



Design and characterization of a novel nickel-free cobalt-base alloy for intravascular stents



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ABSTRACT

Co-Cr-W-Ni alloy (L605) with high tensile strength is used in coronary stents. The thickness of individual strut of the stent is reduced which can decrease the stent restenosis rate. However, about 10% Ni element content in L605 is found to cause allergic reactions and pulmonary embolism, similar to the traditional 316L stainless steel. In this study, a novel nickel-free cobalt-base alloy Co-20Cr-12Fe-18Mn-2Mo-4W-N (wt%) was designed and fabricated in order to efficiently avoid the potential hazards of Ni element. Fe and Mn, essential elements of human body, were added in the alloy to substitute part of Co element. In comparison to L605 alloy, the tensile strength of the new alloy was higher than 1000 MPa while elongation was above 55%. The pitting potential of the new alloy was measured close to 1000 mV, also higher than that of L605 alloy. CCK-8 test indicated that the cytotoxicity of the new alloy is grade 1, reflecting that Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy has no cytotoxic effects. There was no significant difference in the apoptosis rates between Co-20Cr-12Fe-18Mn-2Mo-4W-N and L605 alloy. The newly developed cobalt-base alloy showed excellent mechanical, corrosion resistance and biological properties, which could make it a desirable material for future clinical investigations.

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1. Introduction

Coronary stent is regarded as one of the most well succeeded achievements in intervention cardiology. Stenosis after coronary stenting has been significantly reduced by the application of drug-eluting stent (DES). Polymer-based stent, especially the polylactic acid (PLA) material in the last decades, presents the highlighted research direction due to technology accumulation in polymers. However, the inherent drawback of this stent is its poor mechanical performance, which limits its use in complex lesions with narrowed indications [1, 2]. Metallic stents have been successfully employed in clinical applications. However, metallic stents are nonconductive to noninvasive imaging diagnostic tools, such as magnetic resonance imaging or multi-slice computed tomography. Moreover, vascular stent implant could result in restenosis and thrombosis like complications [3]. Stent restenosis (SR) rate was increased by stent thromboses caused by endothelial dysfunction or latency [4,5]. Mechanistically, this pathology is related to the proliferation and migration of vascular smooth muscle cells (VSMCs) and over-expression of extracellular matrix proteins caused by stent

implantation through the activation of multiple pathways, such as Notch1, Wnt, transforming growth factor (TGF)- β /bone morphogenetic protein (BMP), Hedgehog and cytokine/chemokine-related inflammatory signaling pathways [6–10].

Co-Cr-W-Ni alloy (L605) with high tensile strength is used. The thickness of individual strut of these stents is reduced owing to their high strength compared to the stents made of 316L. Consequently, the contact area of the stents with VSMCs was reduced resulting in the decrease of stent restenosis rate. However, the content of Ni element in L605 is about 10%, similar to the conventional 316 L stainless steel. It has been proved that nickel element causes allergic reactions, induces embolism [11–15] and results in cancer [16]. The influence of allergic reaction on the stent restenosis caused by Ni ion is always controversial [17–20]. It was also found that Ni, Cr and Mo ions, especially Ni ion in stainless steel could cause allergic reactions which aggravate inflammation and increase the stent restenosis rate [18]. Considering the potentially detrimental effects of nickel on the human body, researchers suggested to restrict nickel content in the biomedical metals [21]. Due to the cost of nickel and the prospected possibility of allergic reactions caused by the element, a novel nickel-free cobalt-base alloy (Co-20Cr-12Fe-18Mn-2Mo-4W-N) to be used as an intravascular stent material is designed and fabricated in the present study. The mechanical properties, corrosion resistance, and cytotoxicity of the new implant material are comprehensively investigated with comparison to L605 alloy.

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2. Material and methods

2.1. Material preparations

The nickel-free Co based alloy (Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy) was fabricated by nitrogen gas alloying and adding manganese nitride in a 25 kg vacuum melting furnace. The alloy was forged, rolled, machined to the dimension of 400 mm × 100 mm × 30 mm and then treated at 1150 °C for 1 h followed by quenching in water. Commercial L605 alloy was provided by Kanghui Medical, China. The chemical composition of Co based and L605 alloy is listed in Table 1.

2.2. Microstructure and phase composition

The microstructure of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy was observed using an optical microscope (OM, BX60M, Olympus, Tokyo, Japan). The phase composition of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy was examined by an X-ray diffractometer (XRD, Philips PW1700) using Cu K α .

