SELECTION OF MATERIALS BASED ON HYDROXYLAPATITE USING THE METHOD OF ANALYSIS OF HIERARCHY

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Biomaterials are artificial or natural materials that replace diseased or damaged bone tissue, recently with increasing interest in interdisciplinary approaches, including e.g. bioengineers. Such materials must be mechanically strong and not cause undesirable reactions. Due to the many factors that need to be considered, choosing the right material becomes a challenge. The relevance of the study lies in the development of a method for choosing a synthetic material based on hydroxyapatite for bone tissue restoration. Hierarchy analysis method was used and a set of five materials and their seven mechanical and biological parameters were analyzed.

KEYWORDS

Bone substitute, biocompatibility, mechanical properties, selection methodology, criterion

1 INTRODUCTION

Bone engineering deals with the development of methods to repair damaged bone tissue using a combination of cells, growth factors and biomaterials [Alonzo 2021, Panda 2011a, Valicek 2016]. Not all biological materials are used for every recovery procedure [de Grado 2018, Jurko 2011, Panda 2013]. The ideal substitute is biocompatible and does not provoke unwanted inflammation. It should easily grow into a bone defect and be osteoconductive, osteoinductive, and resorbable [Campana 2014, Jurko 2012, Panda 2011b, Balara 2018, Duplakova 2018, Flegner 2019 and 2020, Monkova 2013, Murcinkova 2019 and 2021, Baron 2016, Mrkvica 2012, Zaborowski 2007, Chaus 2018, Vagaska 2017 and 2021, Straka 2018a,b].

Bone replacement materials vary in chemical composition, mechanical strength, and other characteristics. Each of them has its own advantages and disadvantages, and unfortunately, they have not yet reached optimal mechanical and biological characteristics. Artificial bone tissue substitutes based on hydroxyapatite and β-tricalcium phosphate are now considered as an adequate alternative to auto- and allografts [Sukhodub 2018, Dyadyura 2017, Panda 2013]. When using bone substitutes, a compromise must be made between mechanical and biological characteristics [Sukhodub 2018, Hrebenyk 2017 Jurko 2013].

The purpose of the work is to develop a methodology for choosing the best material for bone tissue regeneration, taking into account their mechanical and biological parameters.

In this study, there is a set of five of the materials used for bone tissue regeneration. For example, materials for spinal fusion are selected [Litak 2022, Bozkurt 2018, Thaler 2013, Barrey 2019]. The choice of the best of them is made using the hierarchy analysis method. Table 1 shows the mechanical and biological properties of the articles.

2 MATERIALS AND METHODS

The Hierarchy Analysis Method (HAI) is a basic decision-making or complex problem-solving approach that incorporates many of the criteria developed by Saaty. It is necessary to determine the relative importance of a set of task criteria for making a decision on several attributes. MAI offers a solution that is the best way to study the problem [Vaidya 2006]. The complete procedure of the AHP method is as follows: [Ginevicius 2021, Ginevicius 2022, Krenicky 2022].

1. formation of a hierarchy of goals;
2. setting priorities;
3. calculation of local priority vectors;
4. verification of expert assessments for consistency (calculation of the consistency index);
5. calculation of priorities for goals and measures for the hierarchy as a whole based on the synthesis of local priorities.

The principle of comparative judgments. To set criteria priorities and obtain estimates for alternative solutions, the MAI uses the method of paired comparisons - the matrices of paired comparisons $A=||\alpha_{ij}||$ are constructed, where $\alpha_{ij} = \omega_i/\omega_j$, ω_i is the "weight" of the i-th element of the hierarchy, $\alpha_{ii} = 1$, $\alpha_{ij} = 1/\alpha_{ji}$ (that is, the diagonal elements of the matrix are equal to 1, the matrix is inverted symmetric). For each matrix, a vector of local priorities is determined and an index of expert opinions consistency is calculated.

The principle of synthesis of values. We will assume that:

1) matrices of paired comparisons are built: one for the second level of the hierarchy (for criteria), and at each next level - as many matrices of paired comparisons as there are elements in the preliminary level of the hierarchy (each matrix contains the results of comparison according to one of the criteria);

2) the vectors of local priorities for each matrix are calculated. Priorities are synthesized starting from the second level of the hierarchy from top to bottom. The local priorities of the alternatives are multiplied by the priorities of the corresponding criteria of the previous level and summed for each element according to the criteria. Thus, the final assessment of the alternative in the method of paired comparisons is the weight of the alternative, calculated as a convolution of the weight coefficients of the criteria (local criteria) of all levels of the hierarchy.

