Mathematical modeling of biodegradation of metal implants in orthopedics

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Background

- At the end of their lifetime, metal implants need to be removed and replaced.
- During this removal surgery, additional bone is removed along with the implant.
- One approach to solve this problem is to make at least part of the implant from biodegradable metal [1].
- This requires tuning the degradation of the implant to the regeneration and growth of the new bone.

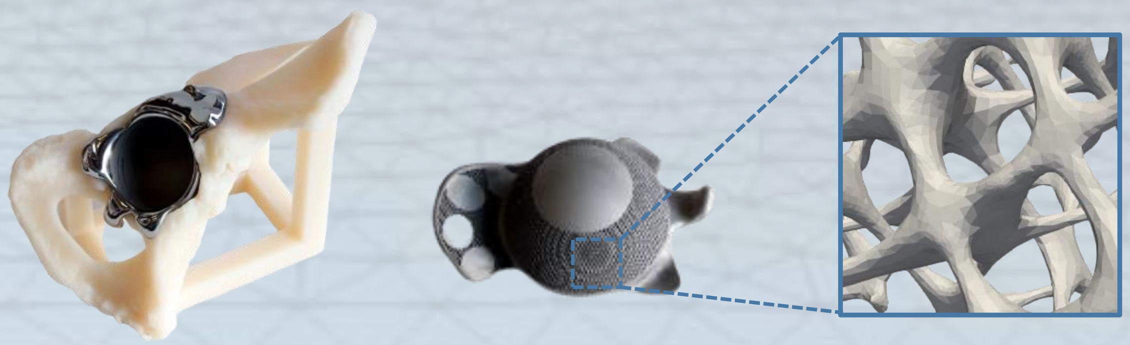

Fig. 1: The pelvis component of a hip joint implant and the part that could be made from a biodegradable metal

Methodology

- Biodegradation is modeled as a set of reaction-diffusion PDEs.
- The model captures:
  - The chemistry of dissolution of metallic implant (here Mg)
  - Formation of a protective film
  - Effect of ions in the medium (currently Chloride ions -Cl⁻-)
- Derived PDEs are solved using finite element schemes.

