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Characteristics of radiation fields to consider in selection of an alternative to ^{137}Cs irradiators

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Why use ^{137}Cs (or ^{60}Co)?

- Very well defined fields useful for **direct comparison between laboratories**
  - Single γ-ray energy: ^{137}Cs – 662 keV
  - Few γ-ray energies: ^{60}Co – 1173 & 1333 keV
  - Other radionuclide sources tend to have more complex photon emissions
- Penetrating radiation
  - Higher energy photons are more penetrating
  - High dose rates (relatively) easily achieved *[Absorbed Dose, 1 Gy = 1 J kg^{-1}]*
    - ^{137}Cs and ^{60}Co quite abundant - high activity sources possible

Alternatives to radionuclide sources

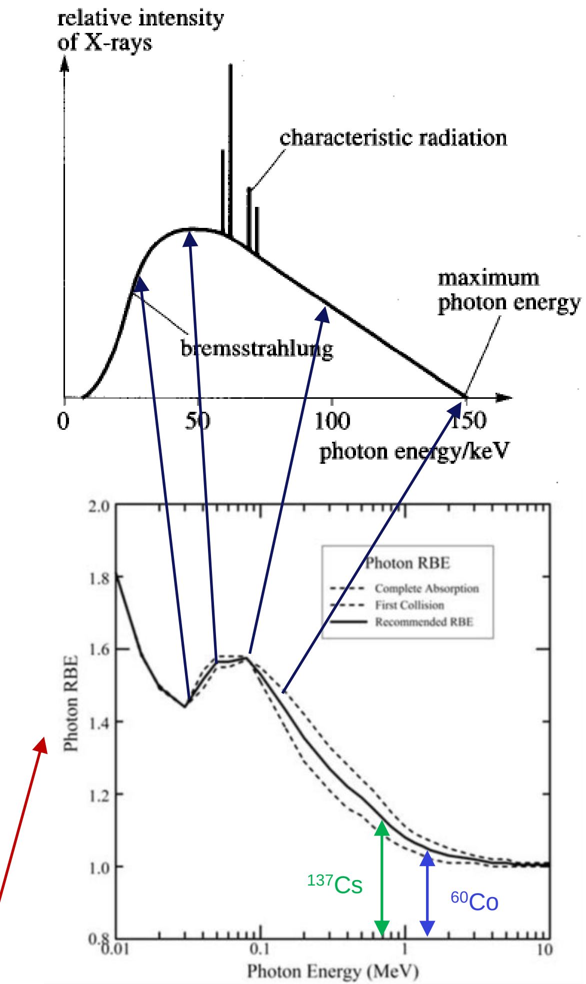
- **Must we stick to photons?**
  - Preferable for “consistent” RBE (‘Relative Biological Effectiveness’)
  - Other radiations would require accelerators and be more expensive
    - Protons, neutrons or alphas have higher RBE
    - Electrons similar RBE to photons, but scatter and produce bremsstrahlung

- **Alternative photon sources?**
  - Characteristic X-rays: stimulation of ‘K-fluorescence’ lines – low dose rate and energy < 100 keV
  - Laser driven sources – high instantaneous dose rate but intensely pulsed
  - **Bremsstrahlung**