Stage 1. Formation of a hierarchy of goals. A decomposition of the decision-making problem is developed with the allocation of main goals, sub-goals and various objective functions (alternatives). Elements of the same levels should be comparable to each other in terms of prioritization. The criteria for all levels of the hierarchy in the hierarchy analysis method should have a common direction (either positive or negative), that is, benefits (income, profit) or costs are evaluated. In using the Saaty method to address this problem, the first step is to clearly identify the potential benefits to be considered. Let us assume that the following hierarchies of benefits are obtained as a result (Fig. 1).

Stage 2. Definition of values. To set the priorities of the criteria, to obtain estimates for alternative solutions, the matrices of paired comparisons A||a_{ij}|| are built. The element aij of the pairwise comparison matrix is the result of measuring the degree of preference of the alternative A_i over the alternative A_j on the fundamental scale. It should be remembered that elements belonging to the same hierarchy level are compared with each other. When constructing matrices of paired comparisons, the fundamental scale of advantages (the scale of relative weight) is used (Table 2).

Table 1. Properties of materials for bone tissue replacement

Material	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Fracture resistance (MPa $^{M1/2}$)	Bending strength (MPa)	Porosity (%)	Solubility (g/l^{-1})	Sources
HA	100-150	40	100	0,8-1,2	60-120	70-85	0.0003	[Osuchukwu 2021, Kaur 2019, Uddin 2019, Dorozhkin 2019]
Brushite	57.2-69.5	8-25	7,9	1,29	2-4,5	37-60	0.088	[Luo 2016, Morgan 1997, Dorozhkin 2019, Maenz 2014]
TCP [1_2]	6.55-5.62	2-50	0,5-21	0,05-0,3	1-16,5	41-77	0,0005-0,0025	[Stares 2013, Gbureck 2004, Dorozhkin 2019, Metsger 1999]
45s5	500	42	35	0,6	40	89-92	High	Mohammadi 2015, Chen 2006a,b, Kaur 2019, Rebelo 2017]
A/W	1080	215	118	2	215	65-80	> than HA	[Kaur 2019, Bozkurt 2018, Uddin 2019, Seidel 2004]

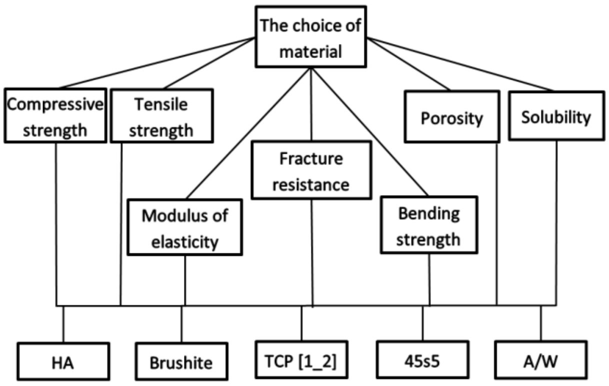

Figure 1. Hierarchical tree for selection

Table 2. Relative importance of factors

Description	Relative importance (a_{ij})
Equal value	1
Moderate value	3
Strong	5
Very big	7
Absolute importance	9
Intermediate values	2,4,6,8

The number of experts' answers to the construction of a matrix of paired comparisons for n compared elements is n*(n-1)/2 or $n^2/2$ - n/2. When filling in the matrix of even comparisons, it is sufficient to determine the elements located above the main diagonal of the matrix. The elements under the diagonal, according to the inverse symmetry property of the matrix, are calculated by the formula $a_{ij} = 1/a_{ij}$.

Initially, a matrix of paired comparisons is built for the criteria that are in the hierarchy (Table 3). For example, the value at the intersection of row 1 and column 2, equal to 3, indicates the priority of the criterion of compressive strength over ultimate strength. Accordingly, the tensile strength is of little significance compared to the compressive strength, so the value at the intersection of the 1st column and the second row is 1/3.

Further, for each criterion, a matrix of paired comparisons of all alternatives is constructed. For example, if a three-level hierarchy is built for 6 criteria and 4 alternatives, then a total of 7 paired comparison matrices will be built (1 matrix of 66 dimensions for comparing criteria and 6 matrices of 44 dimensions for comparing alternatives for each of the criteria). Thus, the total number of paired comparison matrices is equal to the number of criteria plus 1 (for the case of the simplest three-level hierarchy).

3 RESULTS

Stage 3. Calculation of local vectors of priorities. For each matrix, we can calculate the local priorities of the compared elements. To each row of the matrix, and, consequently, to the corresponding element, we put in correspondence the geometric mean of its elements. Summing up the results obtained, we divide the geometric means of each of the rows of the matrix by this sum. As a result, we obtain the local priorities of the corresponding compared elements. As an example, the vector of local priority according to the criterion "Compressive strength" is obtained by dividing 0.514 by 12.156.