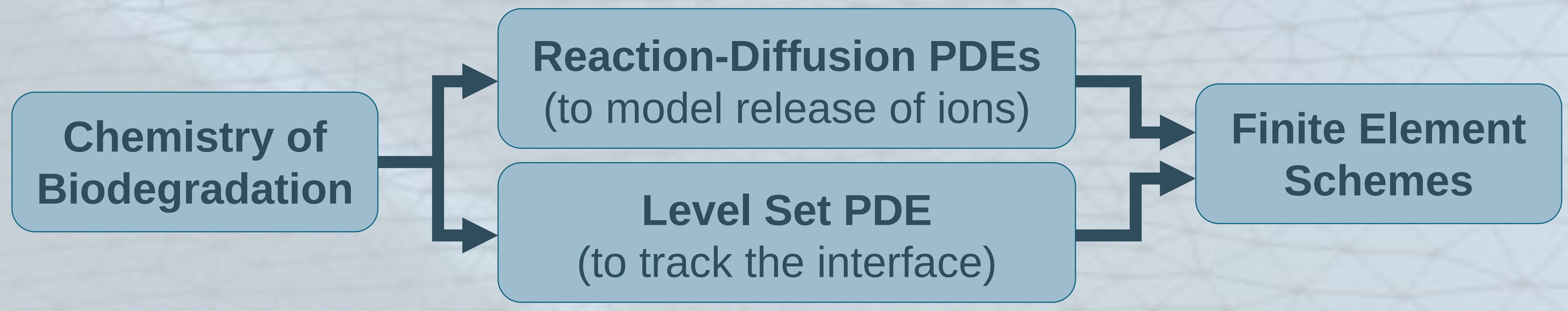

Fig. 2: The overall workflow of biodegradation model

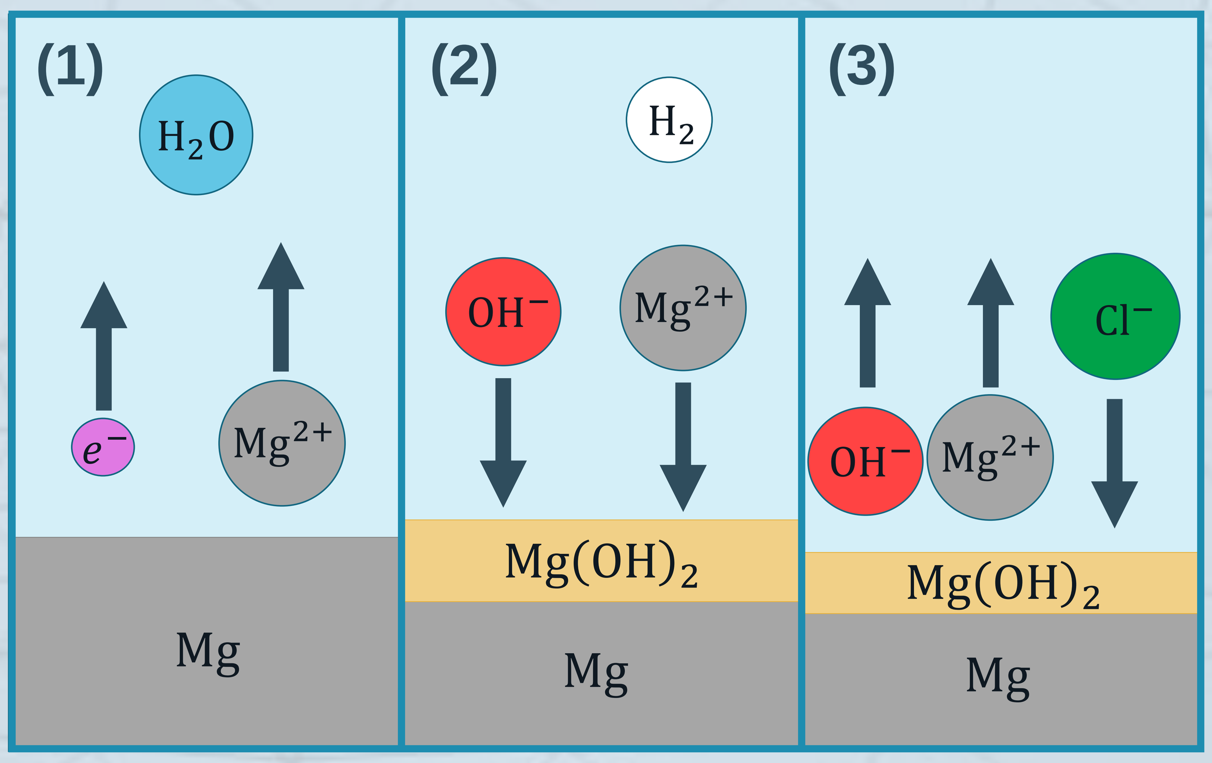

Fig. 3: The chemistry of biodegradation of Mg comprises the release of Mg^{2+} ions, formation of a protective film, and the dissolution of this film due to the effect of Cl^- ions

Results (Mg)

