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A Method for Increasing of Metallic Bone Implant Performance

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Abstract - *Nowadays materials are developing faster than at any other time historically; the challenges and opportunities are therefore greater than ever before. A systematic and numerical method for material selection will help the material designers to choose and compare the new material with the common materials database. This paper introduces a mathematical method based on fuzzy logic which is used in designing of metallic bone implant. Five sets of criteria are defined as follow: total corrosion resistance, biocompatibility, adherence, technical specs and price. Each of these criterions is divided into its subsets. Then membership functions of sets are defined. In continuation the satisfactory degree is calculated. Finally, biomaterial favorability is determined and the effect of price on sensitivity analysis is analyzed. Twelve common metallic biomaterials are used in the database. These methods show the satisfactory value for metallic bone implant as a continuous value ranging from zero to one. Therefore, biomaterial designer can compare a new material to the database systematically and he/she can determine restricted parameters to increase the performance of metallic bone implant.*

Key Words: Design, Fuzzy logic, Materials selection

1. Introduction

Dieter defined the material selection as swiftness of the process of designing any component which its purpose is to reduce cost while gaining product performance goals [1]. Therefore, logical selection of the best material for a given application begins with properties and price of candidate materials.

An Ashby plot is a scatter scheme which displays two or more properties of different materials [2]. Therefore, a material of excellent technical specs may have not sufficient biocompatibility, while a material with good compatibility may have low technical specs.

Nowadays materials are developing faster than at any other time historically; the challenges and opportunities are therefore greater than ever before. Karande and Chakraborty found out that a systematic and numerical method for material selection will help the material designers to choose and compare the new material with the common materials database [3]. Ramalhete et al., Jahan et al., Chatterjee and Chakraborty concluded that on the basis of mathematical methods, it is possible to maximize the utilization of design [4, 5, 6]. Therefore, this paper deals with mathematical strategies of developing metallic bone implant selection.

A few researches, using various approaches, have been done about the selection and optimization of metallic bone implant. Albiñana and Vila analyzed a workflow that breaks the work down into stages and gates, and specifies how the preliminary selection is to be performed [7]. Rao and Patel used subjective and objective integrated multiple attribute decision making method for material selection [8]. Rao and Davim used a combined multiple attribute decision-making method for material selection [9]. Also, Bahraminasab and Jahan used comprehensive special method (VIKOR) for material selection of femoral component of total knee replacement [10]. José et al selected a biomaterial approach to the construction of valve leaflets for cardiac bio-prostheses [11]. Zander and Sandström expected the optimum material is strongly dependent on the chosen target functions and constraints. It is demonstrated that the two approaches for materials optimization give identical results for pressure vessel [12]. As it is clear, none of them focused on material selection of metallic bone implants based on fuzzy logic.

Fuzzy logic investigates the relative properties of the material. In order to accomplish this, fuzzy approach defines a set for each property. For example, various materials have different biologic properties and price, so these materials have different membership degree in the set of biomaterials. Using these sets and fuzzy rules, biomaterial designer can compare and evaluate different materials for specific applications. Therefore, in this paper, a mathematical method based on fuzzy logic is used in selection of metallic bone implant. This method is proposed because it has not been used for selection of metallic bone implant material, until now. It helps metallic bone implant designers to choose which one is the best for metallic bone implant material?

Cost of materials plays a very important role in their selection. The most uncomplicated way to weight cost against properties is to develop a financial metric to measure the properties of components. Optimization of the complicated combinations of technical and price properties is not a flexible process to be attained manually; therefore using rational material selection software is an essential tool. In the other word, customer satisfaction is to choose a favorite metallic bone implant and at the same time not a very expensive one, so it is appropriate to study their properties and cost relatively.

2. Material and methods

1.2 Algorithm

The algorithm of relationship between biomaterial properties and cost, contemplating long usage of metallic bone implant, is shown in Figure 1. Grey boxes show that biocompatibility is affected by total corrosion resistance, whereas total corrosion resistance is affected by corrosion resistance. In addition, adherence is affected by biocompatibility. These are the complex relationships between the biomaterial selection factors which are considered in these methods.

Corrosion and erosion in artificial moving parts like knee joint or screw and sheet systems cause many problems such as reduction of strength and in case of long time usage it can harm the body tissues. So, total corrosion resistance is studied as an independent set.

