worker complains of tenderness and reddening of his index finger and thumb on his right hand. He states he picked up something he didn't recognize under the boiler and examined it – holding it about an inch from the end for approximately a minute - but seeing no use for it, he threw it back in the floor where he found it. Could this be radiation related?

Question 1: Whole body dose

50 Ci of Ir-192 at a distance of 3 feet for 1 hour
Gamma constant (Γ) = 4.8 R-cm^2/hr-mCi
Activity (A) = 50 Ci X 1000 mCi/Ci = 50,000 mCi
Time (t) = 1 hours
Distance (d) = 3 feet X 0.3048 meters/foot = 0.9144 meters = 91.4 cm
Using Equation 2:

$$\textit{Equation 2:} \quad D = \frac{\Gamma A t}{d^2}$$

(4.8)(50,000)(1) / (91.4)^2 = approximately 30 rads

Assume 18" from body while the worker examined the source for 1 minute

(4.8)(50,000)(1 minute X 1 hour/60 minutes) / (18 inches X 2.54 cm/inch)^2 = about 2 rads

Total whole body dose is estimated to be approximately 30-35 rads

Question 2: Dose to fingers

50,000 mCi of Ir-192 at a distance of 1 inch for 1 minute
Gamma constant (Γ) = 4.8 R-cm^2/hr-mCi
Activity (A) = 50 Ci X 1000 mCi/Ci = 50,000 mCi
Time (t) = 1 minute X 1 hour/60 minutes = 0.017 hours
Distance (d) = 1 inch X 2.54 cm/inch = 2.54 cm
Using Equation 2:

$$\textit{Equation 2:} \quad D = \frac{\Gamma A t}{d^2}$$

(4.8)(50,000)(0.017) / (2.54)^2 = approximately 630 rads, so it's possible that this is radiation related (erythema threshold is approximately 600 rads)

Other useful rules of thumb:

Alpha

- Alpha particle of at least 7.5 MeV is needed to penetrate the skin.

Beta

- Range of beta particles (g/cm^2) is approximately equal to E_{max} /2.
  [Density thickness (g/cm^2 = Thickness (cm) X density (g/cm^3)]
- Dose rate (rads/hr) at 1 cm (point source) is approximately 200 X mCi.
- Skin dose (through outer protective layer) is approximately 9 rads/hr from a uniformly thin deposit of $1\mu Ci/cm^2$.

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