Bone tissue mineral density distribution: characterization and modeling

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Introduction

Characterization techniques for human bones are often limited to in-vivo conditions, as physically retrieving big enough bone samples is challenging. Ex-vivo characterization techniques offer a greater understanding into the structural and compositional characteristics of the bone matrix. One such technique is quantitative backscattered electron imaging (qBEI) (Fig. 1), which gives an in-depth insight into the bone mineral density distribution (BMDD). While normal bone has a narrow distribution with pronounced peak, undermineralized bone such as in osteomalacia has a wide distribution with a low peak (Fig. 1 B). More conventional in-vivo measurements of bone mineral density (BMD) are not accurate to estimate BMDD due to the fact that both porosity and bone quality enter the BMD measure [1].

Complimentary to physical characterization methods, computer modeling contributes by providing a deeper understanding of underlying mechanisms. Furthermore, modeling allows applying a variety of different parameters to simulate specific metabolic or environmental conditions.

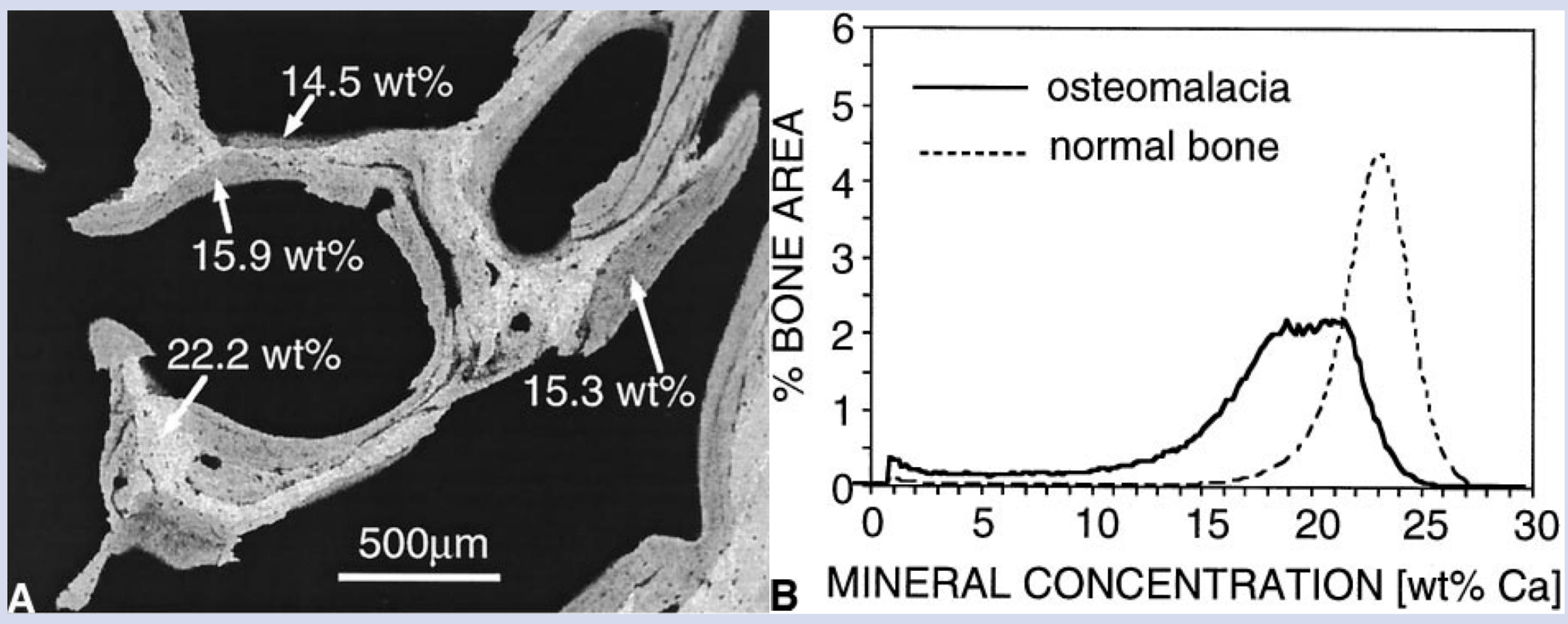
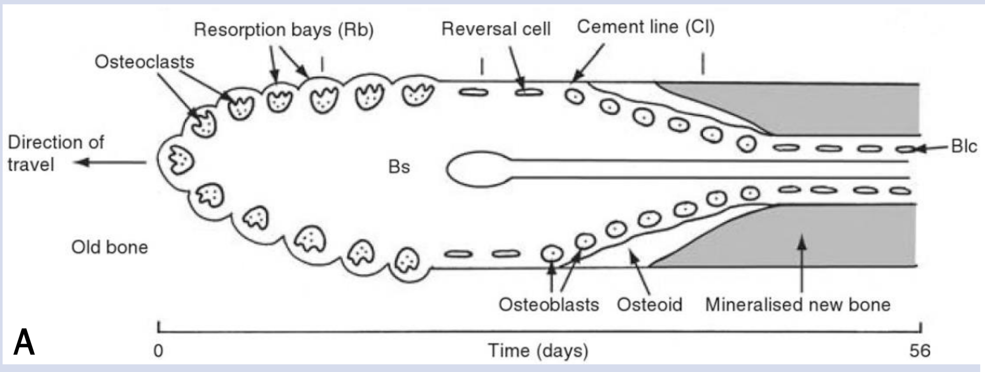


Figure 1: BE image of a transiliac bone biopsy from a patient with a metabolic bone disease [1] (A) and bone mineral density distribution (BMDD) frequency plot from a normal and pathologic bone sample (B).