Biocompatibility is one of the most important properties of a biomaterial which shows how much a biomaterial is compatible with body. Since it is a function of corrosion resistance and oxide stability, different substances have different corrosion rate in human body. It shows how much oxide can resist different situations and how long the oxidation prolongs if corrosion oxidation fails. The corrosion free ions, in long time, could be harmful for body tissues. It leads to disorders such as mutagenic, cancer and sensitivity [13, 14]. Therefore, these parameters are also studied as a subset of biocompatibility. The co-efficiency of the biomaterials IARC (International Agency Research for Cancer) and FDA (Food and Drug Administration of USA) have been studied relatively. However, it may be noted that fuzzy logic is quite useful in uncertain environments, such as the case in this work. Dielectric constant is a subset of biocompatibility. When corrosion occurs in a system it leads to mobility of electron that makes negative results in neurotic system. Material solutions cause them to move to other parts of human body, the way that can be harmful [15, 16]. So, this is another subset of biocompatibility set.

For better adherence of material that leads to better joint, adherence is another set that depends on the ability of bone growth. This ability depends on biocompatibility because if a material doesn't behave biocompatible, there would be putrefaction and welt that prevent the growth. Blood is the most important requirement in bone growth, so the implanted devices should allow blood transition to the joints. So, to gain this purpose the ability of making the material porous is needed as another subset for the bone growth set. Another subset for adherence is the ability to make surface shaggy.

The next big set for biomaterials set is the technical properties that divide into four subsets. The first one is the Young's modulus. The object is to choose a material with Young's modulus equal to the bone's Young's modulus. Then, when force is exerted on the system, changes of elastic length of the bone and that of the devices are similar [13, 15]. For example, when they are the same, the favorability of Young's modulus will be 1. When they are not the same, the favorability of Young's modulus will be less than 1. The bones are under various forces, so the superseded devices should have enough fatigue and mechanical strength. When a biomaterial has the highest fatigue and the highest mechanical strength among their subset, it is the best selection for biomaterial to be chosen in their subset [13, 15]. Thus these are the second and third subsets for the sets of technical properties. The implant should be more flexible to force than the bone. That is, biomaterial tensile strength should be higher than that of bone, but with smaller thickness. Material density is another subset factor. When a biomaterial has the least density in the density subset, it would be the best selected biomaterial among the density subset.

2.2. Methodology of fuzzy approach

In this method some symbols are used that are listed in Table 1. Also, the procedure is done according to flowchart presented in Figure 2.

2.2.1 Membership functions

The definition of fuzzy rules and membership function of each set is presented in Table 2. More explanation is given in remark column.

Finally, by fuzzy conjunctive rules, the favorability degree, as a biomaterial (FdBi), is determined as Esq. (1) just in the same way that a biomaterial designer considers the worse conditions for biomaterial selection; the fuzzy conjunctive rule is used in this paper.

FdBi = Min (TCR, Bi, Ad, MP) (1)

According to the functions, properties and chemical compositions of twelve metallic biomaterials; presented in Table 2, Table 3 and Table 4, and Table 5 respectively, the favorability of these biomaterials are determined, calculated and shown in Table 6. Also the favorability degree, as a biomaterial (FdBi), is determined according to Esq. (1) and shown in Table 6.

TheX2CrNiMo17133 is explained here as an example. Since there is a lack of data, characteristics of favorability degrees of erosion resistance, mutagenic, solvency coefficient constant, surface roughness, fatigue resistance and ability to be porous are supposed to be equal to 1. In the other word, it is supposed that X2CrNiMo17133 has the same value in the above parameters.

$$\text{favorability degree of oxidatiom time} = \min\left(\frac{37}{72000}(\text{for} - 500\text{mV}), \frac{31}{35}(\text{for} + 500\text{mV})\right) = 0.0005$$

$$\text{favorability degree of stabilityofoxide} = \min(1, 0.0005) = 0.0005$$

$$\text{favorability degree of corrosionresistance} = \frac{200}{2400} = 0.0833$$

$$\text{favorability degreeoftotalcorrosionresistance} = (0.0833, 0.0005) = 0.0005$$

$$\text{favorability degree of dielectricconstant} = \frac{0.74}{1.66} = 0.4458$$

$$\begin{aligned}\text{X2CrNiMo17133 favorability degree of carcinogen}\\ &= (0.6539\times 0.99)_{Fe} + (0.0003\times 0.5)_{C} + (0.17\times 0.8)_{Cr} + (0.12\times 0.5)_{Ni} + (0.025\times 0.99)_{Mo}\\ &+ (0.02\times 0.99)_{Mn} + (0.0003\times 0.8)_{S} + (0.01\times 0.8)_{Si} + (0.0005\times 0.1)_{P} = 0.8964\end{aligned}$$

