X-ray filters in microCT imaging

Method note MN 148

Innovation with Integrity

microCT

1. What is an X-ray filter?

The X-ray filter is the first and most important choice you make about how to scan your sample or animal by microCT. In selecting X-ray energy filter is more important than voltage. Both filter and voltage together determine the energy spectrum of your scan X-rays so it's better to consider them together, not separately. (Note that current and camera exposure time have no effect on the X-ray energy spectrum, only on the quantity of X-rays being detected. Energy is about filter and voltage only.)

So, what do we mean by an X-ray "filter"? Since X-rays are penetrating radiation, almost anything can be an X-ray filter. Commonly we use sheets of appropriate metals such as aluminium or copper as filters for microCT. When X-rays are transmitted through material, some are always absorbed. If the X-ray beam consists of a range of different energies (polychromatic), then the absorber is selective about which X-rays are transmitted – higher energies get through while lower energy photons – not so much. The energy distribution is shifted toward a higher mean energy, and we call this the filtering effect. Note that sometimes higher energy X-rays are called "hard" X-rays and the less energetic ones – "soft" X-rays. This helps us understand the meaning of terms such as "beam hardening".

To answer the next question "why do we need a filter?" we need to take a step back and look at what we are filtering: X-rays. X-rays can be produced in synchrotrons where one can obtain "monochromatic" or mono-energetic X-ray photons all with the same energy. If this is the case there is no need of filtering since it will not change the energy. However, the X-rays produced in laboratory X-ray sources are a very mixed bag – in terms photon energy (individual X-rays are called photons). This is why we often need to filter our X-rays:

(a) to obtain the average X-ray energy that we need, and
(b) to reduce the variation between higher and lower energy X-rays, which is bad for CT causing the artefact of beam hardening.

Note – this article will not go into much detail of X-ray absorption physics. It's more intended to help in getting best results for microCT scanning. Some brief reference to the important theory will be made only.

An X-ray source, for example, works by firing electrons at high energy at a metal target, in a fine focused beam. Energetic electrons hitting metal emit X-rays by two interactions. One is called "braking radiation" (physicists use the German term Bremsstrahlung) – rapid deceleration of the electron causes X-ray photons to be emitted with a wide smooth spectrum of energies. The other is the photo-electric effect where fast electrons dislodge an electron in the target metal, causing quantum rearrangement of atomic electrons in their discreet shells and resulting in an emitted X-ray with a specific energy. This is called "characteristic" emission since the emitted energies are specific to the element.

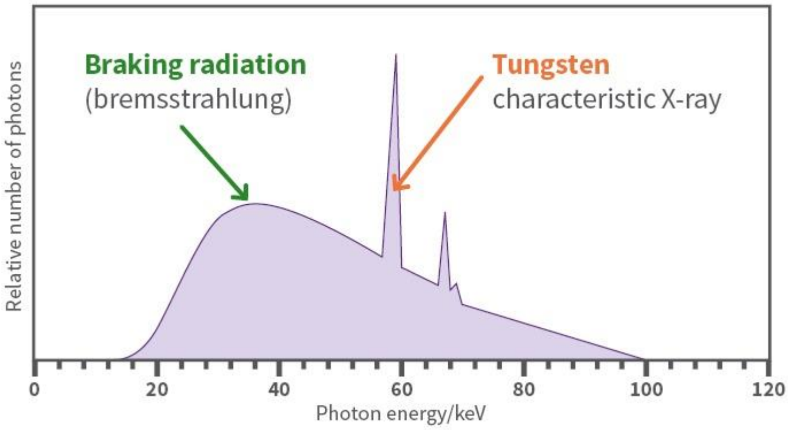


Image 1: the spikes on the X-ray energy spectrum are from photoelectric characteristic X-ray emission; the broad smooth part of the spectrum is from Bremsstrahlung.

When X-rays pass through a filter their energy spectrum is changed, with the low energy end reduced relative to higher energies. This is shown in figure 1 for the case of X-rays with 65kV applied voltage passing through different thicknesses of aluminium. Note that although the Applied voltage does not change, the average energy of the X-rays increases a lot, due to the selective removal of lower energy X-rays.

