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The Role of the Bone Strength on the Cyst Growth in the Mandible

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Intracystic fluid pressure is discussed as a potentially important factor influencing a bone cyst growth. This process can develop in the course of months. However, the exact mechanism remains speculative. In this paper, we use an established mathematical model to evaluate whether the presence of pressurized fluid in bone cavities may result in cyst growth. A continuous function of bone density rate vs. mechanical stimulus is used. The numerical model of the mandible with the cyst is used to predict the stress-stimulated change in bone density around the cavity.

Key words: cyst; intracystic pressure; bone remodelling; mandible; mechanical stimulus.

1. Introduction

The definition of jaw cyst states that it is 'a pathological cavity having fluid, semi-fluid or gaseous contents and which is not created by the accumulation of pus'. Bone cysts are usually discovered and surgically treated in a late stage, after they have become problematic or caused pain. Regarding the etiology of bone cysts, various theories have been proposed in order to describe the cyst growth mechanism. One of them states that pressurised fluid enters the bone through a rupture and fractures trabeculae, thereby leading to the disappearance of bone tissue (osteolysis). Although there is not much evidence indicating that fluid collected inside the cyst fractures trabeculae, actually the loading conditions of the surrounding bone may cause decreasing of bone density and therefore bone loss. This may be described by a mechanoregulated bone adaptation process [10]. According to another theory, pressurised fluid may decrease perfusion and oxygen supply in tissue, thereby leading to osteocytes death and further osteolysis. The basic assumption for both hypotheses is that pressurised fluid plays a crucial role in the development of bone cysts [8]. Intracystic pressure may change during the cyst growth, as it is regulated by various factors such as osmotic tension of the fluid, the elasticity of the cyst wall, and the permeability and the blood pressure of the capillaries in the cystic wall [3, 9]. Over the years, the cyst may regress, remain static or grow in size. The medical observations show that during the cyst growth the surrounding bone tissue is destroyed and replaced by the fluid. This process begins in the trabecular tissue as this tissue is easily penetrable by the fluid due to its 'spongy' structure. During the further expansion, cyst grows to a limited extent in bucco-lingual direction, and the cortical bone thickens and may become fragile. Because of this limitation, the cyst cavity expands in the anterior-posterior direction. Thus, the cavity looks elliptical as a result of growth limitations by the thick cortical bone layer [11]. In this study, we apply a computational model of bone remodelling to evaluate load conditions during the cyst growth.

2. Model and method

The computational approach is linked to the remodelling model [5, 6] that describes the change in the bone density in relation to the remodelling stimulus based on the strain energy density as well as mass density of a tissue:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \begin{cases} B(\psi - K_{\min}), & \psi < K_{\min}, \\ 0, & K_{\min} \le \psi \le K_{\max}, \\ D(\psi - K_{\mathrm{over}})^2 + K_w, & \psi > K_{\max}. \end{cases} \tag{2.1}$$

In this study, parameter ψ is chosen as the remodeling stimulus, which denotes strain energy density U related to bone mass density ρ. It is a local value determined at a material point, very convenient to use because of its scalar character. The following values are used in this work for the model parameters:

- $B = 1\ (\mathrm{g/cm^3})^2/(\mathrm{MPa} \cdot \text{time unit})$,
- $D = \dfrac{K_w}{(K_{\mathrm{over}} - K_{\max})(K_{\mathrm{over}} - K_d)} = -31.8\ (\mathrm{g/cm^3})^3(\mathrm{MPa} \cdot \text{time unit})^{-1}$,
- $K_{\min} = 0.0036$ J/g,
- $K_{\max} = 0.0044$ J/g,
- $K_{\mathrm{over}} = 0.0358$ J/g,
- $K_d = 0.0672$ J/g stands for the end of interval with positive remodeling rate ($\psi \in (K_{\max}, K_d)$),
- $K_w = 0.0314\ \mathrm{g}/(\mathrm{cm^3} \cdot \text{time unit})$.