$$\begin{aligned}\text{X2CrNiMo17133 favorability toxicity degree}\\ &= \left(0.6539\times\frac{30000}{30000}\right)_{Fe} + \left(0.0003\times\frac{10000}{30000}\right)_{C} + \left(0.17\times\frac{71}{30000}\right)_{Cr} + \left(0.12\times\frac{9000}{30000}\right)_{Ni}\\ &+ \left(0.025\times\frac{125}{30000}\right)_{Mo} + \left(0.02\times\frac{9000}{30000}\right)_{Mn} + \left(0.0003\times\frac{8437}{30000}\right)_{S} + \left(0.01\times\frac{3160}{30000}\right)_{Si}\\ &+ \left(0.0005\times\frac{5}{30000}\right)_{P} = 0.6977\end{aligned}$$

$$\begin{aligned}&\text{X2CrNiMo17133 favorability sensitivity degre } =\\ &\left(0.6539\times\frac{1.5}{1.75}\right)_{Fe} + \left(0.0003\times\frac{1.5}{2}\right)_{C} + \left(0.17\times\frac{1.5}{3.75}\right)_{Cr} + \left(0.12\times\frac{1.5}{1.75}\right)_{Ni} + \left(0.025\times\frac{1.5}{2.75}\right)_{Mo} + \left(0.02\times\frac{1.5}{14}\right)_{Mn}\\ &+ \left(0.0003\times\frac{1.5}{5}\right)_{S} + \left(0.01\times\frac{1.5}{3.75}\right)_{Si} + \left(0.0005\times\frac{1.5}{3}\right)_{P} = 0.7517\end{aligned}$$

Hygienic favorability = min(1.000, 0.8964, 0.6977, 0.7517) = 0.6977
Biocompatibility favorability = min(1.0000, 0.4458, 0.0005, 0.6977) = 0.0005
Bone growth ability = min(1.0000, 0.0005) = 0.0005
Adherence favorability = min(0.0005, 1.0000) = 0.0005

$$\text{favorability degree of density} = \frac{4.43}{8} = 0.5538$$

$$\text{favorability degree of E} = \frac{17}{193} = 0.0881$$

$$\text{favorability degree of strength} = 1 \text{ because of strength is grater than 130Mpa}$$

Technical properties favorability = min (1.0000, 0.0881, 0.5538, 1.0000) = 0.0881
Ability as a biomaterial= FdBi = min(0.0881, 0.0005, 0.0005, 0.0005) = 0.0005

2.2.2. Price analysis

A biomaterial may have a high degree of favorability as a bone but it may be expensive. In general, everybody likes using the cheapest one.
Price is an effective parameter in biomaterial selection, so it is defined as a set. In fact, price changes of metallic biomaterial during a day, and approximate prices are mentioned in Table 7 [22, 23]. The price membership function is defined as Esq. (2) and the alloy cheap degree is calculated and shown in Table 7. ACD is calculated as

$$ACD = \frac{CAP}{AP} = \frac{0.1886}{0.1886} = 1.0000 \qquad (2)$$

It is explained for X2CrNiMo17133 as an example. In this research (for body skeleton), the co-efficiency of the price importance is affected just by customer demand. It is done for sensitivity analysis of this algorithm. They are not constant and vary between 0 and 1 (0% and 100%). So the final favorability of a biomaterial is defined as Esq. (3).

FFdBi = (FdBi × FdBi importance) + (ACD × ACD importance)
Whereas FdBi importance + ACD importance =1 (3)

It is explained for X2CrNiMo17133 as an example. X2CrNiMo17133 line is calculated as following:

FFdBi of X2CrNiMo17133 = (0.0005 × FdBi importance) + (1.0000 × (1- FdBi importance)) →
FFdBi of X2CrNiMo17133 = 1-0.9995× FdBi importance

3. Results and discussion

The results of each method about the topic, which was discussed, are as follows:

3.1. Increasing of metallic bone implant performance

For all materials except X2CrNiMo17133, technical properties were not favorable because of their small strength membership degree as a metallic bone implant set. That is because they have a high Young's modulus in comparison with actual bones. So, the chance of Young's modulus in metallic bone implantation decreases in favor of other new techniques. For example, the use of porous material is considered.
In addition, since X2CrNiMo17133 has the lowest favorability value (0.0005), the oxidation time becomes a restrictive parameter which is shown in Table 6. Therefore, it tends to increase its oxidation time. Therefore a new method was introduced for the recognition of restrictive parameters in metallic bone implant selection. In the other word, a new method was presented to increase the metallic bone implant performance.

3.2. Metallic bone implant selection based on technical specs

The most favorable metallic bone implant, which is gained by using fuzzy disjunctive rule, is defined as Esq. (3).

According to data in Table 6, dmFBi, the most favorable metallic bone implant is Ti30T with the degree of 0.2429 based on technical specs.

$$dmFBi = Max(FFdBi) \quad (3)$$

3.3. Price Analysis

The final favorability degree of a metallic bone implant (FFdBi) is calculated according to Esq. (3). Figure 3 shows the degree of the final favorability of the metallic bone implant when the FdBi importance changes between 1 and 0.