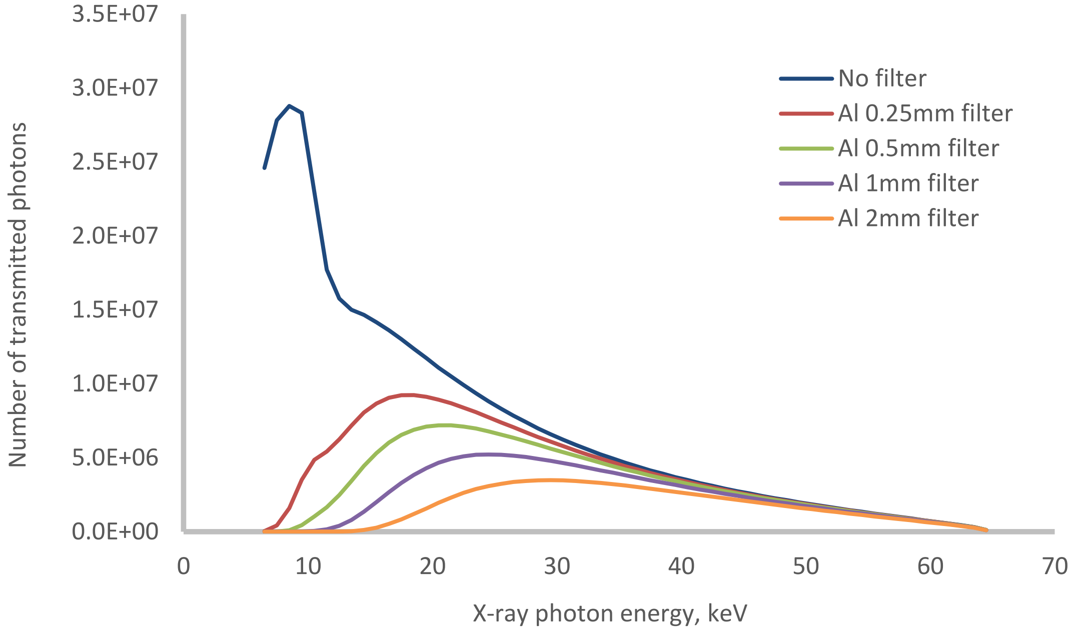


Figure 1. Filters remove X-rays at the low end of the energy spectrum, increasing average energy and decreasing the range of energy variation. All spectra are generated with 65 kV applied voltage. The line for no filter shows the energy spectrum of unfiltered X-rays as they are emitted from the source.

1.1. Kilovolts (kV) and kiloelectronvolts (keV): what's the difference?

A final note on theory: kilovolts (kV) and kiloelectronvolts (keV) are related to each other but are not the same thing. The voltage between anode and cathode in the X-ray source accelerating electrons to the target is the "applied voltage" in kV. This is the voltage that you set this as the user of a microCT scanner. On the other hand, the kiloelectronvolt keV takes X-ray voltage to the quantum level of the individual electron and photon. One keV is the energy a single electron gets when accelerated by one volt; it's small, at 1.602 E-19 joules. X-ray photons also have their individual energy quantified as keV.

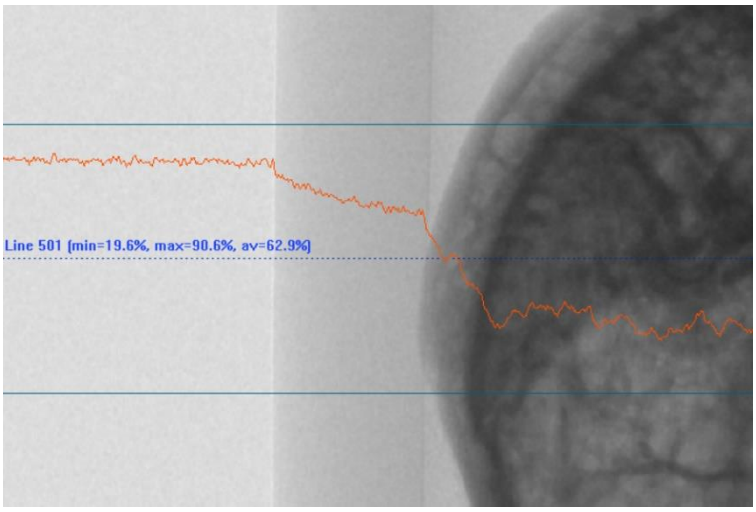
As an example – look again at the X-ray photon energy spectra in figure 1. Here the applied voltage was 65 kV. The spectrum displays the range of X-ray photon energies in keV. You will notice that the maximum photon energy is 65 keV, corresponding to the applied voltage of

65 kV. However, most of the emitted X-ray photons have much lower energies, with peak intensity between 9 and 30 keV depending on what filter is used. The few 65 keV photons are the ones where all the energy from the applied voltage is transferred from the accelerated electron into the emitted X-ray photon. But for the majority of the photons, energy from the accelerated electron is only partially transferred to the photon – as is clear from the emitted X-ray energy spectrum which is very wide. This is an important fact about X-ray emission from laboratory sources – X-rays are “polychromatic” with a wide range of photon energies, and only at the maximum tip of the energy spectrum does the photon energy in keV equal the applied voltage in kV.

2. How to choose which filter to use?

Scanners such as the SkyScan 1272, 1273 and 1276 have a selection of 6 or more filters that are chosen in the control software. To find the right filter for a sample, first take flat field corrections for all the low resolution scan modes. (This will be faster and choice of filter and contrast are not affected by resolution.) Then image the object – at low resolution – with different filters. You should activate the profile line that shows transmitted percentage of X-rays, by right-clicking in the middle of the onscreen image. In figure 2 below this is shown in the case of a scan of a mouse femur bone with the 0.25mm aluminium filter selected.

The principle is straightforward – the filter that gives the best looking image in terms of contrast and visibility of internal structures, will be the right filter. In quantitative terms, the minimum transmission at the most X-ray opaque part of the imaged object should have transmission in the range 15-30% as a general rule. 20% can be considered an ideal value.



