Mathematical modeling of biodegradation of metal implants in orthopedics

M Barzegari[1], L Geris[1,2]

[1] Biomechanics section, *Department of Mechanical Engineering, KU Leuven, Belgium.*

[2] Biomechanics Research Unit, *GIGA in Silico Medicine, University of Liège, Belgium*

INTRODUCTION: The rate and quality of bone regeneration after implantation of orthopaedic implants depends greatly on the achieved mechanical stability. At the end of their lifetime, implants need to be removed and replaced. However, during this removal surgery, additional bone is removed along with the implant, making it harder to achieve proper mechanical stability with the second implant [1]. One of the best approaches to solve this problem is to make at least part of the implant from biodegradable metal which means that the metal implant will disappear and be replaced by newly formed bone during the implant's lifetime. This requires tuning the degradation of the implant to the regeneration and growth of the new bone.

We have developed a quantitative mathematical model to assess the degradation of the implants in silico (in the computer) prior to conducting any in-vitro or in-vivo experiments. In this study, the model has been implemented for magnesium (Mg) implants as a first proof of concept.

METHODS: Biodegradation is modeled as a set of reaction-diffusion PDEs obtained from the chemistry of dissolution of Mg in a medium containing Chloride ions (Cl^-). The model captures the formation of a protective film that slows down the degradation, as well as taking into account the role of Cl^- ions on the dissolution of the formed film. The concentration of Mg and Cl ions, the concentration of the protective film, and the shape of the scaffold over time are the outputs of the model.

The equations are implemented in FreeFem++ [2], and the finite element method is utilized to solve the equations numerically. The complicated interface between the scaffold and the medium is tracked using a level set approach.

RESULTS: Fig. 1 shows the degradation of the investigated scaffold, in which the dark blue regions are the shape of the scaffold after 43.5 days, and the surrounding red regions are the formed protective film. Fig. 2 depicts the finite element mesh and the mesh adaptation approach used to compute the degradation over time.

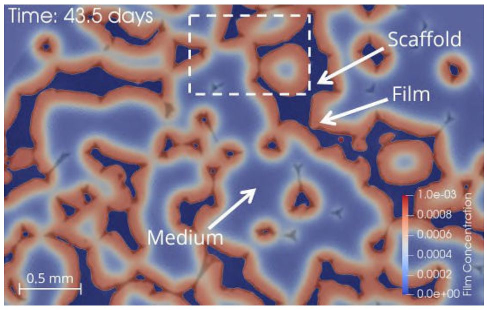

Fig. 1: Degradation of the scaffold and formation of a protective film

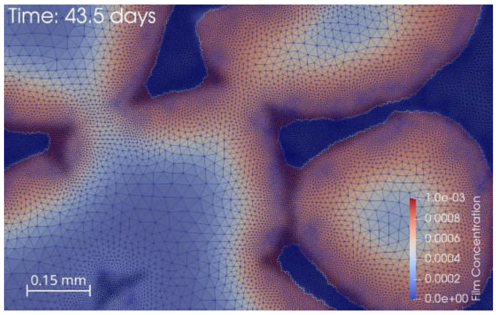

Fig. 2: Zoom from Fig. 1 showing the mesh refinement and the area of degradation. Black regions are the initial scaffold shape that are degraded and vanished over time

DISCUSSION & CONCLUSIONS: Initial results presented here are a demonstration of proof of concept of the metal biodegradation modeling framework. The real timing is yet to be calibrated using experimental data. Once validated, the model will be an important tool to find the right design and properties of the degradable implants ensuring proper mechanical functioning of the implant during the entire implant degradation process and controlling the release products.

REFERENCES: [1] B. Luthringer, et al (2014) *Magnesium-based implants: a mini-review*, Magnesium Research; 27:142-54. [2] F. Hecht (2012) *New development in FreeFem++*. Journal of Numerical Mathematics, 20:251–265

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