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Selection of Biomaterials for Orthopaedic Applications Using the Ponderated Properties Method

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Method description

The choice of material in a product design usually needs realization of compromises in decision adoption regarding conflictual objectives. When realizing a part, the most common objective is the choice of material that fulfils in optimal conditions specific requirements in the frame of the product which uses it. Often, these requirements refer to:

- Cost diminishing;
- Mass diminishing;
- Volume diminishing (overall dimensions);
- Optimization of power/weight or energy/density ratio etc. [5]

These conflicts arise because a choice which optimizes one of the objectives does not have the same effect upon the other objectives. Thus, the best choice is a compromise which does not optimizes a specific objective, but optimizes the global system. So, all the objectives will be fulfilled in the measure that their independence permits. When there are two or more objectives, very rare happens to exist a solution that optimizes both. The design of a product with small weight and low cost is one of the examples in this matter, one can see immediately the difficulties that arises: the two objectives have different measurement units (in our example kg and lei), and they are in conflict, meaning which is improvement for one, is bad for the other.

The ponderated properties method can be utilised for optimization of material selection when more properties must be taken into consideration. A pondering factor is assigned for each material specific requirement or property, depending on the importance of the property. The value of the ponderated property is obtained by multiplying the numerical value of the property with the pondering factor α. For each material, the values of the ponderated properties will be added up, and the so called performance indice γ will be calculated. The material having the bigger performance indice will be considered as optimum for the specific application.

In it's simple form, the ponderated properties method has the disadvantage that it must combine different measurement units, which can lead to irrational results[3]. This is true especially when combining the numerical values of the mechanical, physical and chemical properties. The property having the greatest value will have an influence bigger then that conferred by it's pondering factor.

This disadvantage is eliminated by introduction of the scaling factors.

Each property is scaled so it's maximal numerical value does not exceed 100. Each time when a list of candidate materials is evaluated, each property will be taken only once into consideration. The greatest value in the list is appreciated as being 100, and all the other properties will be scaled proportionally. Introducing the scaling factor facilitates the conversion of the normal values of each property of the candidate material, into dimensionless scaled values.

For a given property, the scaled value *B*, for a candidate material will be [3]:

$$B = scaled\ property = \frac{numerical\ value\ of\ the\ property \times 100}{the\ maximum\ value\ in\ the\ list} \qquad (1)$$

For properties like cost, corrosion, or wear loosing, weight increase by rust, these properties are expected to have low values. In such cases the lowest value is considered as being 100, and then *B* will be:

$$B = scaled\ property = \frac{the\ maximum\ value\ in\ the\ list \times 100}{numerical\ value\ of\ the\ property} \qquad (2)$$

Application of the above described procedure is very simple for those properties which can be represented by numerical values. But in the case of properties such as corrosion resistance, wear resistance, machinability, welding properties, etc., the numerical data is very rarely found, and material appreciation is made by qualificativs: very good, good, satisfactory, poor, etc. In such cases, the qualificative can be converted into numbers, utilizing an arbitrary scale. For example, the corrosion resistance qualificatives: excellent, very good, good, satisfactory and poor, can receive the values: 5, 4, 3, 2 and 1.

The performance indice will be [3] : $\gamma = \sum_{i=1}^{n} B_i \times \alpha_i$ (3)

where the sum is made for all the *n* relevant properties. Determination of the pondering factors α, can be done by a systematic approach using the decisional logic. Corresponding to this logic, the total number of decisions that must be taken is *I*: $I = \frac{n \times (n-1)}{2}$ (4)

The pondering factor for one property is obtained by dividing the number of positive decisions for that property (n_p) with total number of decisions *I:* $\alpha = \frac{n_p}{I}$ (5)

To illustrate the decisional logic, let's say we have to study a material having four relevant properties, so *n*=4. The total number of decisions is : *I*=4(4-1)/2=12/2=6. A decisional table must be made (see **table 1**) and the properties are compared two by two, designating with 1 (this means a positive decision) that one which is considered most important, and with 0 the other. Thus, by horizontal summarization of the positive decisions for each property, the number of positive decisions (n_p) is obtained, and so the pondering factors can be calculated using formula (5).

Table1: Establishing the positive decisions for each property

Property	**Decisions**						**Positive decisions**
	1	**2**	**3**	**4**	**5**	**6**	
P_1	1	0	0				1
P_2	0			1	1		2
P_3		1		0		0	1
P_4			1		0	1	2
TOTAL NUMBER OF DECISIONS (*I*)							**6**

Evaluating the above presented problems, it results that the method introduces a subjective factor, because one property which is considered more important by a material designer, can de disregarded by another, but globally the results are edifying.