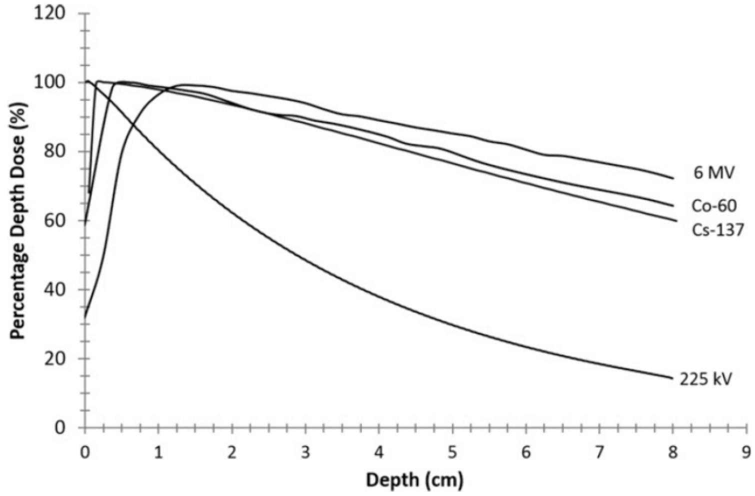
Bremsstrahlung

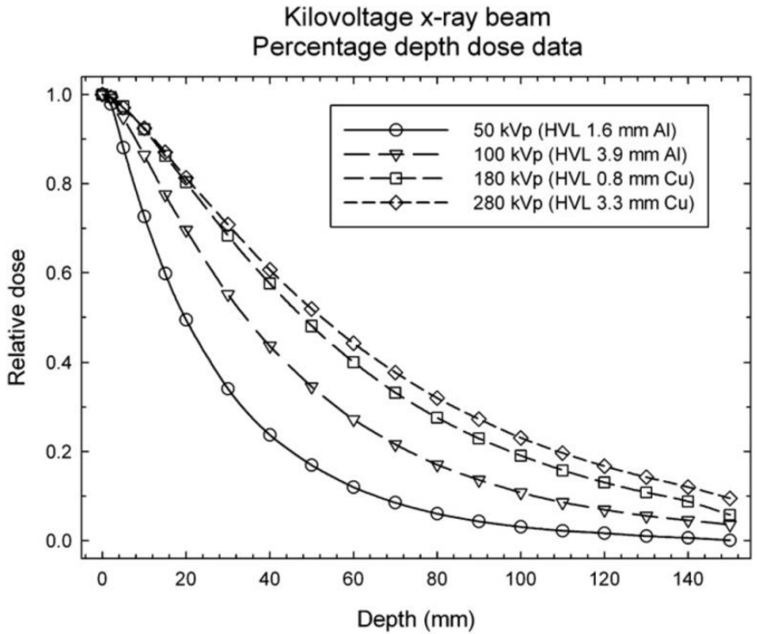
- Tend to distinguish **x-ray** from **linac** fields
- Both **bremsstrahlung:** Generated by electrons hitting a target (“*braking radiation*”)
- Broad energy distribution: $E_{mean} \sim E_{max}/3$
- Maximum energy photon, E_{max} = electron beam energy
  - Tube potential (kV) governs $E_{max} \rightarrow$ “Tuneable”
- Unfiltered field includes a lot of low-energy photons
  - Lower energy component can be filtered-out using metals

Photon RBE (5 keV cut-off) based on first interaction and complete absorption of the photon: Bellamy, M. and Eckerman, K. (2013). *Relative biological effectiveness of low-energy electrons and photons*. Washington, DC: US Environmental Protection Agency.



Depth dose curves





- Variation in the percentage of dose delivered by tissue depth.
- Higher energy results in lower dose at the skin surface and less attenuation at depth.