4. CONCLUSIONS

This paper introduces a mathematical method based on fuzzy logic which is used in designing of metallic bone implant.

(1) According to Figure 3, between 12 metallic biomaterials, it shows Ti30Ta as the most favorable metallic bone implant when the price importance changes between 0 and ≈0.0710. Also, Ti30Nb is the most favorable metallic bone implant when it changes between ≈0.0710 and ≈0.1750. In addition, Ti5Al2.5Fe is the most favorable metallic bone implant when it changes between ≈0.1750 and ≈0.9966. Finally, X2CrNiMo17133 is the most favorable metallic bone implant when it changes between ≈0.9966 and 0. In the other word, the favorability of metallic bone implant was measured by continuous values between 0 and 1 and also price effect is analyzed by continuous values ranging between 0 and 1. Therefore, this method raises the customer satisfaction according to his/her request.

(2) According to Table 6, the favorability of all biomaterials except X2CrNiMo17133 is restricted by technical specs because the favorability of technical specs of biomaterials is the lowest value. Also, the favorability of technical specs is restricted by Young's modulus because the favorability of Young's modulus has the lowest value. It means Young's modulus is the most restrictive parameter for this database. Therefore, it helps the biomaterial designer to raise biomaterial performance by focusing on the restricted parameters.

(3) This method does not require any predetermined weights of criteria to be used in selection process, while in other prevalent methods such as AHP. These weights must be determined by experts.

(5) The line slop of Ti30Ta shows the minimum in Figure 3. Because Ti30Ta has the highest price in the price set.

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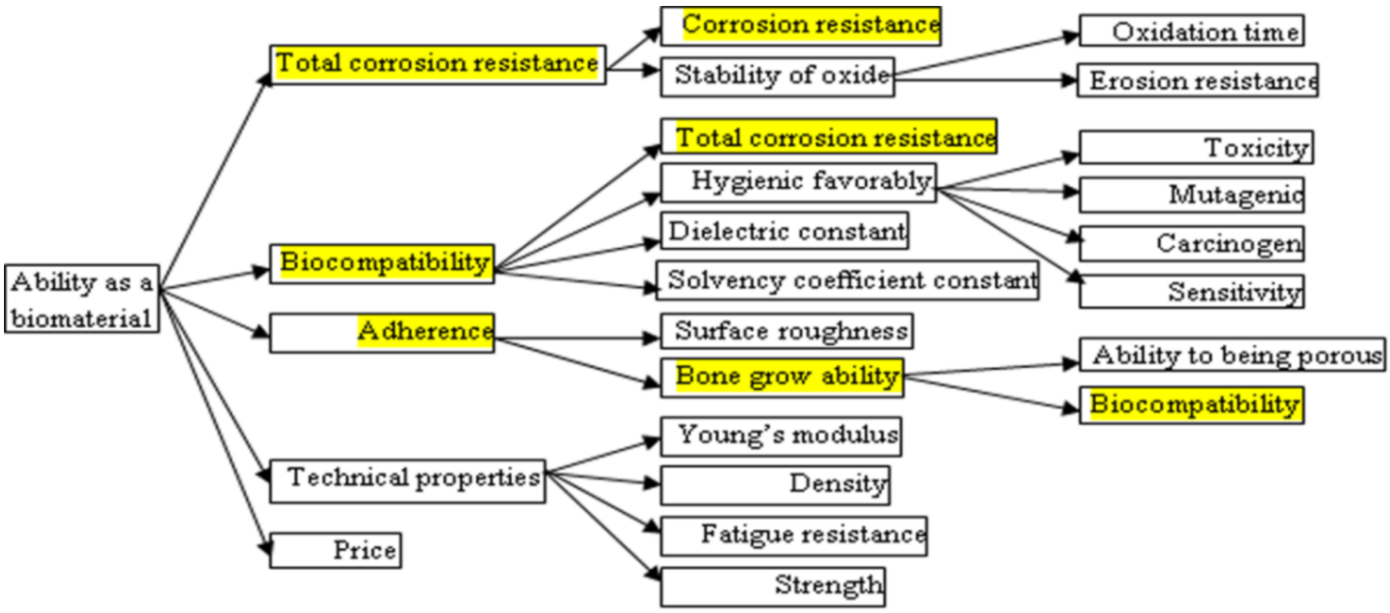

Figure -1: Algorithm of relationship between metallic bone implant properties, a long time usage.