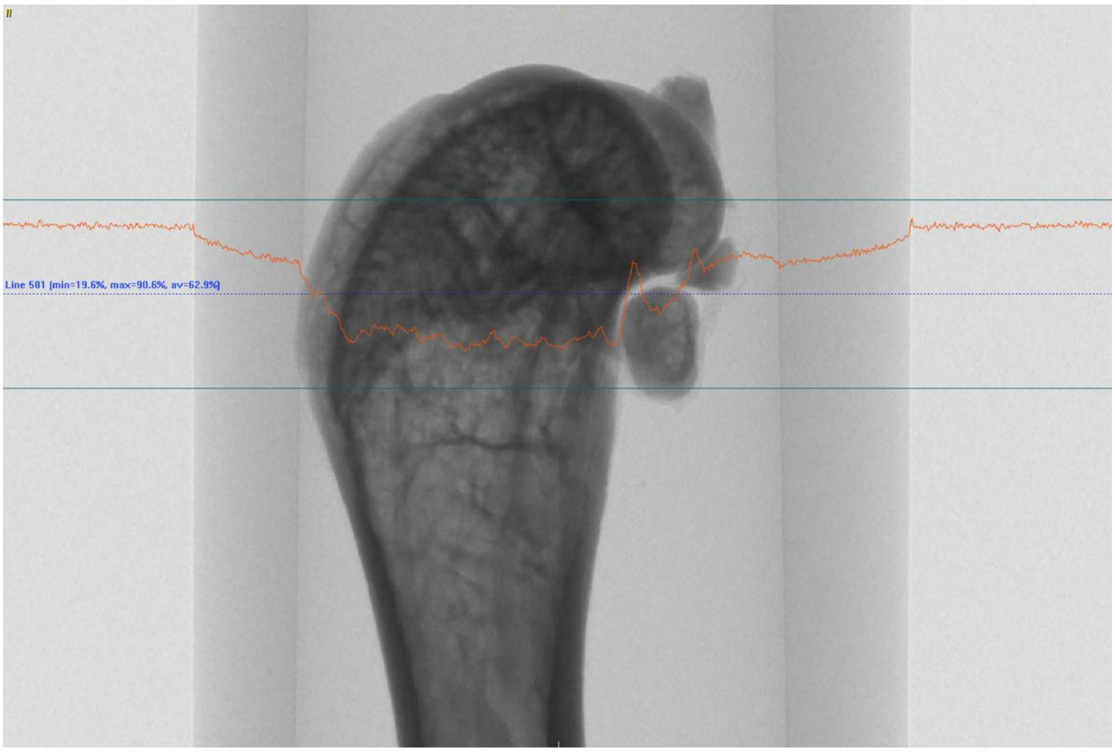


Figure 2. Right-click on the displayed projection image in a SkyScan scanner will activate the profile line which will show the transmitted percentage as a profile and minimum and maximum values. A minimum value close to 20% is ideal as in this case of a mouse bone scanned ex vivo with a 0.25mm aluminium filter. The minimum is the important value here; the maximum and mean – not so much.

This target of percent transmission of 20% (range 15-30%) should not be applied too rigidly, since objects have very different distributions of density, some being uniform while others very nonuniform with for instance, small high-density particles. So there are times when the minimum will not be in this range even with a good filter choice. And of course, that range can't always be attained in materials with either extreme high or low density. In such cases you go to the highest and lowest available energy settings respectively – you can still often get an acceptable scan result.

For some practical examples, the appendix and the end of this document gives some examples with images of both projection images and resultant reconstructed cross-section images, with both correct and incorrect choices of filter. It can be seen that the visual appearance of the projection image is a good guide to which filter is the best, not only a numerical value of transmission.

Please note finally – there is not an exact combination of filter and voltage that are ideal for every sample. In reality a range of combinations will work acceptably, providing the degree of transmission is about right. Section 4.1 below, concerning the technique of "spectrum compression", discusses this further.

3. For *in vivo* scans filter is also important for reducing X-ray dose

Up to now we have talked about filter as a means to get an appropriate average X-ray energy for scanning a certain sample. In the *in vivo* scanning of laboratory animal models such as mice and rats, filter plays an additional important role – that of reducing X-ray absorbed dose to the animal. The filter in *in-vivo* scanners is in front of the source, not camera. This means for example when scanning an animal, that filter should never be less than 0.5mm aluminium. With filter lower than this, absorbed dose will be too high even if there is an advantage in image quality. For a mouse, filter should be 0.5-1mm aluminium and for a rat, from 1mm Al to thin copper filters (e.g. 0.11mm) in the case of large rats.

Another method note, MN-143, gives a full explanation of X-ray absorbed ionising dose in in vivo microCT scanning, of what dose is acceptable and how we measure it.

4. Beam hardening is reduced by filtration as shown by simulated X-ray spectra

Simulations of X-ray energy spectra done using SpekCalc™ software (1) allow us to assess the amount of beam hardening caused by biological tissue with X-rays produced by various combinations of filter and applied voltage. This program can simulate the X-ray energy spectrum resulting from a combination of a given filter and applied voltage (available filters include aluminium, copper and molybdenum). In addition, SpekCalc can simulate water as an absorber. Therefore, if we use water to simulate biological tissue, the program can assess the additional beam absorption and beam hardening (change of the X-ray spectrum) by biological tissue caused by for instance a mouse.

In this simulation reported here, a mouse is simulated as 2mm of aluminium and 18mm of water. This approximates what an X-ray photon would cross in going through a mouse body – a little bone and mostly soft water-like tissue. Note that the X-ray absorption of aluminium is very similar to that of bone, which has an average atomic number close to 13, the atomic number of aluminium. So starting with a range of filter-voltage combinations, we can simulate the beam hardening caused by a mouse scanned with such combinations. We define beam hardening as the percentage increase in X-ray mean energy caused by X-ray passage through the “mouse” (18mm water and 2mm aluminium).

Thus table 1 shows us the difference in energy of X-rays before and after transmitting through our simulated “mouse”. The energies before are very different depending on the filter, but what is noteworthy is that the energy after going through the mouse is quite similar for all filters. This shows the important fact that a sample filters X-rays just like a filter in front of the source (or camera), and that when the sample is quite substantial – a mouse is a relatively large sample by microCT standards – then the initial X-ray filtration makes little difference to the X-ray energy transmitting through the whole sample. (The methodological implication is that appropriate filtration for scanning a mouse will reduce radiation dose to the mouse – a good outcome – without actually changing very much the absorption contrast achieved by the scan in soft tissues as well as bone. Conversely, scanning a mouse or any large sample with insufficient filter does not improve contrast in low density materials, it only increases beam hardening and artefacts associated with insufficient X-ray transmission.)

