8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

Modeling of porous functionally graded biodegradable implants for bone replacement

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Key Words: *biodegradable materials, porous media, multiphase problem, biomechanics.*

ABSTRACT

In the last years, so-called biodegradable materials which substitute the bone during the self-regeneration process have been developed. Temporarily, the biodegradable materials support the body during the regenerating time and degenerate simultaneously at the same rate as the bone is built up again. At the end of the healing process the bone should regenerate completely and the implant should be fully dissolved.

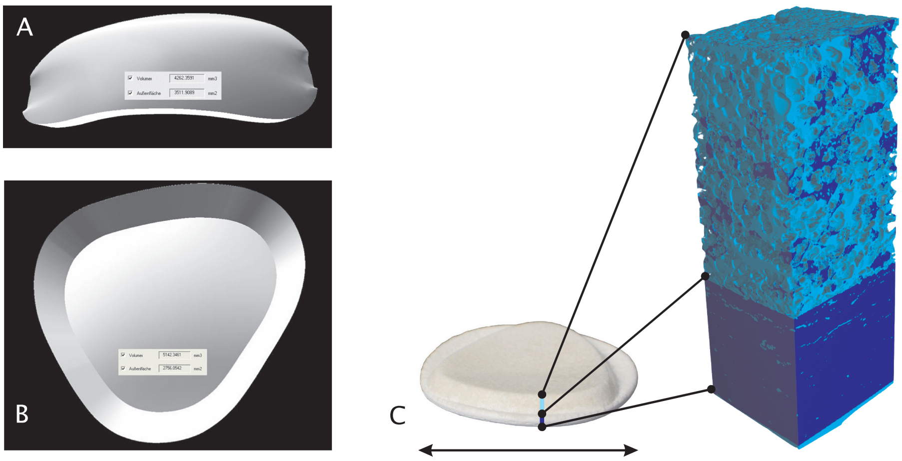

Figure 1: Biodegradable skull implant. (A) Schematic CAD-display of the individual skull implant (outer surface). (B) The skull implant viewed from the bottom. (C) Photograph and SRμCT picture of the graded structure of the implant. Figure taken from EUFINGER ET AL. [1].

The degeneration capacity and the porosity of the implant are outstanding characteristics of the material it is composed of. Bone tissue grows into the porous structure of the implant and can fill out the space which is left by the degrading implant.

Such materials have been developed and successfully tested *in vitro* and *in vivo*. A recent example of these materials represents the biodegradable skull implant given in Fig. 1. The implant shows a porous structure on its bottom (note that the skull implant is viewed from the bottom), i.e., on the side which is oriented to the inner volume of the cranium. Because of this, the newly growing bone tissue is able to combine or interlock with the implant and a higher level of stability is achieved. In order to ensure a stable interconnection between the implant and the tissue, the degeneration rate of the implant material must agree with the growth rate of the regenerating tissue. At the current time, the determination of the degeneration and growth rates is usually derived from in vitro experiments and must then be examined on the basis of complex animal experiments.

However, a complete understanding of both the mechanical properties and the degradation behavior is necessary for optimal application in the clinical practice. To archive this aim we developed a numerical calculation concept to simulate the mechanical behavior of the porous implant coupled with the complex biodegeneration behavior. This will be done using the macro-mechanical Theory of Porous Media (TPM), see e. g. DE BOER [2], providing a continuum-mechanical and volume-averaging description of the multi-phase implant. Constituents of the investigated implant which are accounted for in the model are the solid matrix φ^{S}, the pore fluid φ^{F} and a solution of nutrients φ^{N}. The nutrients are mainly responsible for the speed of the implant's biodegeneration and thus their consideration in the model is essentially necessary.

The macroscopic continuous mechanical description in the framework of TPM leads to a strongly coupled set of differential equations which allows for the determination of the four unknown quantities: motion of the solid matrix $\mathbf{u}_{\mathrm{S}}$, fluid pressure λ, volume fraction of solid matrix n^{S} and amount of nutrient solution n^{N}. Due to the fact that we consider a closed-system approach to the degradation process, the entropy inequality provides the restrictions for a thermodynamically consistent constitutive modeling. In order to describe the processes on the micro-scale of the implant, we use phenomenological material laws that are restricted by the results of an extensive evaluation of the inequality of the mixture entropy.

The theoretical formulations are implemented in the finite element program FEAP. With the presented calculation concept we are able to simulate the basic processes that occur in the biodegradable implant. After presenting the theoretical framework, some numerical examples will be given.

In future works the presented calculation concept will be combined with the already-existing calculation concept for bone growth, see e. g. RICKEN ET AL. [3]. With this we are able to describe both the bone growth and implant degradation allowing for a holistic view of the healing process. Finally, the simulation provides a powerful tool for the disposal optimization of the design and manufacture of biodegradable implants.

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