The cost (material, manufacturing, etc.) can be considered as one of the studied properties, and for it, an adequate pondering factor can be assigned.

The pondered property method can be utilized also for replacing an existing material with a new one [3]. For this purpose, a relative performance indice will be calculated: γ_t :

$$\gamma_t = \frac{\gamma_n}{\gamma_e} \qquad (6)$$

Where γ_n and γ_e are the performance indices for the new/existent material. If γ_t is greater then 1, the new material is much adequated for the application then the old one.

Calculation of the performance indices for the biomaterials used in orthopaedics

The properties of the principal groups of materials used in orthopaedics for implants manufacturing are presented in **table 2**. The cost is among the properties which are analysed. Based on the theory presented above, in **table 3** are accentuated the positive decisions and the pondering factors for the studied biomaterials. Taking in account the great number of properties that were considered, the total number of decisions is 36, and the decisional table would take a lot of space, and only the number of positive decisions were specified. Finally, based on the data summarized in the above mentioned tables, the performance indices are calculated and the results are presented in **table 4**. Calculations were made based on relative cost related to hardened stainless steel 316, with prices updated in the second semester 2008.

Table 2: Properties of usual biomaterials

Nr. crt.	**Material**	**Tissue tolerance**	**Corosion resistance**	**Tensile strength**	**Elasticity modulus**	**Fatigue limit**	**Tenacity**	**Wear resistance**	**Density**	**Relativ cost**
		-	**-**	**MPa**	**GPa**	**MPa**	**-**	**-**	**Kg/m^3**	**-**
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	**Stainless steel 316** (Hardened)	10	7	515	200	350	8	8	8,1	1
2	**SS 316** (Hot worked)	9	7	860	210	415	10	8,5	8,1	1,03
3	**SS 316L** (Hardened)	9	7	505	208	410	10	8	8,1	1,03
4	**SS 316L** (Hot worked)	9	7	860	220	430	10	8,4	8,1	1,1
5	**CoCrMo Alloy** (Casted)	9	9	655	220	425	2	10	8,3	2,7
6	**CoCrMo Alloy** (Forged)	9	9	860	225	415	4	10	8,3	3,5
7	**CoNiCrMo Alloy** (Hardened)	9	9	600	228	455	9	10	8,3	3,8
8	**CoNiCrMo Alloy** (Forged)	9	9	1790	234	600	10	10	8,3	4
9	**Titanium Gr. 1**	10	10	240	102,6	265	7	7,5	4,51	5,56
10	**Titanium Gr. 2**	10	10	345	102,6	290	7	7,5	4,51	5,56
11	**Titanium Gr. 3**	10	10	450	107	290	7	8	4,47	5,56
12	**Titanium Gr. 4**	10	10	550	112	315	7	8	4,47	5,56
13	**Ti6Al4V Alloy**	10	10	895	114	490	7	8,3	4,43	6,16

Tabelul 2 : Deciziile şi factorii de pondere

Nr. crt	Property	Positive decisions	Pondering factors
1	Tissue tolerance	7	0,2
2	Corrosion resistance	7	0,2
3	Tensile strength	3	0,08
4	Fatigue limit	4	0,12
5	Tenacity	3	0,08
6	Rezistenţă la uzură	4	0,12
7	Elasticity modulus	3	0,08
8	Density	3	0,08
9	Cost	2	0,04
TOTAL		**36**	**1**

The introduction into calculations of the biocompatibility and corrosion resistance must be outlined because those properties are indispensable for any synthetic material that must be implanted in the human body. The implants must resist to any corrosive attack from the fluid bodies. Its constitutive elements must have enough strength to resist to any force that could appear during the normal life cycle. The materials must not alter the electrolytic composition of the plasma or of the tissue, must resist to electrochemical corrosion, must not interfere with the normal imunitary system, must not favour the formation of cancerous tissue and must not crack as a result of brittleness. Finally (and this criteria is the most important) the materials for implants must not induce any blood trauma, coagulation, or blood protein denaturising.

All these requirements were introduced in the studied properties and pondered with corresponding values for obtaining a global result.