At this stage, we conclude that the most significant criterion when choosing a material is solubility, and the least significant is the modulus of elasticity.

Table 3. Evaluation of the importance of criteria

Criterion	Compressive strength	Tensile strength	Modulus of elasticity	Fracture resistance	Bending strength	Porosity	Solubility	Product	7√ from the product	Local vector of priorities
Compressive strength	1	3	3	1/3	1/5	1/7	1/9	0.0001	0.514	0.043
Tensile strength	1/3	1	3	3	1/3	1/7	1/9	0.016	0.553	0.046
Modulus of elasticity	1/3	1/3	1	1/3	1/3	1/7	1/9	0.0002	0.295	0.024
Fracture resistance	3	1/3	3	1	1/3	1/7	1/9	0.016	0.553	0.046
Bending strength	5	3	3	3	1	1/7	1/9	2.143	1.115	0.092
Porosity	7	7	7	7	7	1	1/3	5602.333	3.431	0.284
Solubility	9	9	9	9	9	3	1	177147.000	5.620	**0.465**
Sum	**31.000**	**21.000**	**26.333**	**23.667**	**18.200**	**1.889**		**182751.637**	**12.156**	**1.000**

Stage 4. Checking the boundedness of the priority assessment. At this stage, the so-called consistency index (CI) of judgments for each matrix is calculated

$$CI = (\lambda_{max} – n) / (n-1) \quad (1)$$

where n is the dimension of the matrix, and λ_{max} is calculated as follows:

- each column of the matrix of paired comparisons is summarized;
- the sum of the first column is multiplied by the first component of the local priority vector (located in the first row of column 11), the sum of the second column by the second component, etc.;
- received works are summed up.

Then it is necessary to compare the IE with the value that would be obtained with a random choice of judgments on the fundamental scale (1/9...9) for a given value. The values of this quantity are called random consistency (RC), known and presented in Table. 4. There is always a matrix of dimension 2 that is consistent. The value of the RC depends only on the dimension of the matrix of paired comparisons.

Table 4. Random Consistency

Dimension of the matrix	1	2	3	4	5	6	7	8	9	10
Random Consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Having determined the CI and RC, we find the consistency estimate (for matrices of dimension greater than 2):

$$CE = CI / RC \quad (2)$$

If for a particular matrix it is found that CE > 0.1, it can be argued that the expert's judgment, on the basis of which the matrix under study is filled, is strongly inconsistent, and the matrix should be filled in again, more carefully using the scale of paired comparisons. Otherwise, expert judgments are accepted.

We calculate the consistency ratio by the matrix of pairwise comparisons of criteria:

λ_{max} = (25.667*0.043) + (23.667*0.046) + (29.000*0.024) + (23.667*0.046) + (18.200*0.092) + (4.714*0.284) + (1.889*0.465) = 7.866;

CI = (λ_{max} – n) / (n-1) = ((7.866-7) / (7-1)) = 0.144;

For n=7 from table. 4 we get RC = 1.32. Then CE = CI / RC = 0.144 / 1.32 = 0.109 ≤ 0.1. The resulting value of the CE does not exceed 0.1, which means that the expert's assessments are consistent.

At this stage, local vectors are sequentially calculated and the consistency of the results of each element of the hierarchy is checked. The identification of priorities by the factor "Strength modulus" is presented in Table 5.

Table 5. Compressive strength

	HA	Brushite	TCP [1_2]	45s5	a/w	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	3	5	1/3	1/5	1.000	1.000	0.130
Brushite	1/3	1	3	1/5	1/7	0.029	0.491	0.064
TCP [1_2]	1/5	1/3	1	1/7	1/9	0.001	0.254	0.033
45s5	3	5	7	1	1/3	35.000	2.036	0.264
A/W	5	7	9	3	1	945.000	3.936	**0.510**
Sum	**9.533**	**16.333**	**25.000**	**4.676**	**1.787**	**981.030**	**7.718**	**1.000**

Estimation of expert opinions consistency: λ_{max} = (9.533*0.130) + (16.333*0.064) + (25.000*0.033) + (4.676*0.264) + (1.787*0.510) = 5.243; CI = (5.243 – 5) / (5 – 1) = 0.061; CE = 0.061 / 1.12 = 0.054 ≤ 0.1. According to the criterion "Compressive strength" the most priority is the material apatite-wollastonite.