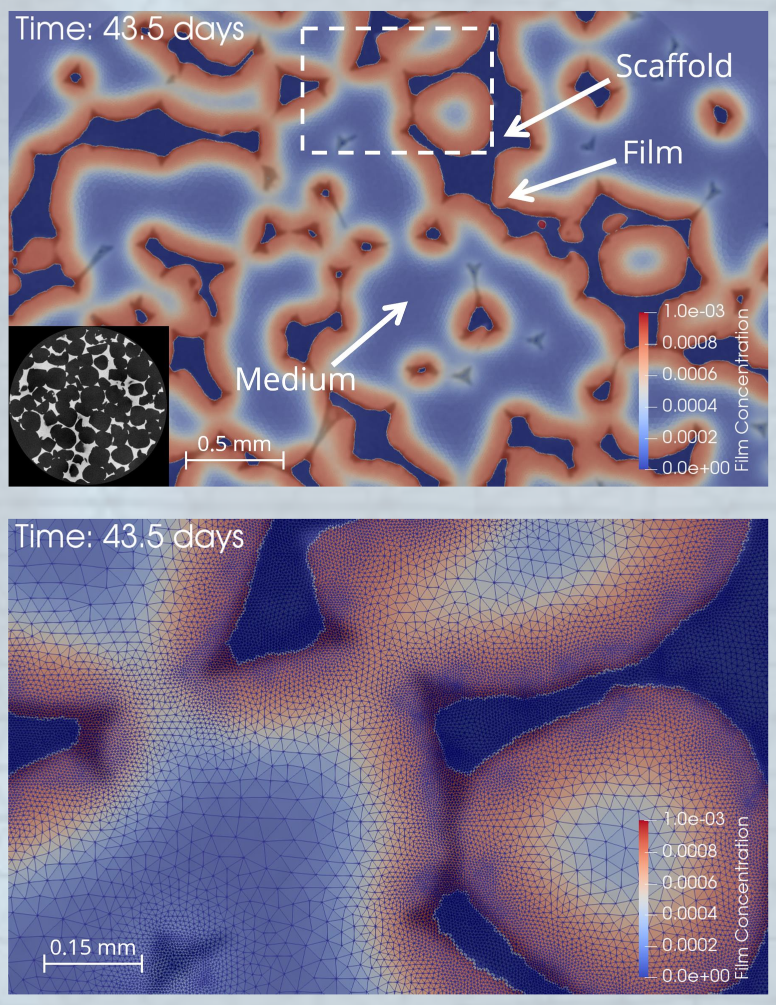

Fig. 4: **(Top)** the degradation of the investigated scaffold. **(Bottom)** the finite element mesh and the mesh adaptation technique. The dark blue regions are the shape of the scaffold after 43.5 days, and the surrounding red regions are the protective film that has been formed.

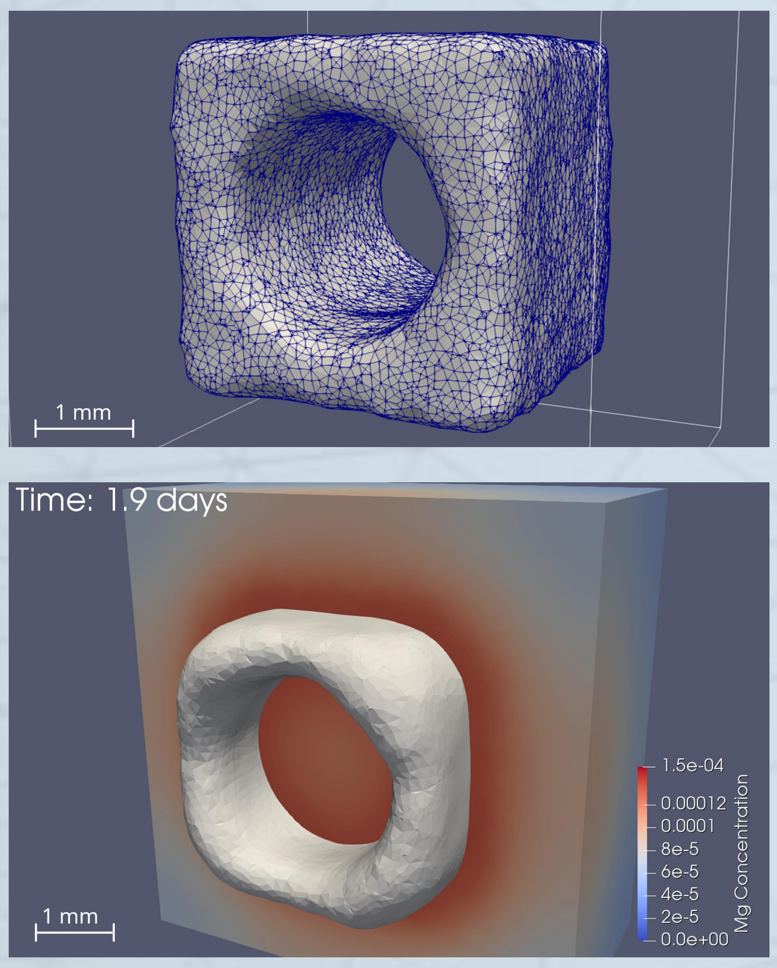

Fig. 5: **(Top)** numerical reproduction of the initial shape of a simple 3D scaffold geometry. **(Bottom)** Degraded shape of the scaffold as well as the concentration of Mg^{2+} released to the surrounding media (uncalibrated timing)