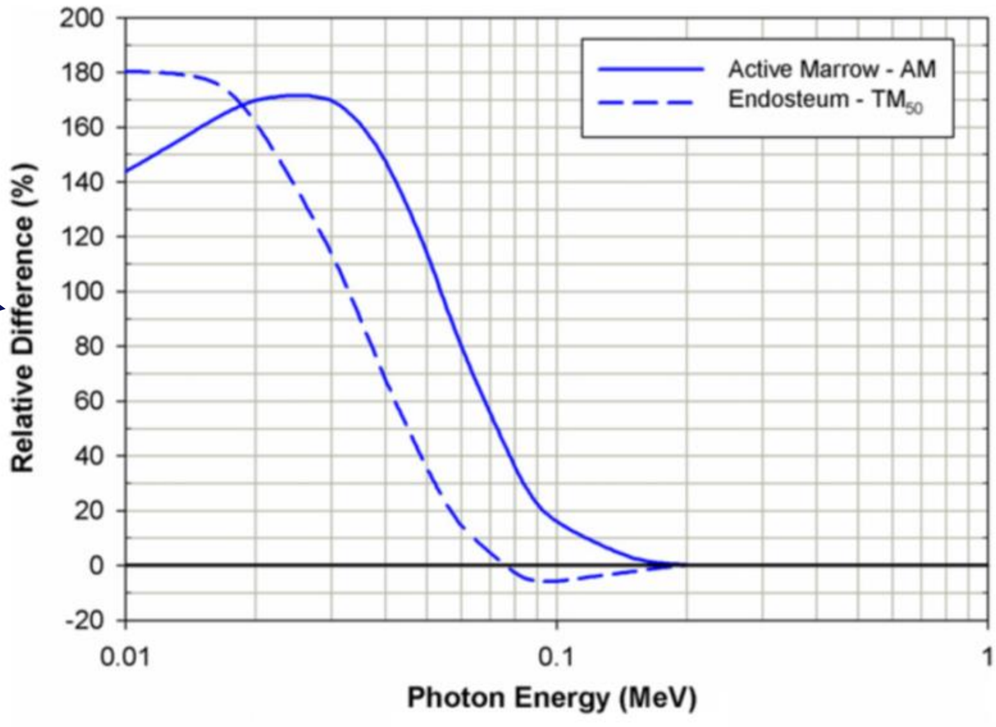
Koontz, B. F., F. Verhaegen and D. D. Ruysscher (2017). "Tumour and normal tissue radiobiology in mouse models: how close are mice to mini-humans?" The British Journal of Radiology **90**(1069): 20160441.

Percentage depth dose curves in water for kilovoltage x-ray beams with tube potentials between 50–280 kVp

Hill, R., B. Healy, L. Holloway, Z. Kuncic, D. Thwaites and C. Baldock (2014). "Advances in kilovoltage x-ray beam dosimetry." Physics in Medicine and Biology **59**(6): R183-R231.

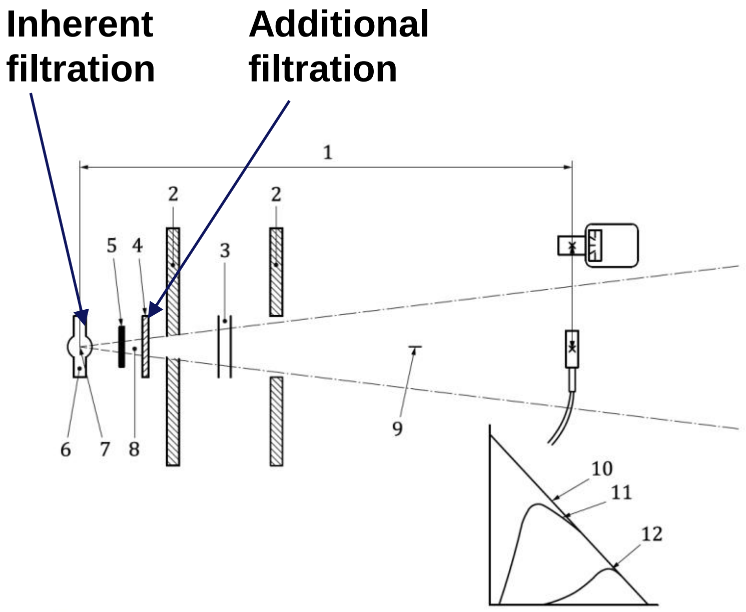
Local energy deposition – low energy photons

- Fine structures that include heavier elements (high-*Z*) strongly affect dose (*D*)
  - *Can lead to significant dose deposition inhomogeneity on local scales*
- Relative difference of *absorbed dose* and *kerma* provides measure of inhomogenity. (Data for active marrow and endosteum)
- Absorbed dose much higher <~100 keV.
- Figure from ICRP Publication 116, using data for human adult male
  - *Don't have analogous data for animals*
- Mitigates against strong low energy component for small animals?