Estimation of expert opinions consistency: λ_{max} = (16.333*0.064) + (25.000*0.033) + (4.676*0.264) + (9.533*0.130) + (1.787*0.510) = 5.243; CI = (5.243 – 5) / (5 – 1) = 0.061; CE = 0.061 / 1.12 = 0.054 ≤ 0.1. According to the criterion "Tensile strength" the most priority is the material A/W.

Table 6. Tensile strength

	HA	Brushite	TCP [1_2]	45s5	a/w	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	3	1/5	1/3	1/7	0.029	0.491	0.064
Brushite	1/3	1	1/7	1/5	1/9	0.001	0.254	0.033
TCP [1_2]	5	7	1	3	1/3	35.000	2.036	0.264
45s5	3	5	1/3	1	1/5	1.000	1.000	0.130
A/W	7	9	3	5	1	945.000	3.936	**0.510**
Sum	**16.333**	**25.000**	**4.676**	**9.533**	**1.787**	**981.030**	**7.718**	**1.000**

Table 7. Modulus of elasticity

	HA	Brushite	TCP [1_2]	45s5	a/w	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	7	5	3	1/3	35.000	2.036	0.264
Brushite	1/7	1	1/3	1/5	1/9	0.001	0.254	0.033
TCP [1_2]	1/5	3	1	1/3	1/7	0.029	0.491	0.064
45s5	1/3	5	3	1	1/5	1.000	1.000	0.130
A/W	3	9	7	5	1	945.000	3.936	**0.510**
Sum	**4.676**	**25.000**	**16.333**	**9.533**	**1.787**	**981.030**	**7.718**	**1.000**

Estimation of expert opinions consistency: λ_{max} = (4.676*0.264) + (25.000*0.033) + (16.333*0.064) + (9.533*0.130) + (1.787*0.510) = 5.243; CI = (5.243 – 5) / (5 – 1) = 0.061; CE = 0.061 / 1.12 = 0.054 ≤ 0.1. According to the criterion "Modulus of elasticity" the most priority is the material apatite-wollastonite.

Table 8. Fracture resistance

	HA	Brushite	TCP [1_2]	45s5	a/w	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	1/3	5	3	1/5	1.000	1.000	0.130
Brushite	3	1	7	5	1/3	35.000	2.036	0.264
TCP [1_2]	1/5	1/7	1	1/3	1/9	0.001	0.254	0.033
45s5	1/3	1/5	3	1	1/7	0.029	0.491	0.064
A/W	5	3	9	7	1	945.000	3.936	**0.510**
Sum	**9.533**	**4.676**	**25.000**	**16.333**	**1.787**	**981.030**	**7.718**	**1.000**

Estimation of expert opinions consistency: λ_{max} = (9.533*0.130) + (4.676*0.264) + (25.000*0.033) + (16.333*0.064) + (1.787*0.510) = 5.243; CI = (5.243 – 5) / (5 – 1) = 0.061; CE = 0.061 / 1.12 = 0.054 ≤ 0.1. According to the criterion "Fracture resistance" the most priority is the material A/W.

Table 9. Bending strength

	HA	Brushite	TCP [1_2]	45s5	a/w	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	7	5	3	1/3	35.000	2.036	0.264
Brushite	1/7	1	1/3	1/5	1/9	0.001	0.254	0.033
TCP [1_2]	1/5	3	1	1/3	1/7	0.029	0.491	0.064
45s5	1/3	5	3	1	1/5	1.000	1.000	0.130
A/W	3	9	7	5	1	945.000	3.936	**0.510**
Sum	**4.676**	**25.000**	**16.333**	**9.533**	**1.787**	**981.030**	**7.718**	**1.000**

Estimation of expert opinions consistency: λ_{max} = (4.676*0.264) + (25.000*0.033) + (16.333*0.064) + (9.533*0.130) + (1.787*0.510) = 5.243; CI = (5.243 – 5) / (5 – 1) = 0.061; CE = 0.061 / 1.12 = 0.054 ≤ 0.1. According to the criterion "Bending strength" the most priority is the material A/W.

Table 10. Porosity

	HA	Brushite	TCP	45s5	A/W	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	5	3	1/3	1/5	0.200	0.725	0.097
Brushite	1/5	1	1/3	1/7	1/9	0.001	0.254	0.034
TCP	1/3	3	1	1/5	1/7	0.029	0.491	0.066
45s5	3	7	5	1	1/3	35.000	2.036	0.274
A/W	5	9	7	3	1	945.000	3.936	0.529
Sum	**9.533**	**25.000**	**16.333**	**4.676**	**1.787**	**980.230**	**7.442**	**1**

Estimation of expert opinions consistency: λ_{max} (9.533×0.0.097) + (25.000×0.034) + (16.333×0.066) + (4.676×0.274) + (1.787×0.529)= 5.084; CI = (5.084 - 5) / (5 - 1) =

0.021; CE = 0.021 / 1.12 = 0.019 ≤ 0.1. According to the criterion "Porosity" the most priority is the material apatite-wollastonite.