Materials and Methods



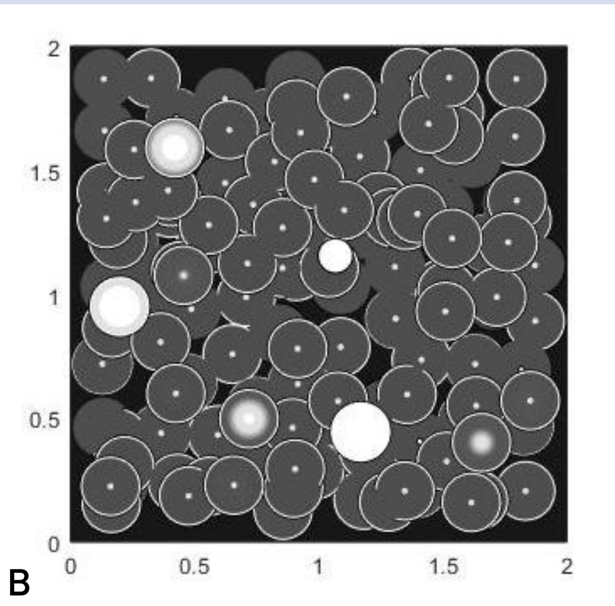


Figure 2: (A) Diagram of a basic multicellular unit (BMU) [2] and (B) remodeling simulation with randomly generated BMUs on a 2D bone cross section (2x2 mm^2).

BMDD is governed by bone remodeling, with high remodeling leading to lower BMDD or vice versa. Bone remodeling is executed by basic multicellular units (BMUs) consisting of bone resorption and bone formation (Fig.2 A). Computer modeling of BMUs can be performed in a 2D section of bone by randomly generating BMU resorption and refilling events (Fig.2 B). The variables for the simulation have been gathered from previous research on mathematical and experimental models of the bone remodeling [3,4]. Currently the model simulates only the resorption and 1st phase of mineralization.
Simulations are performed with *MATLAB R2018b*.

References

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Computer Modeling Results and Conclusions

Various simulations were performed investigating the model. Increasing the bone turnover rate (BMU origination frequency over the cross section) results in an increase of average porosity (Fig. 3).