Reference x-ray fields

- Reference x-ray fields for open laboratories:
  - Dosemeter & Instrument Calibrations: BS ISO 4037-1:2019
    - Filtered to narrow the energy distribution (lowers dose rate)
    - Up to 400 kV
  - Medical Imaging: BS IEC 61267:2005
    - RQR2 40 kV, 1st HVL 1.42 mm Al
    - RQR10, 150 kV, 1st HVL 6.57 mm Al
  - Lead Equivalence: IEC 61331-1:2014
    - 30 kV to 400 kV
- There are no reference x-ray fields for closed calibrators:
  - Blood Dosimetry: ISO/ASTM FDIS 51939:2016
    - Currently available low-energy X-ray irradiators generate X-radiation with a maximum energy of 160 keV
    - The spectrum of the X-ray energy extends from the maximum energy to approximately 30 keV



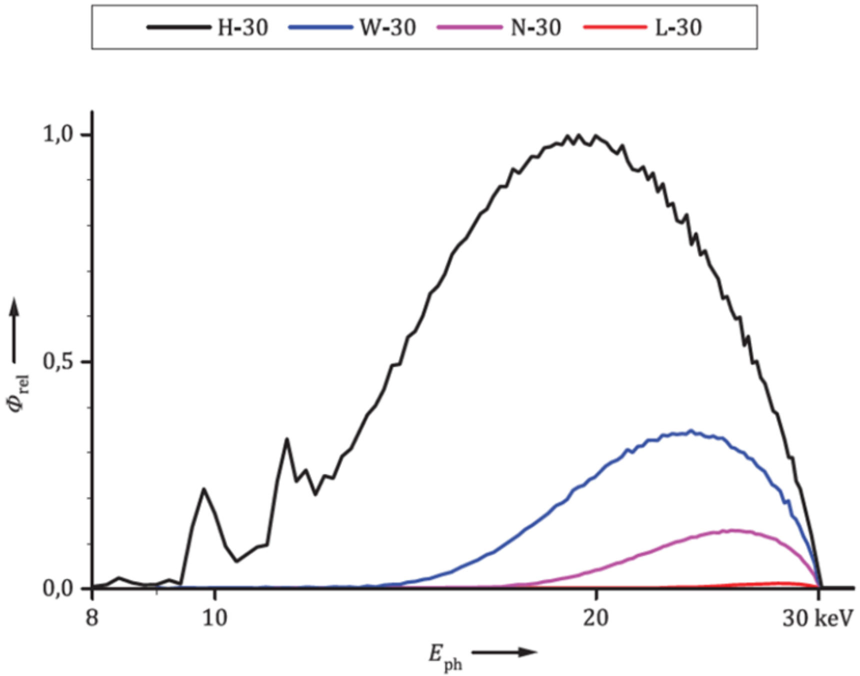
Key

1 calibration distance
2 lead collimator
3 beam monitor chamber
4 additional filtration
5 shutter
6 X-ray tube
7 location A
8 location B
9 location C
10 unfiltered spectrum, location A
11 spectrum with inherent filtration, location B
12 spectrum with additional filtration, location C

