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EFFECTS OF GEOMETRICAL FACTORS ON THE RESORPTION OF CALCIUM PHOSPHATE BONE SUBSTITUTES

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INTRODUCTION: Calcium phosphate ceramics have proved their adequacy and efficiency as bone substitute materials. Despite their widespread use, there is a growing demand for faster resorbable calcium phosphate bone substitutes. The resorption rate of a bone substitute depends on many factors such as the patient (sex, age, metabolism, social habits, etc...), the implant location, the composition of the bone substitute and its geometry. For a surgeon or an engineer, it is difficult to control the first factors, but possible to control the composition and geometry of the bone substitute. Here, we propose to use a new approach to determine the effect of geometry on the resorption rate of bone substitutes.

THEORETICAL: The theoretical approach was based on four main assumptions: (i) the pores are spherical and ordered according to a face-centered cubic packing; (ii) the resorption is surface-controlled; (iii) the resorption is only possible if the surface can be accessed by blood vessels of 50 µm in diameter (= 2 r_i); and (iv) the resorption time of a given amount of calcium phosphate is proportional to the net amount of material. Two separate cases were considered: granules and blocks. Based on these assumptions, the calculations showed that the determination of the optimum pore size depends on two main factors: the time required for bone ingrowth and the time required to resorb the ceramic assuming that all surfaces are resorbed simultaneously. The rate of bone ingrowth, t_I, depends on the smallest one-dimensional distance of the implanted material, W, the minimum interconnection radius required to allow bone ingrowth, r_i (= 25 µm), the radius of the pores, r_p, the distance between the pores, d_p, and the linear resorption rate, R_r (Eq 1). The time required to resorb the ceramic, t_R, depends on the radius of the pores, the distance between pores, and the linear resorption rate (Eq 2).

$$t_I = \frac{\sqrt{r_i^2 + \left(2r_p + d_p - \sqrt{r_p^2 - r_i^2}\right)^2} - r_p}{R_r\left(4r_p + 2d_p\right)} \cdot W;$$

$$t_R = \frac{r_p\left(\frac{\sqrt{3}}{\sqrt{2}} - 1\right) + d_p\left(\frac{\sqrt{3}}{2\sqrt{2}}\right)}{R_r}$$

Therefore, the maximum time required to resorb a ceramic is given by the addition of the ingrowth time, t_I, and the resorption time, t_R. The plot of this total time versus the pore radius indicates that there is a minimum of resorption time in the range of 150 to 300 µm. The position of this miminum depends on the block size (Fig 1). In the range of 150 to 300 µm, there is an optimal combination of bone ingrowth, ceramic resorption and porosity. The model can also be used to assess the time required to resorb granules. The volume of the granules, $V_{g,t}$, is a function of the initial volume, $V_{g,0}$, the linear resorption rate, R_r, the time, t, and the initial granule radius, $r_{g,o}$.

$$V_{g,t} = V_{g,0}\left(1 - \frac{R_r}{r_{g,0}} t\right)^3$$

This equation indicates that the granules are resorbed faster when they are smaller. Taking into account that bone ingrowth between the granules should be possible, the granules should have a relatively small diameter, typically around 100-200 µm. It might be adequate also to have an irregular shape that can on one side increase the specific surface area and on the other side increase the size of the gaps between particles The comparison of the predictions of the model with experimental data shows a very good agreement, i.e. more than 80% of the results were explained with the model. In conclusion, the model is a useful tool to define adequate geometries for bone ingrowth and resorption of the bone substitute.

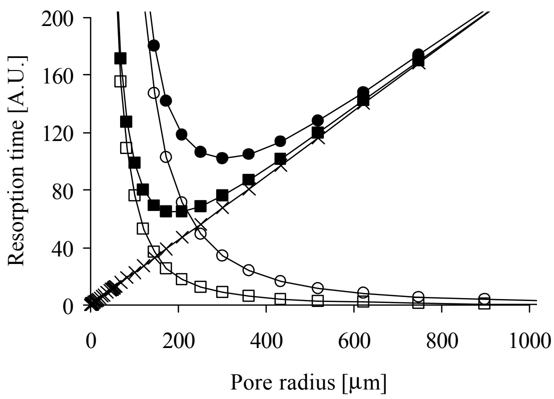

Figure 1: Time to (x) fully resorb one unit cell of the block (= t_R) or to (o, ?) open all the pores of the block to enable bone ingrowth (= t_I). Conditions: d_p = 0; Block thickness: (?) 5 mm; (o) 20 mm. The combined curves (addition of the two curves) are represented by black symbols. Block thickness: (?) 5 mm; (?) 20 mm.