Studding the ierarhization according to the performance indices which is presented in **table3,** it can be observed that the materials with the best performance indices are Ti-6Al-4V alloy and Co-Ni-Cr-Mo forged alloy.

Table 3: Ierarhization according to the performance indice

Nr. crt.	Scaled prop.	Tissue tolerance	Corosion resistance	Tensile strength	Elasticity modulus	Fatigue limit	Tenacity	Wear resistance	Density	Relativ cost	Performance indice with costs
	Material	**-**	**-**	**MPa**	**GPa**	**MPa**	**-**	**-**	**Kg/m^3**	**-**	**-**
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	**Ti6Al4V**	100	100	50,00	90,00	81,67	70	83	100,0	16,23	**85,19**
2	**CoNiCrMo** Forged	90	90	100,00	43,85	100,0	100	100	53,37	25,00	**82,78**
3	**Titan Gr. 4**	100	100	30,73	91,61	52,50	70	80	99,11	17,99	**81,28**
4	**Titan Gr. 3**	100	100	25,14	95,89	48,33	70	80	99,11	17,99	**81,01**
5	**Titan Gr. 2**	100	100	19,27	100,00	48,33	70	75	98,23	17,99	**80,57**
6	**Titan Gr. 1**	100	100	13,41	100,00	44,17	70	75	98,23	17,99	**79,76**
7	**SS 316** Hot worked	90	70	48,04	48,86	69,17	100	85	54,69	97,09	**75,27**
8	**SS 316L** Hot worked	90	70	48,04	46,64	71,67	100	84	54,69	90,91	**74,81**

9	**CoNiCrMo** Hardened	90	90	33,52	45,00	75,83	90	100	53,37	26,32	**74,53**
10	**SS 316L** Hardened	90	70	28,21	49,33	68,33	100	80	54,69	97,09	**73,27**
11	**SS 316** Hardened	100	70	28,77	51,30	58,33	80	80	54,69	100,00	**72,50**
12	**CoCrMo** Forged	90	90	48,04	45,60	69,17	40	100	53,37	28,57	**69,35**
13	**CoCrMo** Casted	90	90	36,59	46,64	70,83	20	100	53,37	37,04	**66,71**

One can observe that the titanium alloy is on the first place, despite of its mechanical properties which are worst than those of some stainless steel materials. This is due to introduction in calculations of the biocompatibility and corrosion resistance, which are higher for the titanium alloy Ti-6Al-4V. The importance of those properties are accentuated by the pondering factor value, which have in these cases the greatest value: 0,2 (see **table 2**).

We must also outline that the differences between the performance indices of the materials situated on the first ten places is not so big (14%) which means that all these materials can be used for an orthopaedic implant. It also can be remarked that the pure titanium materials are well situated, from Ti Gr.4 - Ti Gr.1.

The importance of the material costs (costs per volumetric unit, costs for manufacturing and finishing) are not of extreme importance, this being outlined by the small afferent pondering factor (0,04).

The evolution of the materials science leaded to the apparition of new materials which could find applicability in orthopaedics. Today, the possibilty to use polymers and ceramic materials is intensly studied. Sinterized metallic powders and porous ceramics can be useful for wear reduction and the increase of the implants lifetime. Ensuring a high wear resistance is necessary in order to avoid wear particles accumulation in the surrounding tissue or in other organs. Its a pitty that in present we don't dispose of enough data regarding tissue tolerance, corrosion resistance or wear resistance of the ceramic materials, so in next analysis only composite materials will be analysed, for their evaluation the relative performance indice being used. The fiber orientation of the composite materials must be according to the maximum solicitation direction.

The properties of some composite materials, the scaled values and the relative performance indice related to Ti6Al4V (which was the best material in the first determination) are presented in **tables 4** [4] şi **5.**

Table 4: Properties of the composite materials [4]

Nr. crt.	**Material**	**Tissue tolerance**	**Corosion resistance**	**Tensile strength**	**Elasticity modulus**	**Fatigue limit**	**Tenacity**	**Wear resistance**	**Density**	**Relativ cost**
		-	**-**	**MPa**	**GPa**	**MPa**	**-**	**-**	**Kg/m^3**	**-**
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	**Epoxi/70% with glass fibers**	7	7	680	22	200	3	7	2,1	3
2	**Epoxi- 63% with carbon fibers**	7	7	560	56	170	3	7,5	1,6	10
3	**Epoxi-70%with Kevlar fibres**	7	7	430	29	130	3	7,5	1,38	5