Table one below confirms that scanning a mouse with no filter – as well as causing an unacceptably high X-ray dose – results in extreme beam hardening that we can quantify as an increase in X-ray photon energy of over 100%; that is, more than a doubling of the X-ray energy caused by selective removal of low energy X-rays. Adding just a quarter of a millimeter of aluminium filter reduces this beam hardening to 44%. However, in practice 0.25mm Al is still too low a filter to use with a mouse in vivo since radiation dose will be too high.

Table 1. Simulated (by SpekCalc™) X-ray mean photon energies before and after traversing a mouse, depending on filter and applied voltage. Increased mean photon energy resulting from differential attenuation in "mouse" tissue[1] is expressed as percentage beam hardening. Pre-filtration of X-rays greatly reduces beam hardening. Note that for the same filter (2mm Al), increasing voltage increases beam hardening slightly by widening the X-ray energy spectrum.

Thickness Al X-ray filter, mm	X-ray voltage, kV	X-ray photon energy before mouse, keV	X-ray photon energy after mouse, keV	Percentage beam hardening (increased mean photon energy)
0	50	16.0	33.1	106.9
0.25	50	23.2	33.4	44.0
0.5	50	25.6	33.7	31.6
1	50	28.1	34.3	22.1
2	50	30.9	35.2	13.9
2	70	37.4	42.9	14.7
2	80	40.5	46.6	15.1

4.1. *The technique of spectrum compression*

The appendix at the end of this method note gives graphic examples of projection images with appropriate and inappropriate X-ray photon energy. As we've already seen, X-ray photon energy is determined by two things – first and foremost the filter, but also applied voltage. The result of the filter-voltage combination is the X-ray energy spectrum, and the important parameter of the X-ray spectrum in terms of the transmission through the imaged sample, is the average photon energy. However, as figure 4 shows, different combinations of filter and voltage can achieve the same average photon energy.

[1] A mouse body is simulated as 18mm of water and 2mm of aluminium whose X-ray attenuation is close to that of bone.

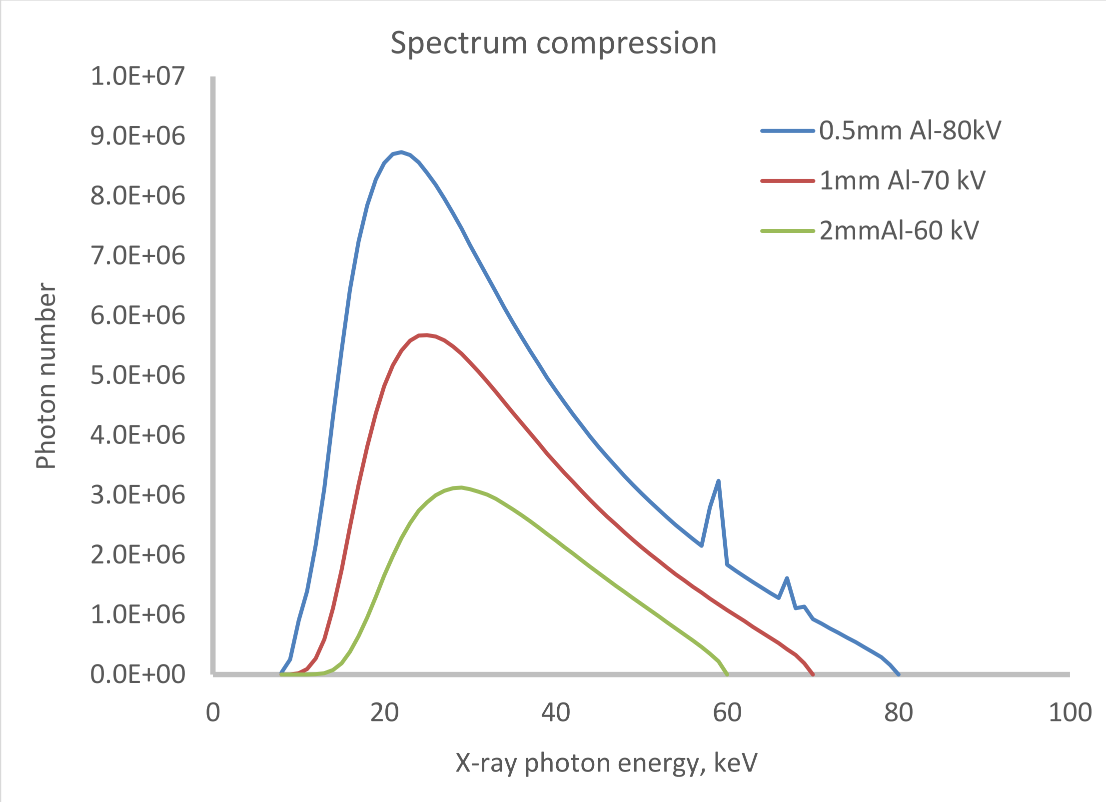


Figure 4. The three filter-voltage combinations shown here all have about the same mean X-ray photon energy. However, the combination of more filter and less voltage for the same energy results in a narrower spectrum and thus less beam hardening, so better image quality. However – the reduced amount of X-rays (lower amplitude spectrum) means longer camera exposure times and longer scan times.