Figure 1 — Example of a typical X-ray setup

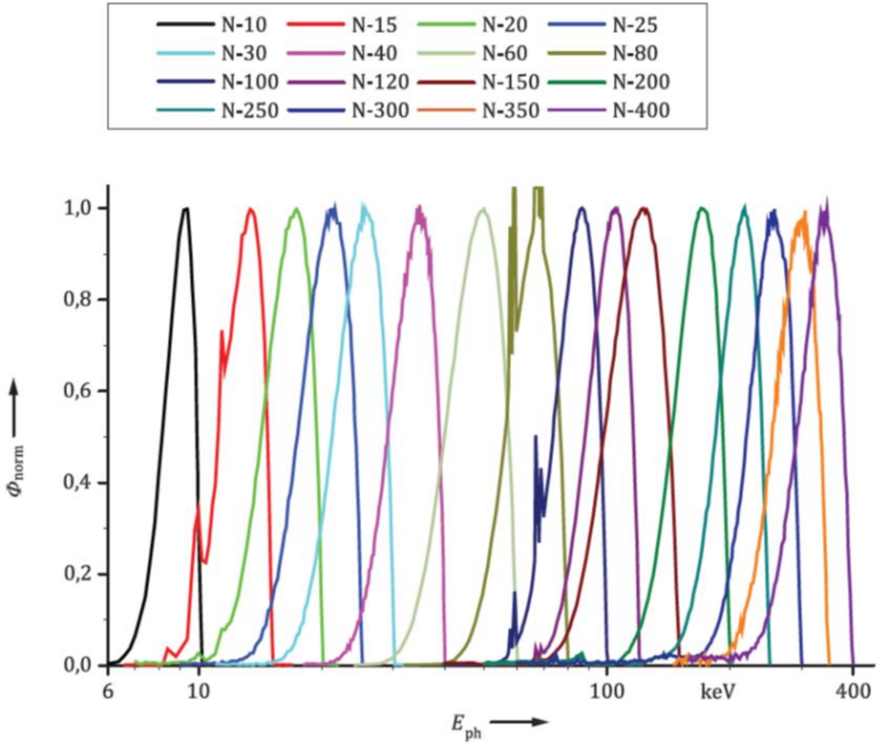
Reference x-ray fields

More filtration →



Impact of more filtration: BS ISO 4037-1:2019

Narrow series X-ray fields (BS ISO 4037-1:2019), self-normalized to a peak fluence of 1



Higher kV small animal irradiator parameters

Field	Inherent filtration	Additional filtration	Half value layer
N300	4 mm Al	5 mm Pb + 3 mm Sn	5.96 mm Cu
W300	4 mm Al	6.5 mm Sn	5.03 mm Cu
H300	4 mm Al	2.2 mm Cu	3.22 mm Cu
X-RAD 320 (3 Gy/min)	Not specified	Not specified	≈ 1 mm Cu
X-RAD 320 (1 Gy/min)	Not specified	Not specified	≈ 3 mm Cu
RS2000 (350 kV)	4 mm Be	Not specified	Not specified
^{137}Cs	n/a	n/a	10.7 mm Cu
^{60}Co	n/a	n/a	14.8 mm Cu

- The half value layer (*HVL, = thickness of material required to halve dose*) is a measure of how penetrating the radiation is:

$\Rightarrow$ Higher HVL = more penetrating field

Lower kV small animal irradiator parameters

Field	Inherent filtration	Additional filtration	Half value layer
L170	4 mm Al	1.5 mm Pb + 3 mm Sn + 1 mm Cu	3.4 mm Cu
N150	4 mm Al	2.5 mm Sn	2.3 mm Cu
W150	4 mm Al	1 mm Sn	1.78 mm Cu
H150	4 mm Al	0.15 mm Sn	0.81 mm Cu
RQR10 (150 kV)	*Not specified*	*2 mm Al*	*6.57 mm Al*
RQA10 (150 kV)	*Not specified*	*45 mm Al*	*13.3 mm Al*
RQT10 (150 kV)	*Not specified*	*0.3 mm Cu*	*10.1 mm Al*
X-RAD 160	0.8 mm Be	2 mm Al	Not specified
^{137}Cs	n/a	n/a	34.5 mm Al or 10.7 mm Cu
^{60}Co	n/a	n/a	46.5 mm Al or 14.8 mm Cu

