Radioactivity and dose concept

Ionizing Radiation: Radionuclides are species of atoms that emit radiation as they undergo radioactive decay. There are two types of radiation; particle and electromagnetic (EM) radiation. The most common particle radiation is alpha (consist of 2 neutrons and 2 protons) and beta (positive and negatively charged electrons) emission. EM radiation is gamma rays which are individual bunch of photons. These radiations occur naturally (X-rays are man-made). Each photon or particle individually have the sufficient energy to ionize the molecules. That means radiation has an energy to eject an electron from its orbit. Covalent bond breaking will result in DNA strand breaks, protein destruction or free radical production. These mechanisms are the origin of radiation injury. The speed and the mass of the particle radiation defines its energy whereas in EM spectrum, photon's wavelength or frequency (inversely related). In EM spectrum, only UV band or shorter have the ability to ionize the molecules. Longer wavelengths than UV (e.g. microwaves, visible light), even though they have higher intensity (quantity) or at extreme exposures, DO NOT ionize atoms. Note that, the total energy transferred to the tissue may be excessive but the situation does not change.

All types of radiation are attenuated according to the Lambert-Beer law. Law states that; the intensity of radiation moving towards the tissue (incident radiation, I_0) will be either absorbed or will continue its pathway without any interaction (transmitted radiation, I). For each unit cross section the ratio of transmitted radiation to incident radiation (I/I_0) is constant. I/I_0 is called transmission and negative logarithm of transmission gives absorption ($-\log I/I_0$). The main factors affecting transmission are; 1-Molecular structure: Visible light can pass through the window but in contrast it can be effectively absorbed by soft tissue although they have similar density. 2- Radiation energy: In general, lower energies of gamma radiation are better absorbed in the soft tissue when compared to higher energy gamma rays. 3- Radiation type: Alpha can be easily stopped by a piece of paper. However, gamma radiation of the same energy can only be attenuated by thick lead blocks.

Radiation dose units: Radiation terms historically has older units which have been used for many decades. Also, today the new unit system has been introduced based on SI (standard international) system. Since in practice both units are currently being used, it is necessary to understand both sets. The basic radiation quantities are exposure, absorbed dose, dose equivalent and activity. **Activity** is the incidence of radiation per second and its unit is becquerel (Bq) in SI system. Thus, radiation per second is 1 Bq. The older unit is **curie** (Ci) and it is defined as the activity of 1 gr of radium (Ra) atom in one second which is $3{,}7 \times 10^{10}$ Bq. Activity unit doesn't give information about the energy, absorption or the harmful effects of radiation. Obviously, we need other units to define the radiation energy. To measure radiation energy, we actually measure the amount of ionization as charge in the air (exposure). In cgs (old unit) system the charge is represented in electro static charge (esu)/cm^3 air. 1 esu/cm^3 equals to 1 **roentgen** (R). In SI (new unit) unit system charge is measured as **Coulomb/kg** air. Note that, the new unit doesn't have a special name. $1R = 2{,}58 \times 10^{-4}$ C/kg. Charge to energy conversion for air is given as an example, the amount of energy needed to be transferred to air molecules to produce 1R of ionization is calculated below.

Number of electrons in 1 R exposure in per gram of air is=

$$\frac{2{,}58.10^{-7}\quad \text{Coulomb/gram}}{1{,}6\text{x}10^{-19}\quad \text{Coulomb (the charge of a single electron)}} = 1{,}6.10^{12}\text{electrons per gram}$$

$1{,}61.10^{12}e^{-}$/gram x 33,7 eV = $5.44.10^{13}$ eV/gram=87 erg/gram ≅ 100 erg/gram
eV=33,7 is the energy needed to eject 1 e^{-} (this is given)
(erg is another energy unit)

In cgs (old unit system) approximately 100 erg/gram is defined as 1 **rad** (radiation absorbed dose). Thus, 1 R exposure in air corresponds to 1 rad of energy transfer to air molecules. The absorbed dose in air is important since air absorption and soft tissue absorption are very similar. That means roughly that, 1R=1 rad (air)= 1 rad (soft tissue)**.** The critical think to understand here is; we need absorbed dose units (rad) to measure how much energy (roentgen) in air is deposited in our tissues to have an idea about the radiation damage. Because same exposures may result in different absorption dose according to the tissue type. For example, 1R exposure results in 3 rad in bone. In SI (new unit system) dose is expressed in joule/kg and has a special name **Gray** (Gy). 1rad=10^{-2} Gray. Finally, we need another unit to measure the exact damage. Radiation type is an important factor in determining tissue damage. Equal absorbed doses of different types of radiation will not necessarily be equally harmful to tissues. Thus, we need to consider radiation type while estimating radiation injury. For this purpose, a factor is added to calculations (Quality factor) (Figure 1). The product of total absorbed dose and quality factor will be proportional to the biological effects. The name of this product is named as dose equivalent. If we measure absorbed dose in grays the unit of dose equivalent will be **sievert (Sv)** in SI system. If we measure absorbed dose in rads then the unit for dose equivalent will be **rem**.