2.3. Mechanical properties

The tensile test specimens were prepared by wire-electrode cutting machine and lathe. Prior to test, all the specimens were ground by SiC paper to remove the surface ripples and flash to avoid notch effect. The tensile test was performed at room temperature on a universal testing machine (Instron, 5582, USA), with a tensile rate of 0.45 mm/min using standard samples (L605 alloy and Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy) of M10 × Φ 5 mm. An average value of three specimens was taken for each material. An automatic extensometer with a gauge length of 25 mm was used to achieve the strain values in the test.

2.4. Electrochemical test

To evaluate the corrosion resistance of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy, the specimens were cut in sheets with dimension of 10 mm × 10 mm × 12 mm, mounted in epoxy resin with an exposed area of 1 cm² and polished with SiC abrasive papers up to 2000 grits. Corrosion behavior of the samples was evaluated by electrochemical tests using a 273 EG&G PARC potentiostat-galvanostat in Hank's solution at 37 °C. The composition of Hank's solution was as follows: NaCl 8 g/L, KCl 0.40 g/L, MgSO₄·7H₂O 0.10 g/L, MgCl₂·6H₂O 0.10 g/L, CaCl₂/0.14 g/L, Na₂HPO₄·2H₂O 0.06 g/L, KH₂PO₄ 0.06 g/L, glucose 1 g/L, NaHCO₃ 0.35 g/L. The experimental set-up was composed of a conventional three electrode cell containing the working electrode, a saturated calomel electrode (SCE) and a platinum sheet as the counter electrode. For the potentio-dynamic polarization measurement, the potential was swept from 100 mV below the anode corrosion potential at a scan rate of 0.5 mV/s. The electrochemical impedance spectroscopy (EIS) measurement was performed using a lock-in amplifier (Model 5210, EG & Instrument) coupled to a Potentiostat-Galvanostat System. EIS tests were operated at open circuit potential, while the AC voltage was 5 mV at a frequency range of 0.01 Hz to 100 kHz. The EIS results were analyzed by fitting the experimental impedance data with equivalent circuit model. The equivalent circuit parameters were calculated by fitting the impedance function to the measured spectra by the ZsimpWin3.2 software for convenience.

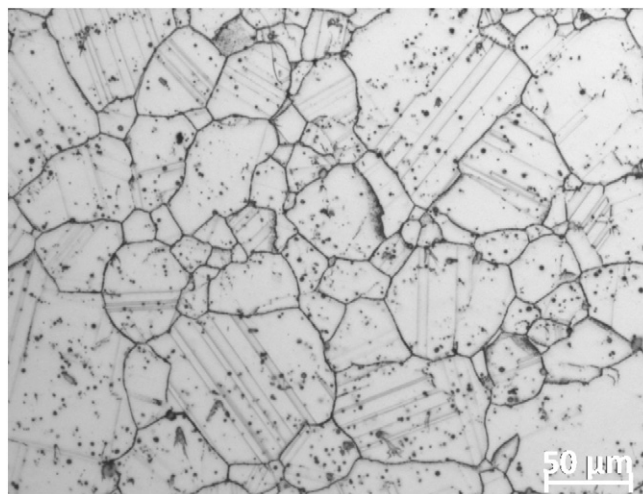


Fig. 1. The microstructure of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy.

2.5. Cell culture and cytotoxicity evaluation

L-929 murine fibroblast cells, provided by the Laboratory Center, China Medical University, Shenyang, were cultured in RPMI 1640 medium with 10% FBS and maintained in an incubator at 37 °C, 5% CO₂. CCK-8 test was performed to evaluate the cytotoxicity of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy in comparison with that of L605 alloy. The detailed test method can be found in our previous study [22]. The cytotoxicity was performed by an indirect contact way. The extraction media were prepared using RPMI 1640 medium with the surface area/extraction medium ratio of 3 cm²/mL in a humidified atmosphere of 5% CO₂ at 37 °C for 72 h. The control groups involved a DMEM medium as the negative control. Cells were seeded in 96-well plates (Corning, NY) at a density of 5 × 10⁴ cells/100 μ L per well and incubated for 24 h to allow attachment. The medium was then replaced by 100 μ L of extraction medium. After the cells were incubated in a humidified atmosphere of 5% CO₂ at 37 °C for 24, 48, and 72 h, respectively, the 96-well culture plates were observed under an optical microscope. The absorbance of the samples was detected at 450 nm using the CCK-8 assay after the cells were