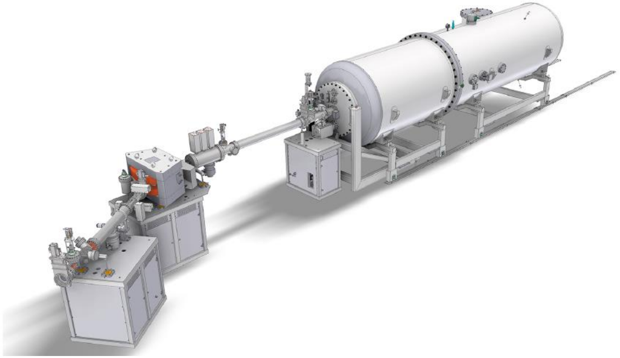
X-ray set size vs Maximum energy

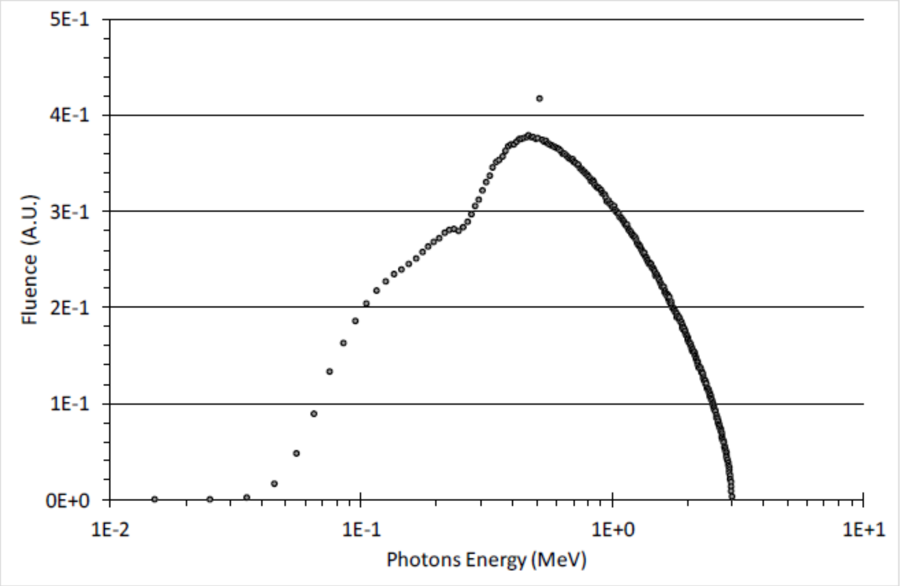
Tube potential	160 kV	225 kV	350 kV
External dimensions	106.7 x 182.9 x 83.8cm	115.2 x 182.9 x 83.8 cm	155.2 x 182.9 x 89.8 cm
Mass	567 kg	645 kg	2560 kg
Internal dimensions	43.2 x 68 x 38.1 cm	43.2 x 68 x 38.1 cm	52.5 x 72 x 52.5 cm

- Higher electron beam potential (kV) needed to get higher energy X-rays fields
- But, higher potential X-ray sets get **larger** & **heavier**, to ensure
  - sufficient cooling
  - adequate shielding
- Increase costs and irradiation room requirements…

Could a linear accelerator (“linac”) be used?

- A linac can operate at higher e⁻ beam potentials than X-ray tube → **Higher energy fields**
- A 3.5 MV (max.) linac operated at 3 MV can be used to ‘replicate’ ^{137}Cs
  - Mean energy ~ ^{137}Cs (i.e. 662 keV)
  - Dose rate 100s mGy h^{-1}
  - Large and expensive
  - Harder to shield





Discussion

- Blood irradiation does not seem to place such strong demands on given dose and RBE of the radiation field
    - Specifications for blood irradiators tend to give the kV but not the filtration
- For biological irradiators the given dose and RBE are important
    - Specifications for biological irradiators tend to give the kV but sometimes the filtration and also the HVL
- When obtaining either type of device, the kV and filtration should be considered
    - The HVL is perhaps the best means of evaluating ^{137}Cs equivalence

Summary I

- Ideally, the new irradiation field will be as close to ^{137}Cs as possible in its interactions with biological materials
- Bremsstrahlung photons are the "optimal" replacement
- A strong low energy photon component can affect the RBE
- Filtration of the low energy component can be achieved using metal filters
  - This reduces the dose rate
  - Raises the mean energy
- To most closely "replicate" ^{137}Cs requires a linac not an x-ray tube
  - *Too bulky and expensive to be practical*

Summary II

- The use of higher kV better replicates ^{137}Cs
  - Additional filters help to make the RBE closer to that of ^{137}Cs
- If results are to be comparable between laboratories, the reference low-LET for RBE should be consistent
- Ideally there would be standards that recommend the optimum irradiation fields for blood irradiation and biological experiments
- Papers should better specify the exact nature of the field used in experiments:
  - The kV, inherent filtration and additional filtration should be given
  - The HVL should also be determined

Any Questions…?

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Next Steps

Thank you for your time today. We hope this discussion has been beneficial to you and your organisation.

If you have any further queries, please direct these to JSaRC@homeoffice.gov.uk

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