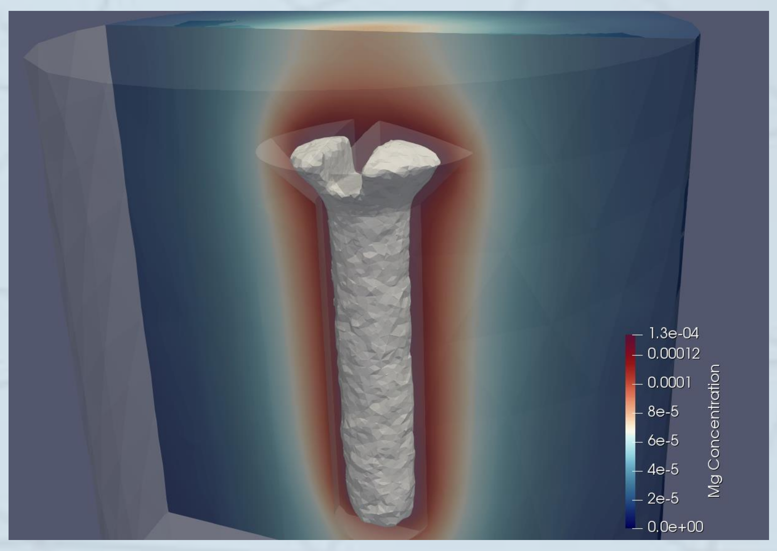

Fig. 6: Comparison of the degraded shape of a screw (white body) with its initial shape (transparent surface). The color contour shows the release of Mg^{2+} to the cylindrical medium.

Time Calibration & Validation

- Reference data and initial conditions are extracted from Mei et al [2].
- Parameter estimation (chemical coefficients) has been performed using a Bayesian optimization algorithm.

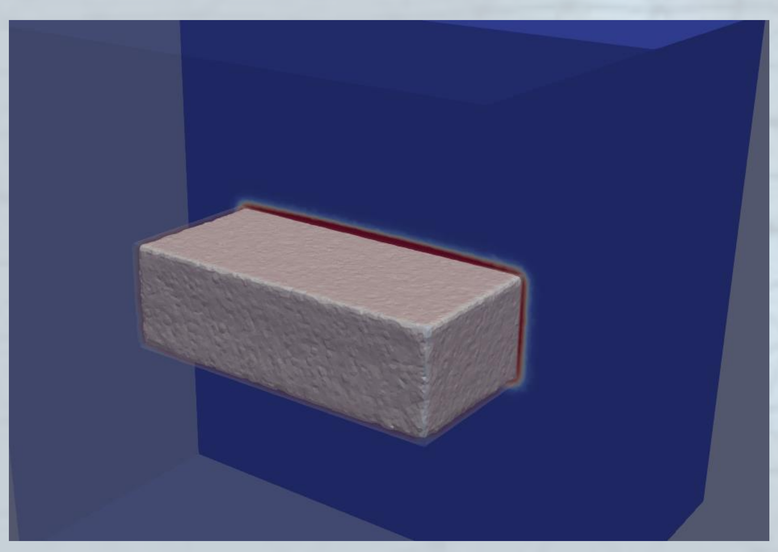

Fig. 7: Reference geometry for the parameter estimation as well as the formed protective film (red region)

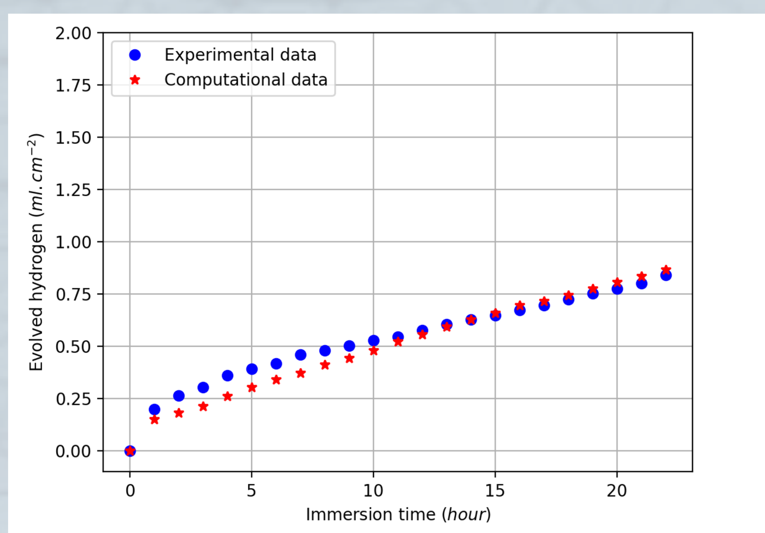

Fig. 8: Time calibration using the produced hydrogen as the criterion to compare the output with experimental data

References

1. B. Luthringer, et al. (2014) *Magnesium-based implants: a mini-review*, Magnesium Research; 27:142-54
2. D. Mei, et al. (2019) *The role of individual components of simulated body fluid on the corrosion behavior of commercially pure Mg*, Corrosion Science, 147: 81-93

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