We mainly focus on the situation when the stimulus exceeds the threshold value K_d, indicating bone loss due to overload. We use the finite element (FE) model (Fig. 1) to predict cyst growth. Bone and cyst architecture changes in

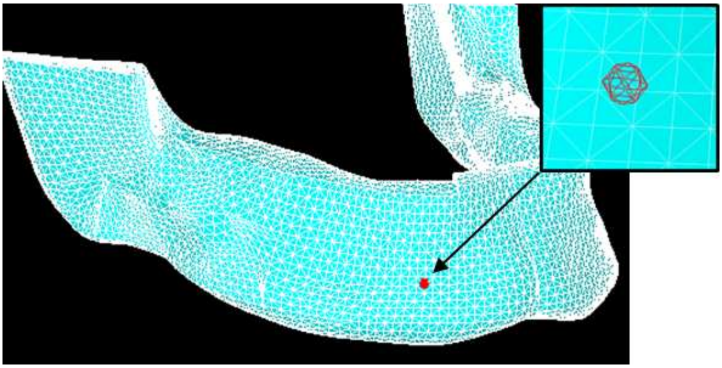

FIG. 1. Finite element model of the mandible with the cyst.

response to pressure load induced by the presence of the intracystic fluid. Therefore, the numerical model of the mandible with the small cavity is created and solved in a repeated static analysis in which the surface of the cyst is loaded with normal pressure [1]. Only the part of the mandible is modelled with two outer layers of cortical bone and the inner trabecular. The cyst is located in the inner part, modelled as a sphere loaded with normal pressure. The model consists of two materials with different properties, namely inner trabecular ($E = 80$ MPa, $\upsilon = 0.19$) and outer cortical bone ($E = 18000$ MPa, $\upsilon = 0.30$), both assumed as linear, isotropic and homogenous [2]. It is noted that there are various relationships between the mass density and bone Young's modulus E available in the literature. In this paper, the following equation is adopted [4]:

$$E = c\rho^3, \tag{2.2}$$

where c is a constant and is equal to 3790 $\text{MPa} \cdot \text{cm}^9/\text{g}^3$. At each element of the FE model around the cyst cavity, the value of the stimulus ψ is calculated as the strain energy density divided by the bone mass density.

Two cases are investigated. In the first one, if the stimulus exceeds the threshold value, the element is removed from the mesh, which models the disappearance of the tissue due to overload. After this mesh change, the boundary load conditions are updated to spread the pressure action over newly created areas. This resorption initiating value depends strongly on the bone elasticity modulus. The stronger a bone is, the higher pressure is necessary to start the process of cyst growth, strictly connected with the bone overload resorption to satisfy the condition $\psi \geq K_d$. The estimation of the pressure needed is not straightforward, since reported cancellous bone density and thus Young's modulus values cover a wide range according to the literature. However, in this study, the exact applied load values are not so important, since the results are evaluated qualitatively and not quantitatively. The initial pressure value is set to cause the overload resorption situation.

In the second case, the iterative process is performed using an algorithm that changes bone material properties over time according to Eq. (2.1). Using equation

$$\rho(t+\Delta t) = \rho(t) + \left.\frac{\mathrm{d}\rho}{\mathrm{d}t}\right|_t \cdot \Delta t, \tag{2.3}$$

the bone density at each time step is calculated. Then, the corresponding elasticity modulus is updated according to Eq. (2.2). The next step of the calculation is performed using modified material properties. Therefore, no element around the cyst is removed and only the change in bone elasticity modulus is analysed in the region of interest.