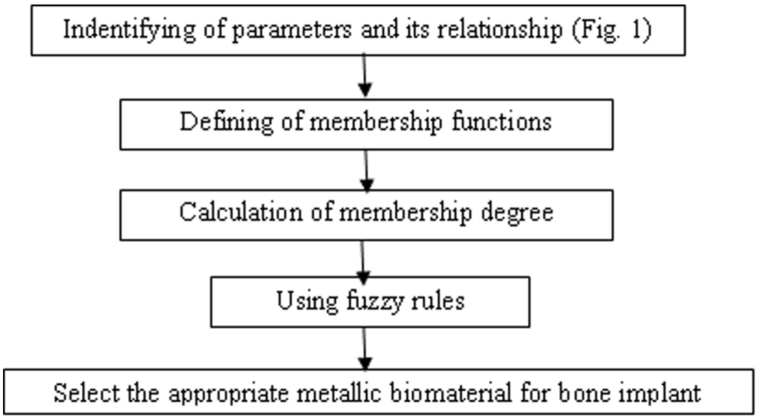

Figure -2: Biomaterial selection methodology of metallic bone implant

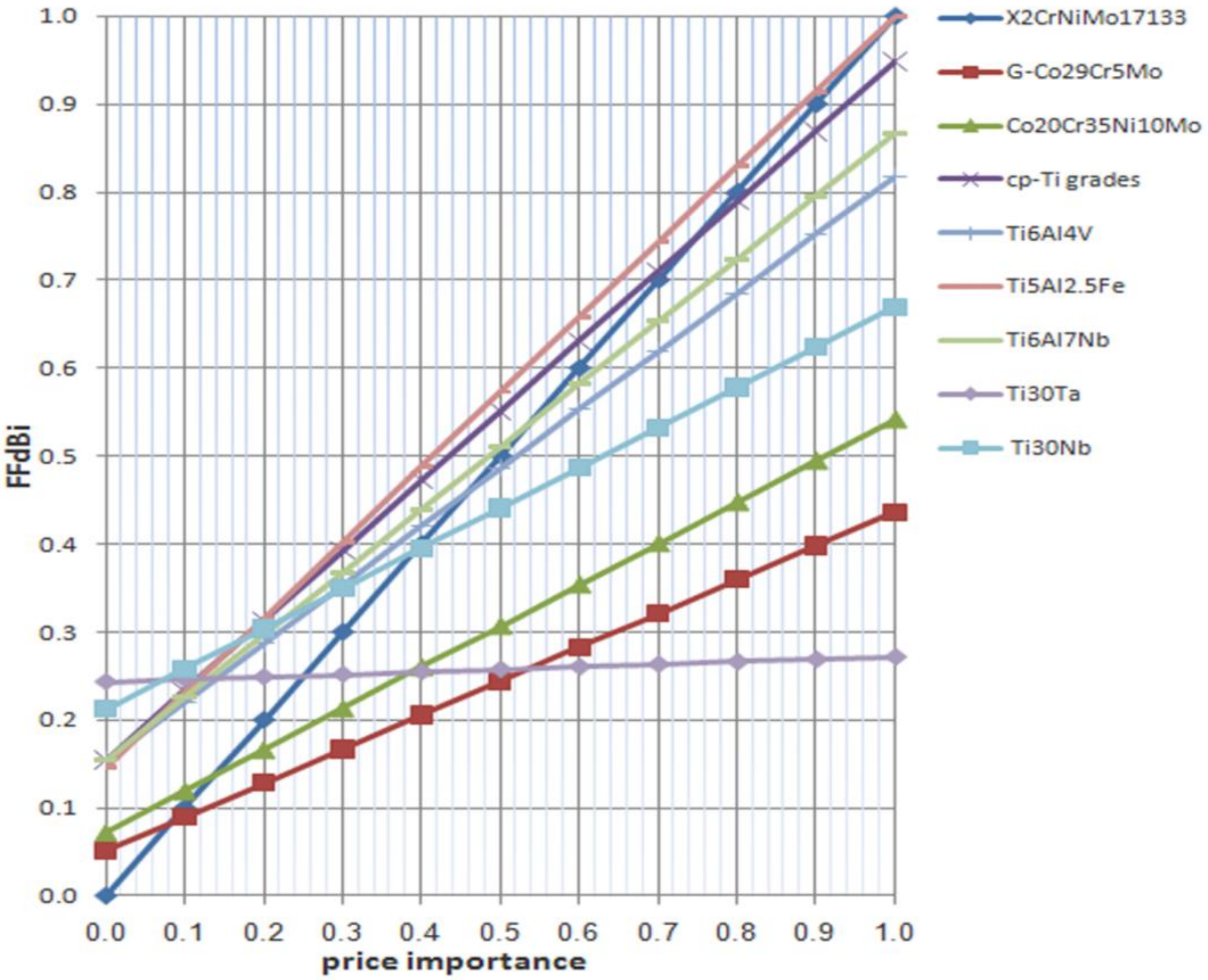

Figure -3: FFdBi of biomaterial for metallic bone implant when the price importance changed between 0 and 1