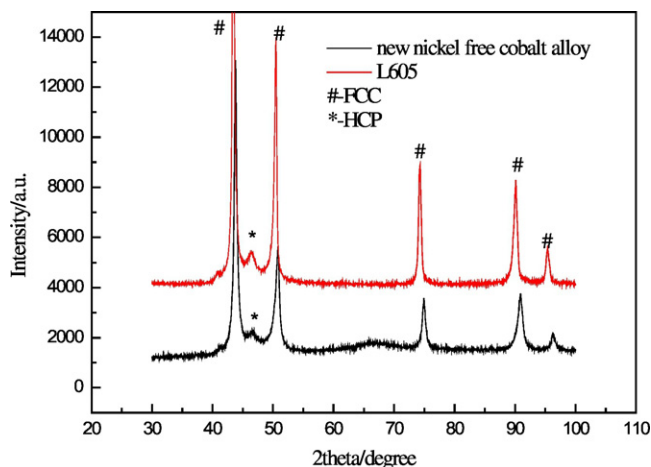


Fig. 2. The XRD patterns of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy.

Table 1

The chemical composition of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy and L605 alloy (wt%).

Co based alloy	C	Cr	Mn	N	Mo	Fe	W	Cu	Ni	Co
Co-20Cr-12Fe-18Mn-2Mo-4W-N	0.027	20.24	18.32	0.41	1.78	11.28	4.54	1.41	0.1	Bal.
L605	0.12	19.33	1.55			1.85	15.1		8.67	Bal.

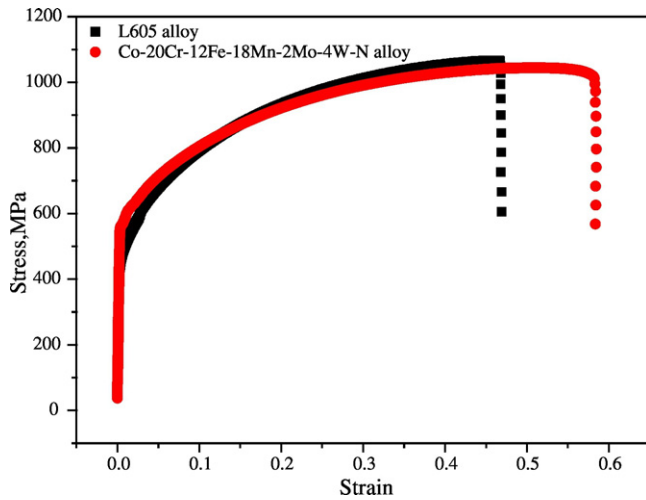


Fig. 3. Typical tensile stress-strain curves of L605 alloy and Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy.

cultured for 24–72 h. Relative growth rate (RGR) was calculated by the following equation: $\text{RGR} (\%) = (\text{OD value of the experimental group} / \text{OD value of the negative control group}) \times 100$. The cytotoxicity of the samples was evaluated by the criteria according to The United States Pharmacopeia [23].

2.6. Cell adhesion

L929 cells were cultured in RPMI1640 medium containing 100 IU/mL penicillin, 100 $\mu\text{g/mL}$ streptomycin sulphate and 10% (vol/vol) fetal bovine serum (FBS). Then, L929 cells were incubated at 37 °C with 5% CO_2 in a humidified chamber. To investigate the earlier cell adhesion behavior on surface of the alloys, 12-well plates were used. Cell suspension was seeded on L605 and Co-20Cr-12Fe-18Mn-2Mo-4W-N samples as well as the as-rolled pure titanium samples (control group) at a cell density of 1×10^5 cell/ μL . After 3 days of incubation, the culture media was removed. The samples were then fixed with 2.5% glutaraldehyde solution at 4 °C for 4 h and rinsed 3 times with PBS, followed by dehydration in a gradient ethanol/distilled water mixture (30%, 50%, 75%, 95%, 100%) for 10 min and dried in the air. Afterwards, the samples were observed using a scanning electron microscopy (SEM, Hitachi S-3400N).

2.7. Flow cytometry

Extracts were prepared using RPMI 1640 medium supplemented with 10% FBS as the extraction medium with the surface area of extraction medium ratio 1.25 mL/ cm^2 in a humidified atmosphere with 5% CO_2 , 37 °C for 72 h. L929 cells were seeded in 6-well plates (Corning, NY) at 1×10^6 cells/mL medium in each well and incubated for 24 h to allow attachment. Then the medium was replaced with 2 mL of extracts and incubated for 48 h. Cell apoptosis was performed by Flow Cytometry (FACS, FACSCalibur, Becton Dickinson, USA) following the instruction of Annexin V-FITC/PI Apoptosis Detection Kit (Biossea Biotechnology Co., Ltd., China) at a provocation wavelength of 488 nm. The results were analyzed by Modfit LT3.0 Software. Early apoptotic cells were localized in the lower right quadrant of a dot-plot graph. The test method in detail can be found in our previous study [22,24].