Dose equivalent =Absorbed dose x Quality factor
Sievert (Sv)=Gray x Quality factor
rem=rad x Quality factor

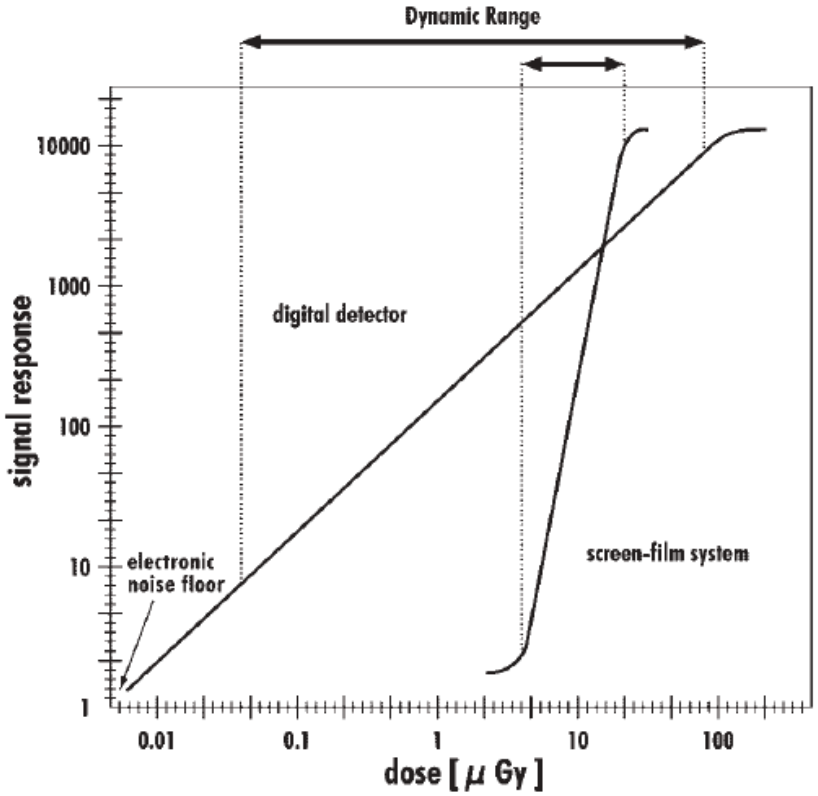
Radiation	*Energy*	*Q*
gamma	all	1
beta	all	1
neutrons	slow	5
neutrons	fast	20
alpha	all	20

Figure 1: Quality factors (Q) of different radiation types.

Conventional and digital radiography principles in X-ray imaging

In conventional screen film radiography, when x-ray radiation reaches to the patient, it will be absorbed according to the tissue type (bone or soft tissue). Then, transmitted photons will

deposit their energy into the film grains. Film grains are tiny silver nitrate ions that responds to the light. Regions of the film with a greater density of exposed grains have higher optical density and appears as dark. In contrast, if no grains were exposed, it will appear as white. The film responses in between white and dark will appear as grey tones. The ratio between two grey tones is defined as **contrast**. Maximum contrast is the ratio between white and black. Today, screen-film radiography is replaced by digital radiography since it has several advantages such as handling and storage. Instead of a film, a digital detector is used in digital radiography. Grains correspond to pixel in digital detector, where pixel response to photons is a digital signal. Then, it is converted into a digital image for the display on the computer screen. But, raw images must be processed first. Processing means, original detector signal must be assigned into another signal value. **Why do I have to process the image?** In conventional screen-film, dose response relation (dynamic range) is S-shaped (Figure 2A). It means a narrow exposure range for optimal film darkening (contrast). Thus, the film has a lower tolerance for an exposure that is higher or lower than required. Because of the S-shaped dynamic range film generates an automatic higher contrast between similar tissue absorptions and doesn't need to be processed. In contrast, digital detectors have a wider and linear dynamic range (Fig 2A). That means higher tolerance for an exposure but poor contrast. Contrast disadvantage can be improved by processing. Processing for a better contrast has limitations. Improving the contrast in region of interest means indispensably losing the contrast in other regions. This is **windowing** (Figure 2B).