Table 11. Solubility

	HA	Brushite	TCP [1_2]	45s5	a/w	Product	$^5\sqrt{}$ from the product	Local vector of priorities
HA	1	7	5	3	1/3	35.000	2.036	0.264
Brushite	1/7	1	1/3	1/5	1/9	0.001	0.254	0.033
TCP [1_2]	1/5	3	1	1/3	1/7	0.029	0.491	0.064
45s5	1/3	5	3	1	1/5	1.000	1.000	0.130
A/W	3	9	7	5	1	945.000	3.936	**0.510**
Sum	**4.676**	**25.000**	**16.333**	**9.533**	**1.787**	**981.030**	**7.718**	**1.000**

Estimation of expert opinions consistency: λmax = (11.111×0.162) + (4.944×0,237) + (7.611×0,194) + (37.000×0.069) + (1.894×0.339) = 7.269; CI = (7.269 - 5) / (5 - 1) = 0.657; CE = 0.657 / 1.12 = 0.587 ≤ 0,1. According to the criterion "Solubility" the most priority is the material apatite-wollastonite.

Stage 5. Calculation of priorities for the entire hierarchy in the aggregate.

Now let's turn to the principle of priority synthesis. The local priorities of the alternatives are multiplied by the priorities of the corresponding level criteria and summed for each element according to the criteria. As a result, the global priorities of alternatives are determined taking into account the priorities of the criteria. The highest ranking will correspond to the alternative with the highest global priority value. The calculation of the vector of global priorities is presented in Table 11. The criteria priorities calculated in Table 3 are highlighted in bold.

Table 11. Global priority calculation

	Compressive strength	Tensile strength	Modulus of elasticity	Fracture resistance	Bending strength	Porosity	Solubility	Global priority
	0.043	**0.046**	**0.024**	**0.046**	**0.092**	**0.284**	**0.465**	
HA	0.130	0.064	0.264	0.130	0.264	0.097	0.162	0.148
Brushite	0.064	0.033	0.033	0.264	0.033	0.034	0.237	0.140
TCP	0.033	0.264	0.064	0.033	0.064	0.066	0.194	0.131
45s5	0.264	0.130	0.130	0.064	0.130	0.274	0.069	0.145
A/W	0.510	0.510	0.510	0.510	0.510	0.529	0.339	**0.436**
Sum	**1.044**	**1.047**	**1.025**	**1.047**	**1.093**	**1.284**	**1.466**	**1.001**

GP (1) = (0.043*0.130) + (0.046*0.064) + (0.024*0.264) + (0.046*0.130) + (0.092*0.264) + (0.284*0.097) + (0.465*0.162) = 0.148;

GP (2) = (0.043*0.064) + (0.046*0.033) + (0.024*0.033) + (0.046*0.264) + (0.092*0.033) + (0.284*0.034) + (0.465*0.237) = 0.140;

GP (3) = (0.043*0.033) + (0.046*0.264) + (0.024*0.064) + (0.046*0.033) + (0.092*0.064) + (0.284*0.066) + (0.465*0.194) = 0.131;

GP (4) = (0.043*0.264) + (0.046*0.130) + (0.024*0.130) + (0.046*0.064) + (0.092*0.130) + (0.284*0.274) + (0.465*0.069) = 0.145;

GP (5) = (0.043*0.510) + (0.046*0.510) + (0.024*0.510) + (0.046*0.510) + (0.092*0.510) + (0.284*0.529) + (0.465*0.339) = 0.436.

Comparing the obtained values of global priorities, we determine the ratings of materials. The material apatite-wollastonite has the highest priority 0.436. According to the evaluation by the MAI, preference should be given to this particular material.

4 CONCLUSIONS

The choice of material for bone replacement is difficult due to their large number and their existing shortcomings. The right choice leads to the efficient use of the bone substitute in the human body. Several alternatives must be considered and evaluated in terms of many different conflicting criteria in the biomaterial selection task.

Therefore, an efficient approach to evaluating alternatives is important for improving the quality of decisions. The Hierarchy Analysis Method (HAI) was used to select a material from five alternatives, taking into account the mechanical and biological properties of the materials.

The results showed that the best suitable material is apatite-wollastonite glass-ceramic with a global priority of 0.436. The next alternative materials that can be used are HA and 45s5 with global priorities of 0.148 and 0.145, respectively.

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