Table -1: List of Symbols

Symbol	Description	Symbol	Description
CAP	Cheapest alloy price in the set	dmFBi	Degree of the most favorable biomaterial as a bone
Ad	Adherence degree	FdBi	Favorability degree as a biomaterial
AP	Alloy price	FFdBi	Final favorability degree as a biomaterial
Bi	Biocompatibility degree	MP	Mechanical properties degree
ACd	Alloy cheap degree	TCR	Total corrosion resistance degree

Table -2: Strength Membership function of fuzzy set as a metallic bone implant [17-19]

Set name and their fuzzy rules						Variant (=X)	Membership function		Remark
Ability as a biomaterial (FdBi)	Biocompatibility (Bi)	Biocompatibility = min(hygienic favorably, total corrosion resistance, dielectric constant, Solvency coefficient Constant)	Hygienic favorably	Hygienic favorably =min(Sensitivity, Carcinogen, Toxicity, Mutagenic)	Sensitivity*	Quantity of disease	$\frac{1}{x}$		Nomination of less disease agent[19]
					Carcinogen*	Carcinogen Group In IRAC [17]	Group1	0.1	Nomination of less carcinogenicity
							Group2b	0.5	
							Group3	0.8	
							Group4	0.99	
					Toxicity*	LD50 [18 and 19]	$\frac{x}{\max(x)}$		Toxicity limit (amount of metal that lead to 50%of cell die) nomination of less toxicity
					Mutagenic	Material mutagenic resistance [19]	$\frac{x}{\max(x)}$		Materials Mutagenic
			Total corrosion resistance			---	---		Total corrosion resistance set
			Dielectric constant			Oxide electricity resistance at 20C	$\frac{x}{\max(x)}$		Amount of electric resistance
			Solvency coefficient constant			Solvency coefficient constant	$\frac{\min(x)}{x}$		Ion transition to different part of body after solution of material
	Total corrosion resistance (TCR)	Total corrosion resistance =min(oxide Stability, Corrosion resistance)	Corrosion resistance			Alloy break down potential(mV) hanks solution	$\frac{x}{\max(x)}$		Inception of corrosion depends on break down potential(mV) in hanks solution
			Stability of oxide	Stability of oxide =min (Erosion resistance, Oxidation time)	Erosion resistance	---	---		Erosion lead to removing of oxide layer
					Oxidation time	Time of oxidation (ms)	$\frac{\min(x)}{x}$		Oxidation rate after remove of oxide layer
	Adherence (Ad)	Adherence =min(Surface roughness, Bone grow ability)	Surface roughness			Surface roughness	$\frac{x}{\max(x)}$		More surface roughness lead to better adherence
			Bone Grow Ability	Bone grow ability = min (biocompatibility, Ability to being porous)	Biocompatibility	---	---		Biocompatibility set
					Ability to being porous	Ability to being porous	$\frac{x}{\max(x)}$		Porosity allow the vessel to transmit the blood to the joint
	Technical properties (MP)	Technical properties = min (Young's modulus, Density, Fatigue resistance, Strength)	Strength**			Ultimate tensile strength (MPa)	UTS<130	$\frac{x}{\max(x)}$	Mechanical Strength
							UTS=130	1	
							UTS>130	1	
			Fatigue resistance			Fatigue limit (stress ratio=-1)	$\frac{x}{\max(x)}$		Endurance of cycle of tension
			Young's modulus ***			Young's modulus(GPa)	$\frac{17}{E}$		Change in the dimension depends on tension
			Density			Density (g/cm3)	$\frac{\min(x)}{x}$		Material weight in the unit volume

** They are obtained from IARC and FDA sites [17 and 18]. Above functions are for element and for alloy we have:*

Member ship degree for Sensitivity, Carcinogen and also Toxicity = sum of element percentage in alloy multiply by member ship degree Sensitivity, Carcinogen and also Toxicity element one by one

*** : Bon tensile strength is 130MPa [15]*

**** : Bon Young's modulus is 17GPa [15]*

Table -3: Biomaterial properties which are used to calculate favorability degree [20, 21]