So which of the three filter-voltage combinations shown in figure 4 will give the best scan result? The answer is that the combination with the highest filter and lowest voltage will be best – it will have the least beam hardening. The X-ray energy spectrum is the narrowest, so the beam hardening, the amount of mean photon energy increase during passage through a solid, will be lowest. This will minimize all the artefacts associated with beam hardening – the artificial surface-to-volume attenuation gradients and the “halo” of noise “shine” around the edges of reconstructed objects. This can be seen if we repeat the calculation of beam hardening through a simulated mouse sample, mimicked by transmission through 18mm of water and 2mm of aluminium. These values – again calculated in SpekCalc – are shown below in table 2.

Table 2. Beam hardening from three filter-voltage combinations all having the same average photon energy, simulated by SpekCalc™. Again, a mouse body is simulated as 18mm of water and 2mm of aluminium. For the same average energy, combinations with more filter and less voltage have lower beam hardening. However, camera exposure times and thus scan times will be longer for such combinations with narrower spectra.

Thickness Al X-ray filter, mm	X-ray voltage, kV	X-ray photon energy before mouse, keV	X-ray photon energy after mouse, keV	Percentage beam hardening (increased mean photon energy)
0.5	80.5	34.0	44.6	31.2
1	70	34.0	41.7	22.6
2	59	34.0	38.9	14.4

It's quite a big effect: 59 kV applied voltage with a 2mm Al filter will give less than half the beam hardening through our simulated mouse, than 80.5kV applied and a 0.5mm Al filter – both giving the same average photon energy and thus also giving the same appearance in the projection image and the same sample transmission.

5. Always report what filter you used in the methods for microCT publications

Finally - the filter used in microCT scans should always be reported in the methods section of a journal article or other publication. Methods text about microCT in scientific journals even of high impact factor, is sometimes poor in quality. Important information – such as filter – is often omitted. Referees seem to pay equally little attention to this method text. As mentioned above, the X-ray filter is the most important scan parameter, which makes its frequent omission in methods sections of microCT papers unhelpful. Some early models of microCT scanner had a fixed X-ray filter which could not be changed by the user. This resulted in the habit of not reporting the filter since it was not a selectable scan setting. But filter is important, it should be selectable in microCT.

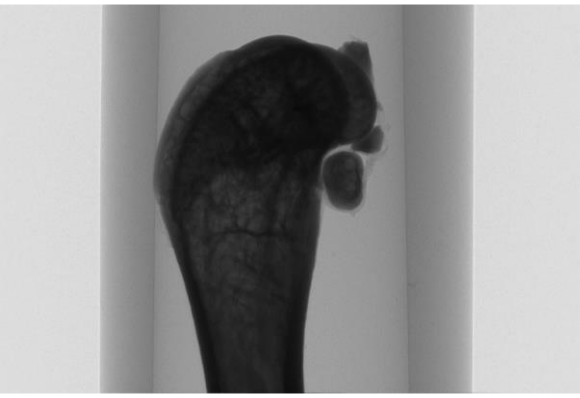
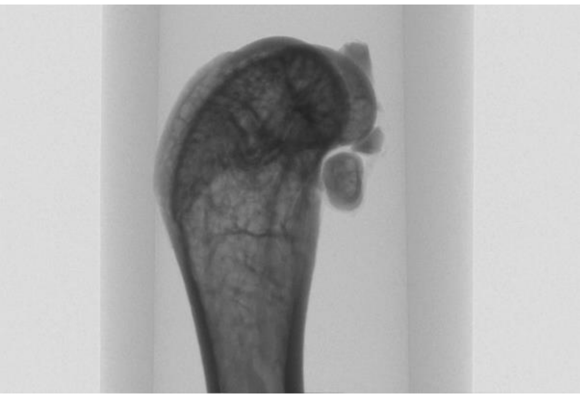
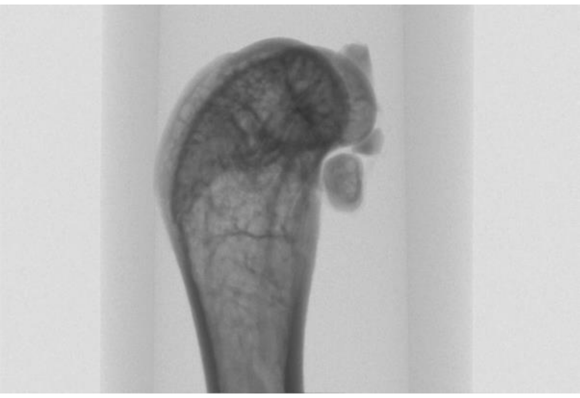
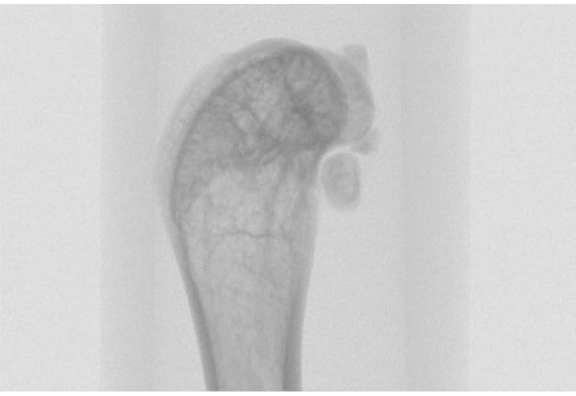
A previous method note – MN 45 – gives guided examples of how to construct appropriate and concise methods text for journal articles employing microCT imaging.

