X-ray dual energy spectral parameter optimization for bone Calcium/Phosphorus mass ratio estimation

P. I. Sotiropoulou1, G. P. Fountos2, N. D. Martini1, V. N. Koukou1, C. M. Michail2, I. G. Valais2, I. S. Kandarakis2 and G. C. Nikiforidis1

1 Department of Medical Physics, Faculty of Medicine, University of Patras, 265 00 Patras, Greece
2 Radiation Physics, Materials Technology and Biomedical Imaging Laboratory, Department of Biomedical Engineering, Technological Educational Institute of Athens, Egaleo, 122 10 Athens, Greece

E-mail: gfoun@teiath.gr

Abstract. Calcium (Ca) and Phosphorus (P) bone mass ratio has been identified as an important, yet underutilized, risk factor in osteoporosis diagnosis. The purpose of this simulation study is to investigate the use of effective or mean mass attenuation coefficient in Ca/P mass ratio estimation with the use of a dual-energy method. The investigation was based on the minimization of the accuracy of Ca/P ratio, with respect to the Coefficient of Variation of the ratio. Different set-ups were examined, based on the K-edge filtering technique and single X-ray exposure. The modified X-ray output was attenuated by various Ca/P mass ratios resulting in nine calibration points, while keeping constant the total bone thickness. The simulated data were obtained considering a photon counting energy discriminating detector. The standard deviation of the residuals was used to compare and evaluate the accuracy between the different dual energy set-ups. The optimum mass attenuation coefficient for the Ca/P mass ratio estimation was the effective coefficient in all the examined set-ups. The variation of the residuals between the different set-ups was not significant.

1. Introduction
Osteoporosis has been recognized as a worldwide disease that affects more than 75 million people in the United States, Europe and Japan [1,2]. Several methods [2,3] are available for measuring an individual’s bone mineral status. Bone mineral density (BMD) is the gold standard measurement, determining the bone health, which primarily measures the quantity of bone in the skeleton. However, about one-half of fractures occur in women with a T-Score above the World Health Organization (WHO) diagnosis threshold of osteoporosis [1,4], suggesting that other factors, besides bone quantity, are involved in the appearance of fractures. The major and essential component of human bones is hydroxyapatite (Ca10(PO4)6(OH)2), a mineral form of calcium (Ca) and phosphorus (P) that gives bones their rigidity. Researchers [2,5,6] have determined alterations in skeletal Ca/P molar ratio. There are indications [5-10] that the alterations on Ca/P ratio have a negative effect on bone health.
In this study, an optimization in the Ca/P bone mass ratio estimation was held based on the dual energy method, previously described in previous works of our group [7,8,11]. Simulated data were obtained using the K-edge filtering technique and single X-ray exposure. The modified X-ray output was attenuated by nine calibration points produced by various Ca/P mass ratios. The analysis presented here, investigates the use of effective or mean mass attenuation coefficient in Ca/P mass ratio estimation. The optimization was based on the minimization of the accuracy of Ca/P ratio, with respect to the coefficient of variation of the Ca/P ratio (CV\textsubscript{Ca/P}). The standard deviation of the residuals was used to compare and evaluate the accuracy between the different dual energy set-ups.

2. Materials and Methods

2.1 Simulation input functions and parameters

The theory for the in vivo determination of Ca/P ratio, in the radius, was described previously [8,11]. The Ca/P mass ratio is obtained assuming that there is a three-component system: Ca, PO\textsubscript{4} and water (w). The photon beam is transmitted through an object of total thickness \( t = t_{Ca} + t_{PO_4} + t_w \) where \( t_{Ca} \) is the thickness of calcium, \( t_{PO_4} \) is the thickness of phosphate and \( t_w \) is the thickness of water. The total thickness was equal to 5 cm, corresponding to a human forearm. Assuming that both surfaces of Ca and PO\textsubscript{4} were exposed to the same radiation beam and considering that the molecular weight ratio PO\textsubscript{4}/P is 3.0679, the Ca/P mass ratio [7,11] is given by:

\[
\frac{Ca}{P} = \frac{t_{Ca}}{t_{PO_4}} \cdot 3.0679
\]

In a previous study [11], a wide range of filter materials and thicknesses, combined with different maximum tube voltages (kVps), were simulated producing the different set-ups. The set-ups were used for the dual energy spectra optimization, in the Ca/P mass ratio estimation. The simulation considers a photon counting energy dispersive detector that allows energy peak discrimination and counting.