Alloy	Young's modulus (GPa)	Tensile yield strength (MPa)	Fatigue Limit	Density (g/cm3)	Time of oxidation (ms)[1] (+500mV)	Time of oxidation (ms) (-500mV)	Break down potential (mV) Hanks solution	Special electric resistance in 20C (μΩm)
X2CrNiMo17133	193	170-310	505	8	35	72000	200	0.74
G-Co29Cr5Mo	210-330	450	300	8.2-8.4	36	44	420	1.03
Co20Cr35Ni10Mo	235	300	200	8.43	31	36	420	1.03
cp-Ti grade 1	105-110	200	200	4.5	44	43	2400	1.66
cp-Ti grade 2	105-110	250	200	4.5	44	43	2400	1.66
cp-Ti grade 3	105-110	320	200	4.5	44	43	2400	1.66
cp-Ti grade 4	105-110	390	200	4.5	44	43	2400	1.66
Ti6Al4V	100-110	870	500	4.43	41	37	2000	1.66
Ti5Al2.5Fe	110-116	780	450	4.45	160	130	---	1.66
Ti6Al7Nb	110	811-952	450	4.52	---	---	---	1.66
Ti30Ta	70	500			48	42	1500	1.66
Ti30Nb	80	590			43	45	1500	1.66

Table -4: Element properties which are used to calculate favorability degree [17-19]

Element	LD50 for rate mg/kg body weight	Quantity of disease[2]	Carcinogen grouping with IARC	Element	LD50 for rate mg/kg body weight	Quantity of disease	Carcinogen grouping with IARC
Cr	71	3.75	3	Ti	24000	1.5	3
Mo	125	2.75	4	Fe	30000	1.75	4
W	5000	-----	4	C	10000	2	2b
Co	7000	1.75	2b	Mn	9000	14	4
Al	10000	2	4	P	5	3	1
Ta	8000	1.75	4	Si	3160	3.75	3
Zr	1688	-----	4	SO_2 or S	8437	5	3
Sn	20000	-----	4	Ni	9000	1.75	2b
$V(V_2O_5)$	10	15	2b	Nb	4000	1.75	4

Table -5: Element percentage in biomaterial alloy

Alloy element%	Ta	Al	Co	Mo	Cr	V	Nb	Ti	Ni	S	Si	P	Mn	C	Fe
X2CrNiMo17133	0.00	0.00	0.00	2.50	17.00	0.00	0.00	0.00	12.00	0.03	1.00	0.05	2.00	0.03	65.39
G-Co29Cr5Mo	0.00	0.00	60.65	5.50	28.00	0.00	0.00	0.00	2.50	0.00	1.00	0.00	1.00	0.35	1.00
Co20Cr35Ni10Mo	0.00	0.00	36.53	9.00	19.00	0.00	0.00	1.00	33.00	0.01	0.15	0.02	0.15	0.15	1.00
cp-Ti grade 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.72	0.00	0.00	0.00	0.00	0.00	0.08	0.20
cp-Ti grade 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.67	0.00	0.00	0.00	0.00	0.00	0.08	0.25
cp-Ti grade 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.60	0.00	0.00	0.00	0.00	0.00	0.10	0.30
cp-Ti grade 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.55	0.00	0.00	0.00	0.00	0.00	0.10	0.35
Ti6Al4V	0.00	6.00	0.00	0.00	0.00	4.00	0.00	89.62	0.00	0.00	0.00	0.00	0.00	0.08	0.30
Ti30Ta	30.00	0.00	0.00	0.00	0.00	0.00	0.00	70.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti30Nb	0.00	0.00	0.00	0.00	0.00	0.00	30.00	70.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti5Al2.5Fe	0.00	5.00	0.00	0.00	0.00	0.00	0.00	92.50	0.00	0.00	0.00	0.00	0.00	0.00	2.50
Ti6Al7Nb	0.00	6.00	0.00	0.00	0.00	0.00	7.00	87.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

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[1] This parameter is calculated in two different potential and the minimum of them is considered as membership degree

[2] Elements (from implants) make disease in the body. Some disease happens certainly, some disease happen ordinary and the others happen rarely. Quantity of disease is formulated as follows:

$$\text{quantity of seriously disease} = \text{quantity of seriously disease} + \frac{\text{quantity of ordinary disease}}{2} + \frac{\text{quatity of rary disease}}{4}$$

