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Title: Measuring bone density using MARS spectral CT

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Introduction:

Osteoporotic and osteoarthritic diseases often greatly reduce quality of life for those inflicted. Disease progression can be insidious where intervention isn't considered until late stages, by which time only the most extreme options such as joint replacement are left. Hence there is a need for early detection in changes in bone density or quality, and a tool with which to monitor effectiveness of any treatments. Currently the most well established approach to imaging bone density for osteoporosis is dual energy x-ray absorptiometry (DEXA), but this technique has a number of shortcomings. DEXA only gives a 2D projected measure of density which assumes everyone is the same shape and size, and the technique can't be applied to specific remote regions of bone such as those at joints. Osteoarthritis on the other hand has no well-established early detection method, instead relying on late stage symptoms and advanced indicators on MRI or x-ray to diagnose.

With the advent of spectral computed tomography (CT), a new modality currently being developed by the MARS group, there is potential for the advancement of medical imaging capability. Spectral CT to regular CT is like colour TV to black and white film. Different materials indistinguishable on traditional CT due to showing the same shade of grey can be distinguished by virtue of the spectra, or 'colour', of the x-rays passing through them with spectral CT. With the ability to differentiate and quantify material through 'colour', there is great promise MARS spectral CT can overcome the shortfalls of current approaches to measuring bone density and one day become the new standard in clinical practice.

Aim:

To explore how MARS spectral CT can be used to improve quantification of bone health

Method:

Bone mineral is mainly composed of calcium hydroxyapatite (CaHA) and one measure of bone quality would be to quantify the density of this material within bone. To achieve this, firstly a Perspex phantom with slots containing rods of known concentrations of CaHA (0, 50, 200, 800, and 1200 mg/mL) as well as sealed tubes of water and lipid was imaged with a prototype MARS spectral CT scanner. This scanner's tungsten x-ray source peak kilovoltage was set to 120 kVp, the equipped cadmium telluride Medipix3RX detector was set to view x-rays of 4 energies (18, 27, 33, and 49 keV), and the gantry set to scan in continuous motion helical mode. A second scan with the same parameters was then performed on a bovine tibia plug of 8 mm diameter: an excised biological sample containing cartilage, compact bone and spongy bone – enclosed within a plastic tube. Resulting raw data was processed and then used to reconstruct images of transverse slices through each object. The spectral response of each material in the phantom scan was then analyzed, and the data was used to identify which part of the image was similar to CaHA, which was similar to water and which was similar to lipid. This 'material decomposition' process was then applied to the images of the bone sample and with this, the mineral content of the bone sample can be isolated from other components such as cartilage and fat, and its density measured against the known densities of the CaHA within the phantom.

Results:

The unique spectral behavior of each material included in the phantom showed that each material could be identified as different. Water was identified in every material except lipid, and most strongly in the pure water sample. This was expected, as water or water-like substances were known to exist in every given material other than lipid. Lipid was mainly identified in the lipid slot of the phantom, and calcium was identified in each sample containing it – with sensible differences associated with the different concentrations present.

This validated the method for identifying lipid, water, and bone-like material, distinguishing them from each other and also provided a means of measuring the CaHA concentration from the x-ray data. In turn this yielded a calibration curve given by the equation:

$$[HA] = 129.69x^2 + 822.36x + 2.5023$$

[HA] is the estimated density of CaHA within the bone in mg/mL, and *x* can be found by isolating CaHA content within a bone image. From the data obtained in the biological bone scan, *x* in the equation above was determined to be 0.966. Therefore, the estimated CaHA concentration, or bone densitometry equivalent measurement, was 918 mg/mL.

Discussion:

This experiment demonstrated that by using a phantom containing various concentrations of calcium hydroxyapatite, MARS spectral CT has the capability to isolate the mineral component of bone. It was also shown that a quantity can be assigned to the CaHA density within scanned bone samples, which could potentially be indicative of bone health.

However this experiment falls short in terms of verification. It is still not known whether this measured value is truly the CaHA density within the biological sample, what the statistical uncertainty of this technique is, and more importantly whether or not the MARS spectral CT has the sensitivity to distinguish healthy from unhealthy levels of CaHA density.

Future research needs to be done to investigate the repeatability of this technique, and hence provide a measure of uncertainty. This can be done by repeating identical scans and observing variation. Also, confirmation is needed of whether or not the differences between bones from different body locations or bones of different levels of quality can be detected. This can be done by applying this approach to a variety of bone samples with some known attributes. Finally, a true analysis of bone health would need to include consideration of bone micro-architecture in addition to mineral density.

At the moment MARS spectral CT has not reached a stage where it can top current methods of quantifying bone health. Much more research needs to be done not only in refining the approach explored in this study, but in relating the results to clinically significant outcomes such as fracture risk. However this first step has shown promising results. There may yet come a day when spectral CT is integral to everyday clinical use, and osteoporosis or osteoarthritis can be treated while they are still reversible – preventing fractures and the eliminating the need for joint replacement.