2.2 Mass attenuation coefficients

In Table 1 the step thicknesses for Ca and PO\textsubscript{4} are shown, used to generate the detector data. The three pairs of Ca and PO\textsubscript{4} thicknesses correspond to molar ratios of 1.40, 1.58, and 1.67, respectively. The combined thicknesses results in 9 calibration points, where the total thickness of Ca, PO\textsubscript{4} and water is maintained constant.

| Material | Thickness (cm) |
|----------|----------------|
| Ca       | 0.0533 0.0671 0.0704 |
| PO\textsubscript{4} | 0.1168 0.1017 0.0996 |

In the accuracy (\( \alpha \)) determination [11] of the Ca/P mass ratio (Eq. 1), instead of the effective mass attenuation coefficient \( \mu/\rho_{eff} \) that was used in the previous study [11,12], the mass attenuation coefficient, corresponding to the mean energy of the incident spectrum (mean mass attenuation coefficient, \( \mu/\rho_{ME} \)), can be used to estimate the Ca/P mass ratio. The accuracy of the estimated Ca/P mass ratio values was calculated for both \( \mu/\rho_{eff} \) and \( \mu/\rho_{ME} \) values.
For every calibration point, the residuals ($\delta$) were calculated as the difference between the true ($tr$) and the estimated values ($est$) according to following equation:

$$\delta = Ca/P_{tr} - Ca/P_{est}$$

(2)

The standard deviation of the residuals ($\delta_{rms}$) was used to compare and evaluate the accuracy between the different dual energy set-ups. $\delta_{rms}$ values close to zero indicates that the set-up has a smaller random error component. Different set-ups were examined, based on the K-edge filtering technique and single X-ray exposure [13]. This study used three set-ups with optimum $CV_{Ca/P}$ described in a previous study [11]. These are La (0.15cm, 100 kVp) (set-up S1), Ce (0.13cm, 100 kVp) (set-up S2) and Sm (0.13cm, 100 kVp) (set-up S3).

3. Results and Discussion

The accuracy values were calculated using both the effective ($\mu/\rho_{eff}$) and mean ($\mu/\rho_{ME}$) mass attenuation coefficients. For the set-ups S1, S2 and S3, the accuracy ranged from 2.31 to 5.18%, using $\mu/\rho_{eff}$ for the calculations, and from 8.33 to 18.98% using $\mu/\rho_{ME}$, respectively. Set-up S3 appeared to have the lower accuracy value (2.31%), as well as the optimum $\delta_{rms}$ (0.014) value. The results for set-ups S1, S2, S3 are shown in Table 2. The $\delta_{rms}$ values in three set-ups close to zero (Table 1) suggest that the errors from the Ca/P estimation will be sufficiently small in the calibration region. $\delta_{rms}$ values between the different set-ups were comparable. This implies that the accuracy values of each set-up are the main indicator for the optimum set-up and spectra optimization.

| $\delta_{rms}$ | $\alpha$ (range) | $\delta_{rms}$ | $\alpha$ (range) |
|---------------|-----------------|---------------|-----------------|
| set-up S1     | 0.033           | 3.60-4.22     | 0.067           | 15.47-18.98    |
| set-up S2     | 0.019           | 4.25-5.18     | 0.066           | 15.49-18.61    |
| set-up S3     | 0.014           | 2.31-2.97     | 0.077           | 8.33-12.31     |