Table -6: Favorability degree for 12 metallic biomaterials

Raw	Alloy	Favorability of biomaterial as a bone	Ability as a biomaterial																
			Favorability of Technical properties				Favorability of Adherence			Favorability of Biocompatibility							Favorability of Total corrosion resistance		
			Density	Fatigue resistance	Strength	**Young's modulus**	Bone grow ability		Surface roughness	Solvency coefficient Constance	Dielectric Constance	Total corrosion resistance	Hygienic favorably				Stability of oxide		corrosion resistance
							Ability to being porous	Biocompatibility					Mutagenic	Sensitivity	Carcinogen	Toxicity	Erosion resistance	Oxidation time	
1	X2CrNiMo17133	0.0005	0.0881				0.0005			0.0005							0.0005		
			0.5538	1.0000	1.0000	0.0881	0.0005		1.0000	1.0000	0.4458	0.0005	0.6977				0.0005		0.0833
							1.0000	0.0005					1.0000	0.7517	0.8964	0.6977	1.0000	0.0005	
2	G-Co29Cr5Mo	0.0515	0.0515				0.1649			0.1649							0.1750		
			0.5274	0.5941	1.0000	0.0515	0.1649		1.0000	1.0000	0.6205	0.1750	0.1649				0.7995		0.1750
							1.0000	0.1649					1.0000	0.7247	0.9209	0.1649	1.0000	0.7995	
3	Co20Cr35Ni10Mo	0.0723	0.0723				0.1750			0.1750							0.1750		
			0.5255	0.3960	1.0000	0.0723	0.1750		1.0000	1.0000	0.6205	0.1750	0.2041				1.0000		0.1750
							1.0000	0.1750					1.0000	0.7386	0.7891	0.2041	1.0000	1.0000	
4	cp-Ti grade 1	0.1545	0.1545				0.6982			0.6982							0.6982		
			0.9844	0.3960	1.0000	0.1545	0.6982		1.0000	1.0000	1.0000	0.6982	0.7951				0.6982		1.0000
							1.0000	0.6982					1.0000	0.9495	0.8013	0.7951	1.0000	0.6982	
5	cp-Ti grade 2	0.1545	0.1545				0.6982			0.6982							0.6982		
			0.9844	0.3960	1.0000	0.1545	0.6982		1.0000	1.0000	1.0000	0.6982	0.7936				0.6982		1.0000
							1.0000	0.6982					1.0000	0.9494	0.8018	0.7936	1.0000	0.6982	
6	cp-Ti grade 3	0.1545	0.1545				0.6982			0.6982							0.6982		
			0.9844	0.3960	1.0000	0.1545	0.6982		1.0000	1.0000	1.0000	0.6982	0.7932				0.6982		1.0000
							1.0000	0.6982					1.0000	0.9494	0.8019	0.7932	1.0000	0.6982	
7	cp-Ti grade 4	0.1545	0.1545				0.6982			0.6982							0.6982		
			0.9844	0.3960	1.0000	0.1545	0.6982		1.0000	1.0000	1.0000	0.6982	0.7921				0.6982		1.0000
							1.0000	0.6982					1.0000	0.9493	0.8023	0.7921	1.0000	0.6982	
8	Ti6Al4V	0.1545	0.1545				0.7381			0.7381							0.7561		
			1.0000	0.9901	1.0000	0.1545	0.7381		1.0000	1.0000	1.0000	0.7561	0.7381				0.7561		0.8333
							1.0000	0.7381					1.0000	0.9007	0.8002	0.7381	1.0000	0.7561	
9	Ti5Al2.5Fe	0.1465	0.1465				0.1938			0.1938							0.1938		
			0.9955	0.8911	1.0000	0.1465	0.1938		1.0000	1.0000	1.0000	0.1938	0.7792				0.1938		1.0000
							1.0000	0.1938					1.0000	0.9361	0.8145	0.7792	1.0000	0.1938	
10	Ti6Al7Nb	0.1545	0.1545				0.7207			0.7207							1.0000		
			0.9801	0.8911	1.0000	0.1545	0.7207		1.0000	1.0000	1.0000	1.0000	0.7207				1.0000		1.0000
							1.0000	0.7207					1.0000	0.9310	0.8264	0.7207	1.0000	1.0000	
11	Ti30Ta	0.2429	0.2429				0.6000			0.6000							0.6250		
			1.0000	1.0000	1.0000	0.2429	0.6000		1.0000	1.0000	1.0000	0.6250	0.6000				0.6526		0.6250
							1.0000	0.6000					1.0000	0.9350	0.8570	0.6000	1.0000	0.6526	
12	Ti30Nb	0.2125	0.2125				0.6250			0.6250							0.6250		
			1.0000	1.0000	1.0000	0.2125	0.6250		1.0000	1.0000	1.0000	0.6250	0.6400				0.7143		0.6250
							1.0000	0.6250					1.0000	0.9350	0.8570	0.6400	1.0000	0.7143	

Table -7: Alloy price and alloy cheap degree [22, 23]

Alloy	Price (Pound / gram)	Cheap degree
X2CrNiMo17133	0.1886	1.0000
G-Co29Cr5Mo	0.4309	0.4365
Co20Cr35Ni10Mo	0.3474	0.5414
cp-Ti grade 1	0.1984	0.9483
cp-Ti grade 2	0.1979	0.9506
cp-Ti grade 3	0.1977	0.9516
cp-Ti grade 4	0.1973	0.9534
Ti6Al4V	0.2299	0.8182
Ti5Al2.5Fe	0.1887	0.9995
Ti6Al7Nb	0.2171	0.8665
Ti30Nb	0.2810	0.6694
Ti30Ta	0.6920	0.2718