3. Results

In the first case, bone resorption in response to the pressure inside the cyst leads to the growth of the cavity, which takes an irregular shape (Fig. 2). The cyst growth and its shape depend on the Young's modulus of the surrounding bone, as its value determines whether the condition $\psi \geq K_d$ is satisfied or not. That observation indicates the unstable process of the cyst growth, which continues in spite of decreasing pressure value. After the initial stage, decreasing pressure maintains further expansion of the cyst in the mandible (Figs 2 and 3). This is due to the mechanical behaviour of the model in which the applied pressure

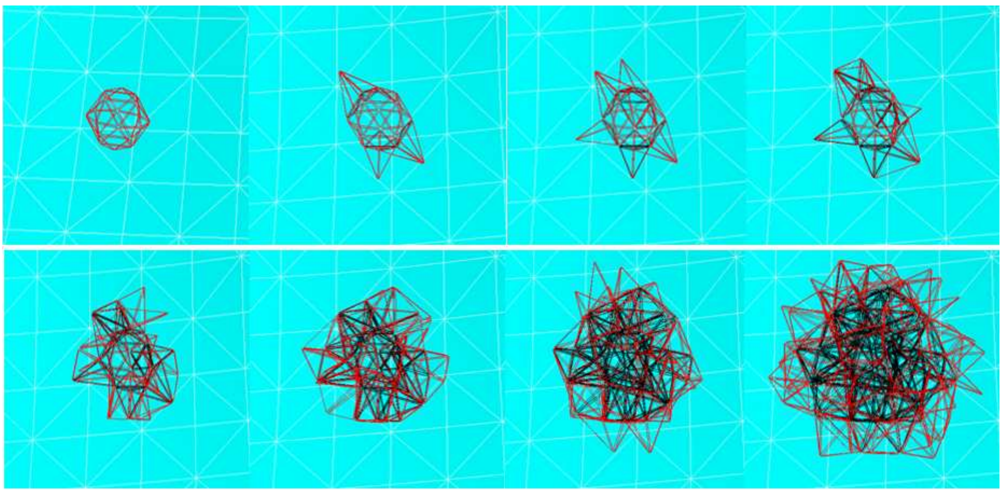

Fig. 2. Subsequent stages of the cyst growth in the first case.

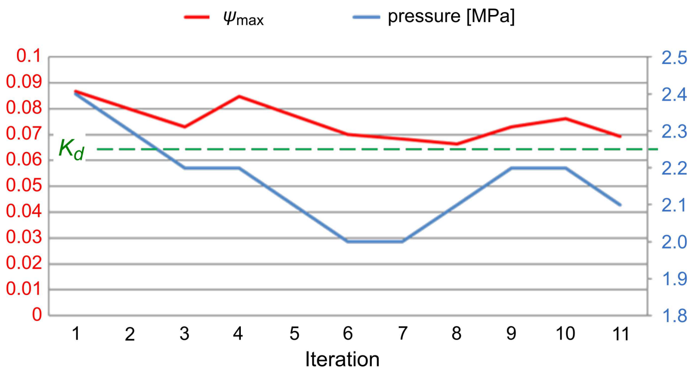

FIG. 3. Mechanical stimulus ψ and the corresponding pressure value during subsequent stages of the cyst growth in the first case.

is directly connected with the overload resorption effect to satisfy the condition $\psi \geq K_d$. The comparison of simulation results with clinical observation is presented in Fig. 4, where the shape of the cyst in the mandible obtained from the medical data is compared with the numerical model. As observed in the model, the growth of the cyst stops at the edge between the cortical and trabecular bone. When the cyst reaches the cortical bone, its growth is halted in the bucco-lingual direction and then it expands in the anterior-posterior direction (Fig. 4b). These results are consistent with the clinical observation in which the cyst diagnosed at the beginning of the growth is round and spherical [1], but at the further stages it is elliptical and elongated in the anterior-posterior direction (Fig. 4a).

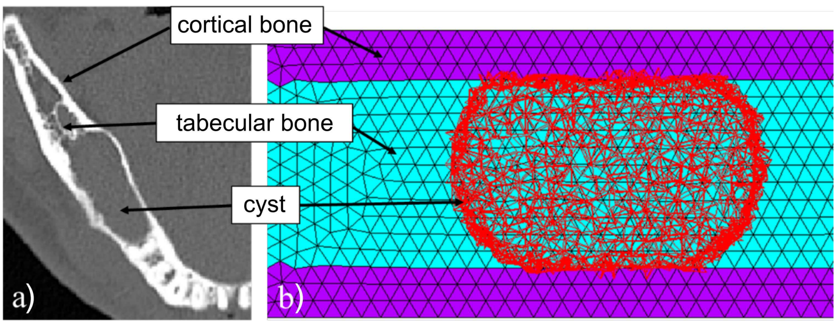

FIG. 4. The shape of the cyst: a) in the clinical view of the mandible and b) in the numerical model.