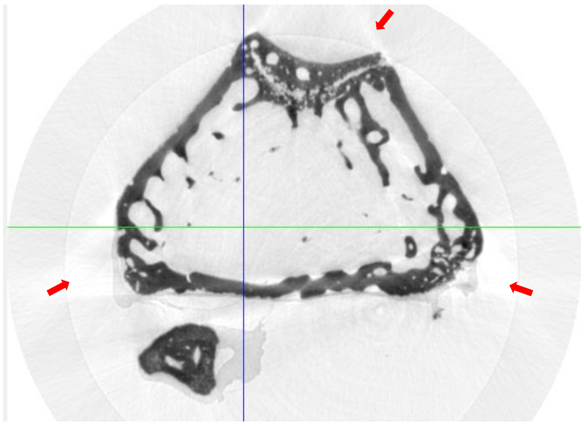
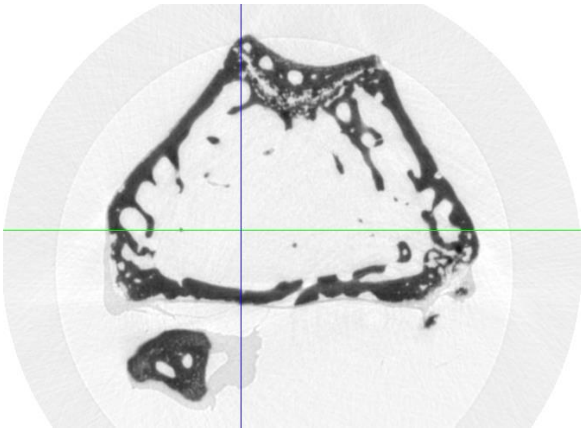
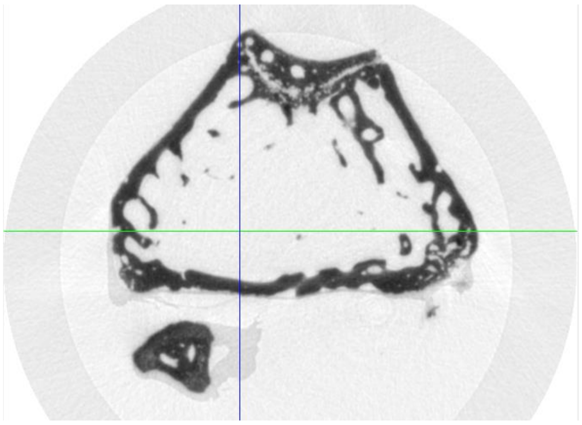
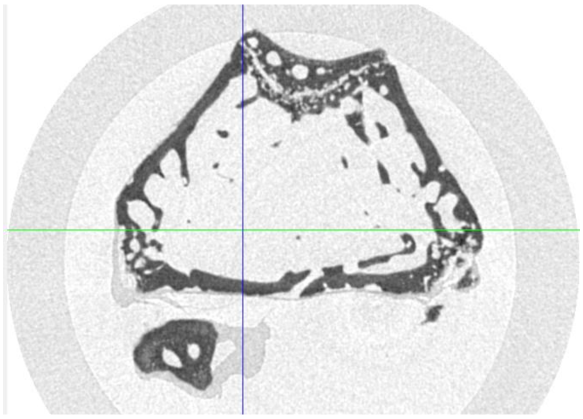
So remember – filter is important, and should always be reported in the method text of your papers.

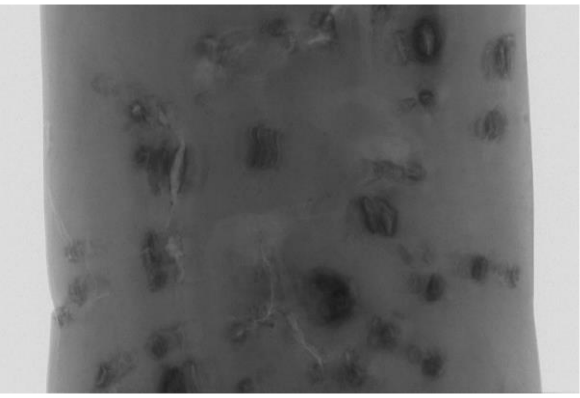
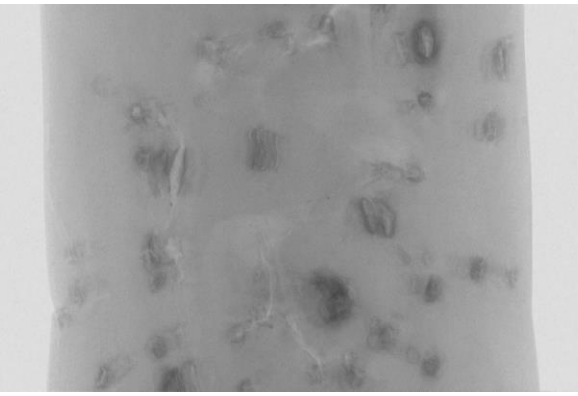
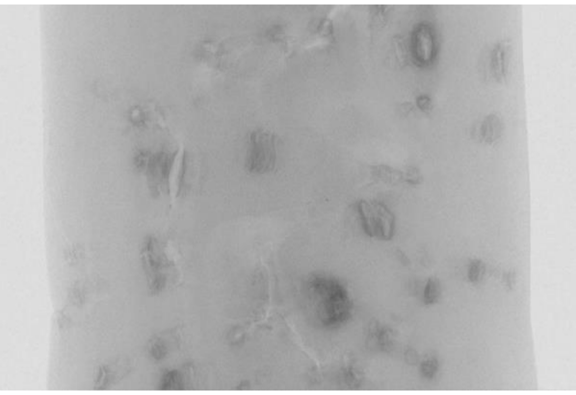
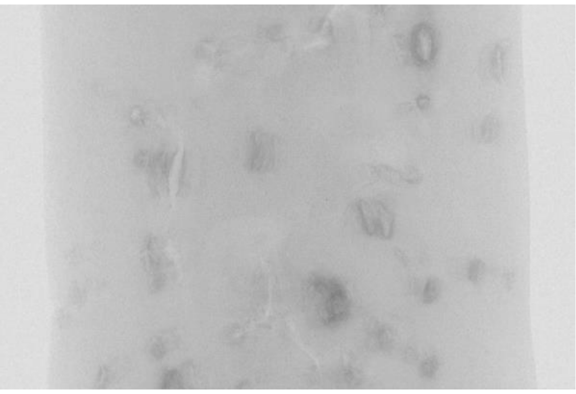
References