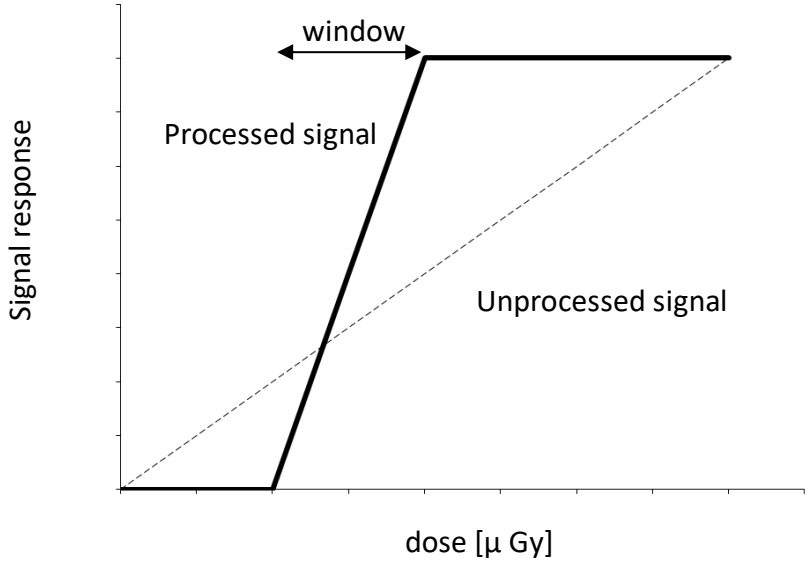


Figure 2. A) Comparison of film and detector dynamic ranges (adapted from Körner et. al., 2007). B) In the window range (region of interest) original raw signal was processed to improve contrast. Since detector has a maximal response limit high dose responses are saturated thereby contrast information is lost after windowing. Similarly, low dose responses are discarded as well.

Nevertheless, an important thing to keep in mind is, altering the processing features on digitally acquired images is not trivial. If one of the features is improved, then the others may be supressed and this will lead into an unwanted masking if diagnostically relevant features occur.

Biological effects of radiation: Radiation induced free radical injury

Radiation has the ability to break covalent bonds between atoms or molecules. Ionizing radiation when encounters with water molecules (e.g. in the cytoplasm) it splits into two radicals. Hydroxyl radical (OH·) and hydrogen radical (H·). Radicals has unpaired electrons in its orbitals and especially OH· is by far the most reactive oxygen species inside the cell. The first molecule it finds it will immediately react. The main components of the cells are lipids, proteins and nucleic acids. Nucleic acids can be damaged by radicals in two ways. Firstly, it can modify the base. OH· can bind to base and add a hydroxyl group (Figure 3A). This usually can be repaired by defence mechanisms and cells get rid of it. But sometimes due to the modification in the pairing (e.g. in the replication) it behaves like a different base which can lead to mutation. Mutations can even lead to cancer formation. If the OH· reacts with sugar molecule, it can cause strand breaks in the backbone. So, the whole strand can be broken. Strand breaks can also be repaired but sometimes this can lead to mutation, chromosome damage or recombination. Thiol (-SH) groups are part of the cysteine residues in proteins. They can easily be oxidised by OH· radical. The oxidation can have several different forms. One of the possibilities is the oxidation of thiol group is the reaction with another thiol group and formation of a disulphide bridge (S-S) (Figure 3B). Disulphide bridges are part of protein structure but radical induced disulphide bridge formation in places that shouldn't be there normally disrupts protein function. Again, this process could be repaired by the cell's defence

mechanisms up to a limit. Lipids especially polyunsaturated fatty acids (one of the membrane lipids). Polyunsaturated fatty acids (PUFAs) are long carbon chains and have a methylene group between the double bonds (unconjugated). Hydrogens in this methylene group are very susceptible to oxidation (Figure 3C). OH· wants to be reduced to water so it took on hydrogen from the methylene group. When a hydrogen is stripped fatty acid becomes radical itself. This radical also has the ability to attack intact neighbouring lipids in the membrane until the radical groups finally reduced to hydrophilic hydroxyl groups (OH^-). Hydrophilic groups allow entrance of water molecules inside the membrane and destroys its structure.

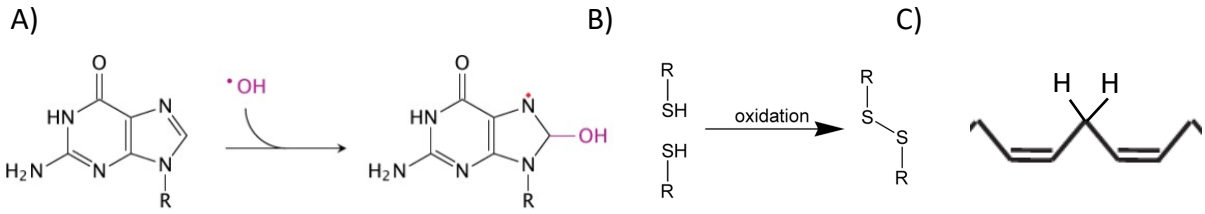


Figure 3: A) Guanine base oxidation by OH·. Such base modifications may result in mispairing during DNA replication, which will then give rise to mutations. B) Disulphide bridge formation in cysteine residues of proteins. C) Methylene group hydrogens in polyunsaturated unconjugated fatty acids.

References

1. "Biyophysics" Lecture book. Prof. Dr. Ferit Pehlivan
2. Markus-Korner et. al Advances in digital radiography: Physical principles and system overview Radiographics 2007;27:675-686.

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