In the second case, the change in the bone elasticity modulus is analysed. In this study, we mainly focus on the value of the elasticity modulus in the region around the cyst, so only the finite elements around the cyst are taken into consideration for calculations. This is due to the fact that the decrease of the bone Young's modulus creates an environment that enables cyst growth. As presented in Fig. 5, under the constant value of the intracystic pressure, the value of the elasticity modulus decreases – coloured elements around the cyst. It is worth to mention that this phenomenon is not uniform around the cyst. One may observe that in some regions, the Young's modulus value does not decrease but even grows. That numerical effect comes probably from the asymmetry of the mesh or the fact that the stimulus value makes bone stronger ($K_{\max} \leq \psi \leq K_d$). This phenomenon affects only a few elements; thus, it is neglected. For the vast majority of the elements, the density decreases below the initial value, and the mean density around the cyst decreases from the initial 80 MPa to 62.5 MPa.

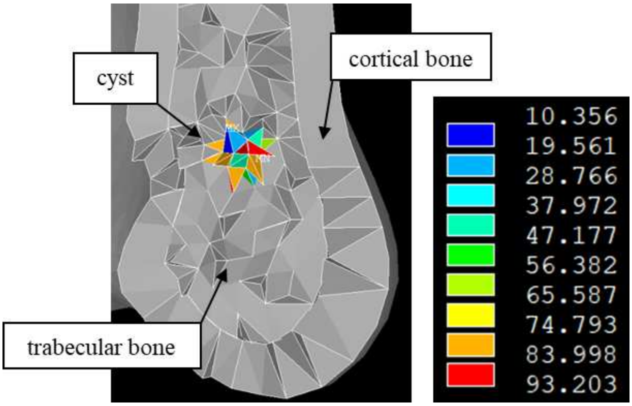

Fig. 5. The Young's modulus [MPa] distribution in the region of interest around the cyst in the second case.

4. Conclusion

As observed in the first case, after the initial stage, decreasing pressure maintains further expansion of the cyst in the mandible that may indicate an unstable, self-propelled process. This might be linked with the clinical observation in which the medical surgeons state that the regulatory mechanisms of intracystic pressure and the growth of cyst under lower pressure are unclear and remain speculative [3]. In the second case, remodelling in response to the presence of the pressurized fluid may result in the growth of the cavity. The further decrease of the bone Young's modulus around cyst may lead to the disappearance of the tissue, thus enabling the cavity growth. When comparing these two cases, the first approach focuses on simulating the shape change of the cyst and the results are consistent with the clinical observation, while the second case describes the bone properties around the cyst. In both cases, the presence of the pressurized fluid leads to change in the properties of the cyst neighbourhood either by decreasing the bone elasticity modulus or tissue disappearance. As a further work, it would be advisable to combine both approaches.

There are several limitations associated with this study, including the idealization of cyst spherical geometry. Also, the heterogeneity of the trabecular bone should be considered in this type of study. It was shown that the initial value of the Young's modulus is responsible for the mechanical stimulus value, and hence, the presence of the overload resorption. The smaller is the value of the elasticity modulus, the higher is the stimulus value. This may result in the appearance of the favourable zones of tissue resorption. Also, as reported by the literature, mandible cyst grows to a limited extent in the bone towards buccal and lingual sides, and looks elliptical as a result of growth limitations by the thick cortical bone layer [11]. As reported, intracystic pressure may cause the initial growth of the cyst, and the bone resorption may occur under continuous and intermittent compressive pressure [7]. Even with mentioned limitations, we believe this is still a valuable analysis and can be considered as a basis for further work.

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