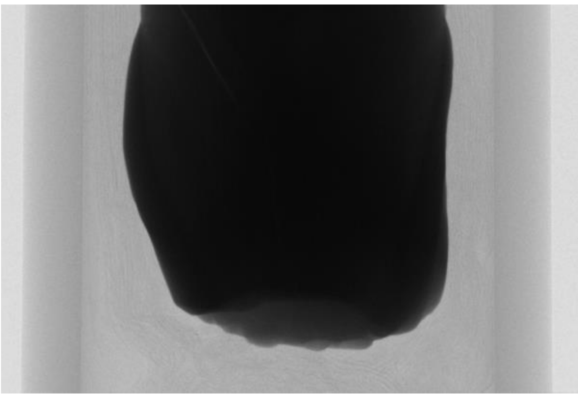
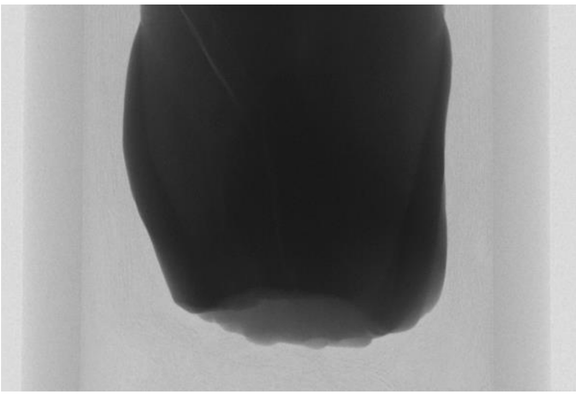
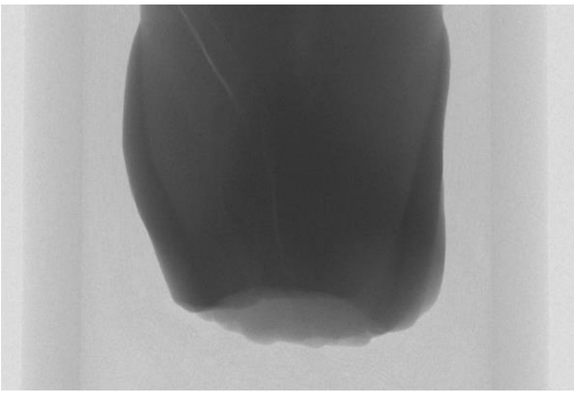
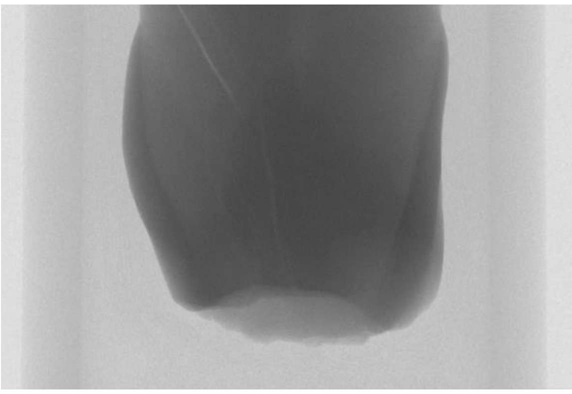
1. Poludniowski GG, Landry G, DeBlois F, Evans PM, Verhaegen F (2009) SpekCalc: a program to calculate photon spectra from tungsten anode x-ray tubes. Physics in Medicine and Biology 54: N433. http://iopscience.iop.org/article/10.1088/0031-9155/54/19/N01/meta