Nr crt	**Scaled Prop.** / **Material**	**Tissue tolerance**	**Corosion resistance**	**Tensile strength**	**Elasticity modulus**	**Fatigue limit**	**Tenacity**	**Wear resistance**	**Density**	**Relativ cost**	**Performance indice with costs**	**Relative Performance indice**
		-	**-**	**MPa**	**GPa**	**MPa**	**-**	**-**	**Kg/m^3**	**-**	**-**	**-**
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	
1	**Epoxi/70% with glass fibers**	70	70	37,99	100,0	33,33	30	70	65,71	33,33	61,83	**0,87**
2	**Epoxi- 63% with carbon fibers**	70	70	31,28	39,29	28,33	30	75	86,25	10,00	54,48	**0,77**
3	**Epoxi- 70%with Kevlar fibres**	70	70	24,02	75,86	21,67	30	75	100,0	20,00	59,36	**0,83**

Table 4: Relative performance indices

Conclusions

Studding the relative performance indices it results that the composite materials are less adequate then titanium Ti-6Al-4V alloy for implant manufacturing, but their future development for mechanical properties improvement and lowering costs (obtaining and machining costs), is a domain that must be studied in the future.

Analysis of the obtained results using ponderate properties method shows that caution is necessary when utilizing new non-metallic materials, the opinion of the materials specialist being indispensable for evaluating the influence of the micro-structural characteristics upon the implant-tissue interface, especially when the micro-structure is complex and has a high finishing degree.

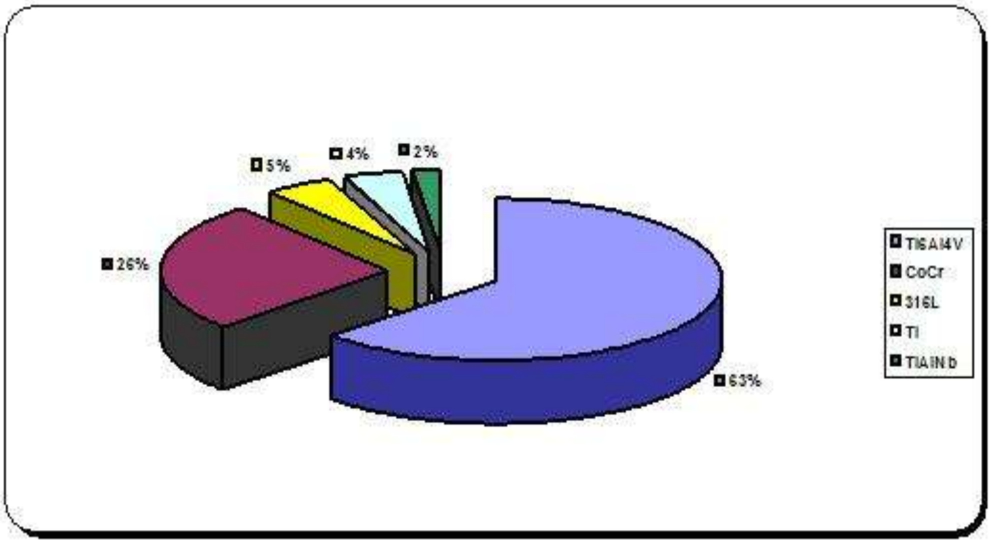
Calculation of the relative performance indice for the polymeric materials reveald that those do not have enough strength comparative with other biomaterials which are already in use in the medical practice and the cost of materials is still too high. We must also remind that when utilising composite materials the fiber orientation must be according to the maximum solicitation direction, which is another problem that must be taken into account when using this class of materials.

As a final conclusion, the most indicated materials for use in orthopaedic implants, are those that can form superficial protective layers that "closes" the metal pores for the environment. For long term body implants, titanium and titanium alloys are the most appropriated. Another group of alloys that can be used in implant manufacturing are Co-Cr alloys. The experience in implanthology leaded to the use of precious and semiprecious metals and alloys (based on silver, platinum, zirconium and tantalum), memory shape alloys

(Ni-Ti), Zr-Nb alloys, but these does not have mechanical characteristics comparable with the classic materials, or the obtaining and processing costs are still too high.

The conclusions of this study are sustained by a statistical study of the National Register of Arthroplasty, from where we can see that the most used materials in orthopaedics are Ti6Al4V, CoCr alloy, Stainless steel 316L and pure titanium (see figure 1).

Figure 1: Distribution of the implant materials



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