The use of $\mu/\rho_{eff}$ instead of $\mu/\rho_{ME}$ provides results with lower accuracy values. The accuracy values can be up to 6 times higher if calculated with $\mu/\rho_{ME}$. In Table 3 the values of $\mu/\rho_{eff}$ and $\mu/\rho_{ME}$ are given for set-up S1. The $\mu/\rho_{ME}$ values are lower from the $\mu/\rho_{eff}$ values in all cases. These differences, in $\mu/\rho_{eff}$ and $\mu/\rho_{ME}$, justify the accuracy differences in Ca/P estimation.

| $\mu/\rho_{eff}$ | $\mu/\rho_{ME}$ |
|------------------|-----------------|
| Ca(Ehigh)        | 0.7589          | 0.6866          |
| Ca(Elow)         | 2.2670          | 2.2570          |
| PO$_4$(Ehigh)    | 0.2574          | 0.2458          |
| PO$_4$(Elow)     | 0.5082          | 0.5069          |
| W(Ehigh)         | 0.2105          | 0.2072          |
| W(Elow)          | 0.2897          | 0.2897          |
The data from radius are included in this study solely as a proof-of-concept demonstration. The accuracy and the precision of measurements from bone phantoms and specimens is the subject of ongoing work in our lab.

4. Conclusions
Analysis of the bone composition increases sensitivity and specificity in metabolic bone diseases diagnosis and their monitoring. In this study an optimization in the Ca/P bone mass ratio estimation was investigated using the either the effective or mean mass attenuation coefficients. The use of the $\mu/\rho_{\text{eff}}$ instead of $\mu/\rho_{\text{ME}}$ provides results with lower accuracy values.

Acknowledgements
This research has been co-funded by the European Union (European Social Fund) and Greek national resources under the framework of the “Archimedes III: Funding of Research Groups in TEI of Athens” project of the “Education & Lifelong Learning” Operational Program.

References
[1] Ruppel M, Miller L, Burr D 2008 Osteoporos. Int. 19 1251
[2] Kyriazis V and Tzaphlidou M. 2004 Scien. World J. 4 1027
[3] Travert C, Jolivet E, Brosses ES, Mitton D, Skalli W 2011 Med Biol Eng Comput 49 1355
[4] Sornay-Rendu E, Munoz F, Garnero P, Duboeuf F, Delmas PD 2005 J Bone Miner Res 20 1813
[5] Kourkoumelis N, Balatsoukas I, Tzaphlidou M 2012 J Biol Phys 38 279
[6] Kounadi E, Fountos G, Tzaphlidou M 1998 Connect. Tissue Res. 37 69
[7] Fountos G, Yasumura S, Glaros D 1997 Med. Phys. 24 1303
[8] Fountos G, Tzaphlidou M, Kounadi E, Glaros D 1999 Appl. Radiat. Isot. 51 273
[9] Neues F and Epple M 2008 Chem. Rev. 108 4734
[10] Zoehrer R, Perilli E, Kuliwaba JS, Shapter NL, Fazzalari NL, Voeleker NH 2012 Osteoporos Int 23 1297
[11] Sotiropoulou P, Fountos G, Martini N, Koukou V, Michail C, Kandarakis I and Nikiforidis G 2015 Phys. Medica 31 307
[12] Sotiropoulou P, Fountos G, Martini N, Koukou V, C Michail C, Valais I, Kandarakis I and Nikiforidis G 2014 X-ray spectra for bone quality assessment using energy dispersive counting and imaging detectors with dual energy method XIII Mediterranean Conf. on Medical and Biological Engineering and Computing 2013 (Seville, Spain, 25-28 September) (IFMBE Proceedings Vol 41) ed LM Roa Romero (Springer Int.) p 463
[13] Martini N, Koukou V, Michail C, Sotiropoulou P, Kalyvas N, Kandarakis I, Nikiforidis G, Fountos G 2015 J. of Spectr. Article ID 563763, 8 pages