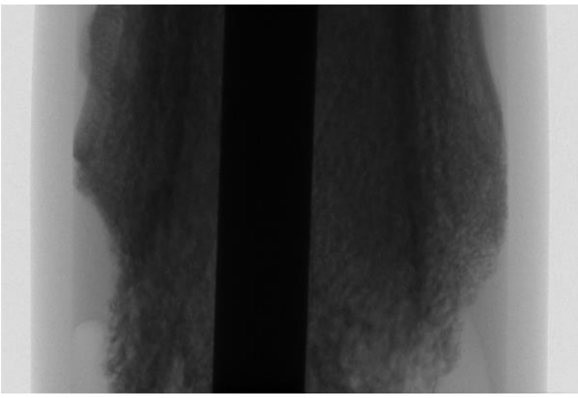
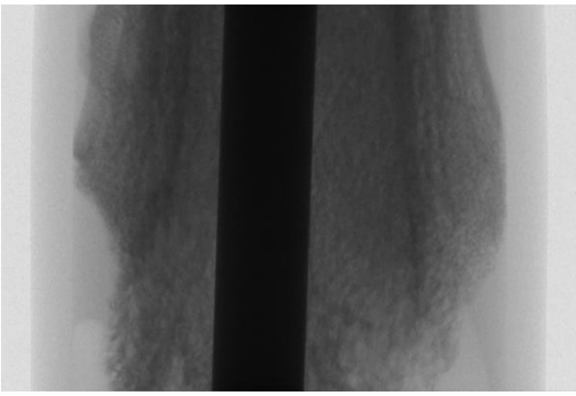
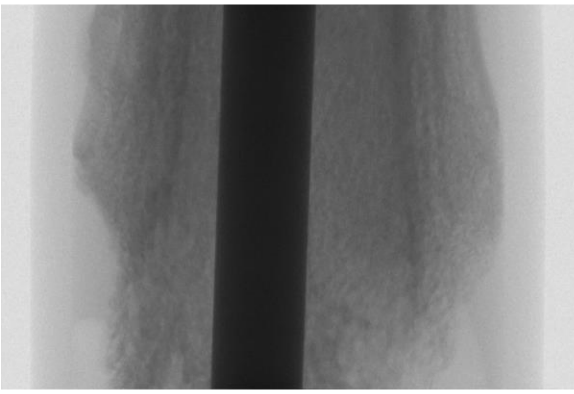
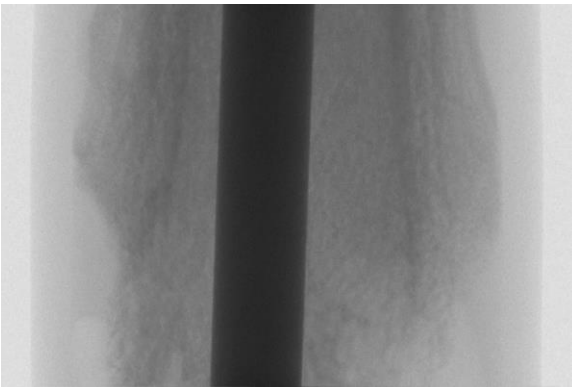
APPENDIX: Image examples of right and wrong filters

	Mouse femur (bone) No filter, 30 kV Transmission minimum 6.3% **Wrong** filter choice – too little transmission. Image too dark, limited visible dynamic range, low visibility of internal structure and contrast
	Mouse femur (bone) 0.25mm aluminium filter, 40 kV Transmission minimum 19.6% **Right** filter – this will work. Close ideal minimum transmission of 20%.
	Mouse femur (bone) 0.5mm aluminium filter, 45 kV Transmission minimum 28.6% **Also OK** – this will work. Minimum transmission is above ideal 20% value but still acceptable; more filter means less beam hardening so good for densitometry
	Mouse femur (bone) Cu + Al filter (equivalent to 2mm Al), 90 kV Transmission minimum 54.9% **Wrong** filter – much too little transmission. Image too pale, weak contrast and dynamic range

	Mouse femur (bone) No filter, 30 kV Reconstructed cross-section: • Beam hardening artefacts are prominent as both density gradients and low density shadows or “flash” outside the bone at the corners (arrows) • Ring artefacts are worse
	Mouse femur (bone) 0.25mm aluminium filter, 40 kV Reconstructed cross-section: • Good uniformity of density, beam hardening much less (than no filter) • Ring artefacts minimal • Much less shadow or “flash” artefacts from beam hardening
	Mouse femur (bone) 0.5mm aluminium filter, 45 kV Reconstructed cross-section: • A bit noisier than 0.25mm Al filter • Good uniformity – beam hardening low • Ring artefacts also low
	Mouse femur (bone) Cu + Al filter (equivalent to 2mm Al), 90 kV Reconstructed cross-section: • Noise is increased a lot because of the higher X-ray energy • Contrast between materials is reduced also due to the higher energy

	Cork from a wine bottle No filter, 30 kV Transmission minimum 19.6% **Right** filter choice – ideal value for minimum transmission (~20%)
	Cork from a wine bottle 0.25mm Al filter, 40 kV Transmission minimum 49.8% **Wrong** filter – energy too high, image too pale, contrast less than optimal
	Cork from a wine bottle 0.5mm Al filter, 45 kV Transmission minimum 58.0% **Wrong** filter – energy too high, image too pale, contrast less than optimal
	Cork from a wine bottle 1mm Al filter, 65 kV Transmission minimum 67.1% **Wrong** filter – energy way too high, image too pale, contrast much less than optimal

	Tooth – crown part 0.5mm Al filter, 45 kV Transmission minimum 3.1 % **Wrong** filter – transmission way too low.
	Tooth – crown part 1 mm Al filter, 65 kV Transmission minimum 9.0 % **Wrong** filter – transmission too low.
	Tooth – crown part Cu + Al filter (equivalent to 2mm Al), 90 kV Transmission minimum 20 % **Right** filter – transmission is just right for optimal contrast and low noise.
	Tooth – crown part Cu 0.11 filter, 100 kV Transmission minimum 25.9% **Also OK** – the transmission is in an acceptable range (15-30%)

	Titanium implant rod in bone 0.5mm Al filter, 45 kV Transmission minimum 1.6 % **Wrong** filter – transmission much too low
	Titanium implant rod in bone 1mm Al filter, 65 kV Transmission minimum 4.3 % **Wrong** filter – transmission still too low through the densest object, the titanium rod
	Titanium implant rod in bone Cu+Al filter (equivalent to , 90 kV Transmission minimum 10.6 % **Just about OK** - 10% transmission is marginally acceptable if it is only in a small part of the scanned sample
	Titanium implant rod in bone Cu 0.11mm filter, 100 kV Transmission minimum 14.9 % **Right** filter - 15% transmission is a good value if only for a small part of the scanned object.