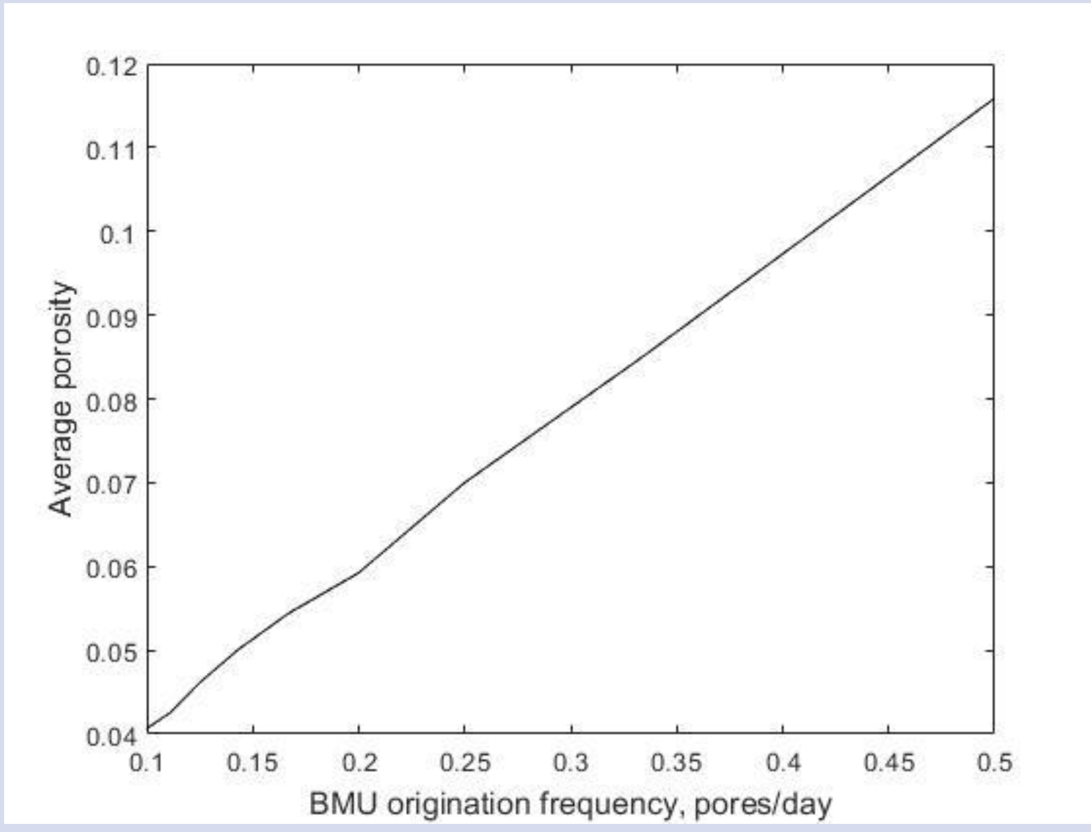

Figure 3: Model simulation: BMU origination frequency versus average porosity plot.

Refilling deficit of BMUs as it occurs in bone diseases such as osteoporosis lead to significant loss in bone material which may ultimately lead to bone fractures (Fig. 4). This model, being in simple nature, provides adequate representation of the metabolic bone conditions.

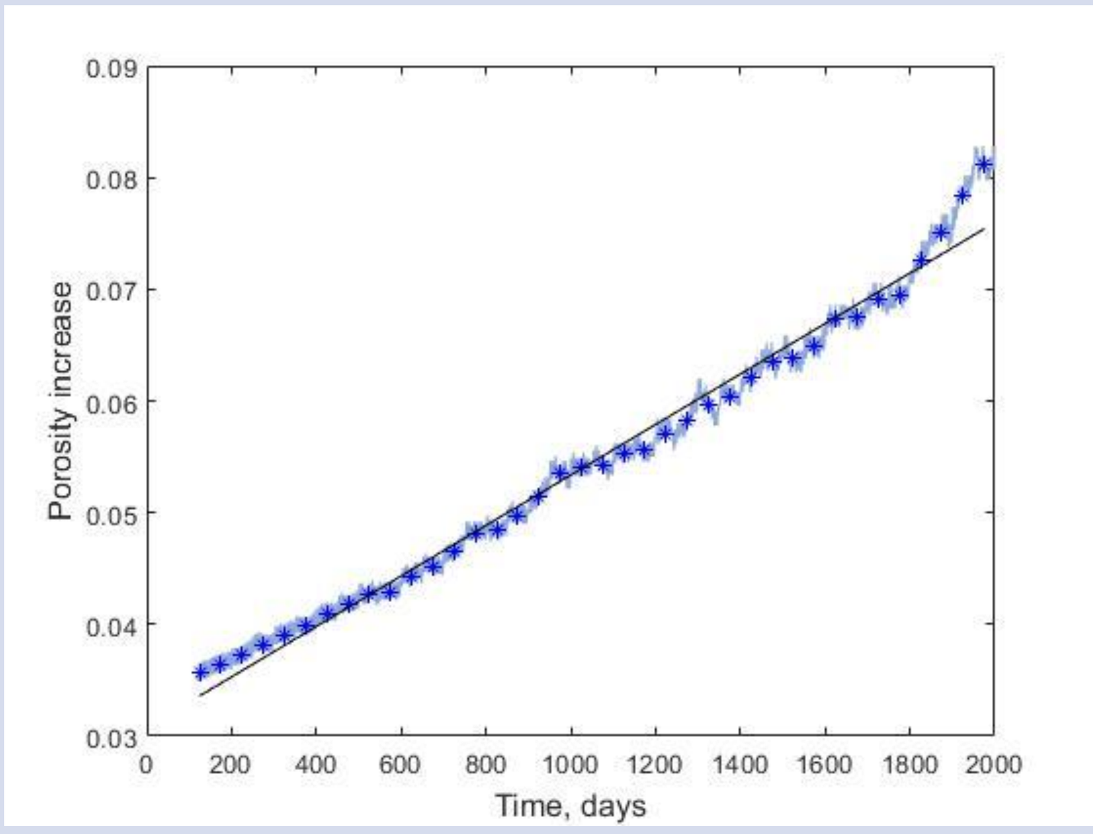

Figure 4: Model simulation: porosity evolution versus time as mediated by the refilling deficit of pores.

The next step for the further development of this model would be including the mineralization law for the pore refilling, where the 1st phase is characterized by a quick linear mineralization up to 60% of the final concentration, and a exponentially decaying 2nd phase with reaching converging towards full mineralization in a time amount of couple of years. This in turn would provide more intuition into how metabolism affects bone mineralization and structure.

Outlooks

With continuing work on this topic, the further goals would consist of, but not limiting to:

- Improve the model to be able to represent both cortical and cancellous bone, as well as include 2nd mineralization phase.
- Undertake the characterization methods for the existing bone samples, compare with simulations, investigate for connecting factors, similarities.