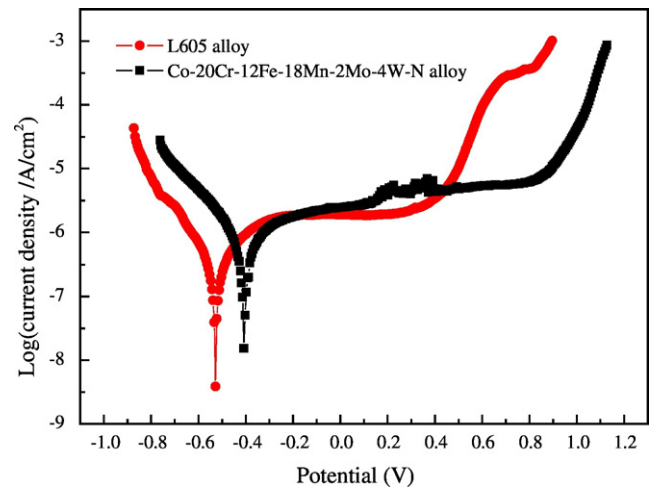


Fig. 4. Potentiodynamic curves of new nickel-free cobalt-base alloy Co-20Cr-12Fe-18Mn-2Mo-4W-N and L605 alloy.

3. Results and discussion

3.1. Microstructure and XRD characterization

Fig. 1 shows the microstructure of the Co-20Cr-12Fe-18Mn-2Mo-4 W-N alloy. XRD patterns shown in Fig. 2 indicates that L605 consists of more ϵ (hexagonal close-packed, hcp) matrix phase whereas Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy consists of γ (face-centered cubic, fcc) matrix phase and trace amount of ϵ matrix phase. The newly developed nickel-free Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy has a high Fe and Mn content, but low W and a negligible Ni (0.10%) content while 0.4% N element is added to substitute C element. The Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy is non-ferromagnetic with relatively stable austenitic phase, which is the preferential requirement for orthopedic implant materials [21].

3.2. Mechanical test

The typical tensile stress-strain curves of L605 and Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy are shown in Fig. 3. Table 2 summaries the mechanical properties under uniaxial tension for all specimens, obtained from the stress-strain curves. The specimens of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy have higher yield strength and ductility as compared to L605 alloy while the tensile strength of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy is similar to L605 alloy. The Young's Modulus of the Co-20Cr-12Fe-18Mn-2Mo-4W-N and L605 alloy is around 189 and 196 GPa, respectively. The similar mechanical properties were also reported by other literatures. It was reported that the yield strength (YS) and the ultimate tensile strength (UTS) of the Co-base alloy were about 423 MPa and 576 MPa while the elongation was about 10.7% [25]. Ling Ren et al. proved that the tensile strength, yield strength and elongation are 1084 ± 12.56 MPa, 565 ± 5.68 MPa and $26.5 \pm 1.2\%$, respectively [26]. For Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy, inexpensive Fe and Mn elements are added to substitute Ni element and a portion of Co element which lowered the cost of alloy. However, the mechanical properties of the alloy were remained unaffected, while compare to L605 alloy, the ductility of the new alloy is improved. The mechanical improvement of the new alloy is due to the reduction of C

Table 2

Mechanical properties of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy and L605 alloy.

Mechanical properties	Yield strength ($\sigma_{0.2}$ /MPa)	Tensile strength (σ_b /MPa)	Young's modulus (GPa)	Elongation (%)	Reduction of area (%)
Co-20Cr-12Fe-18Mn-2Mo-4W-N	577.3 ± 41.0	1031.1 ± 11.5	189.0 ± 5.6	55.8 ± 2.9	40.5 ± 4.7
L605	481.7 ± 48.3	1072.7 ± 12.2	196.0 ± 7.3	46.8 ± 0.9	34.0 ± 1.4

Table 3

Results of electrochemical parameters of the Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy and L605 alloy.

Material	$E_{\text{corr}}/\text{mV}$	$I_{\text{corr}}/\mu\text{A cm}^{-2}$	B_a	B_c
Co-20Cr-12Fe-18Mn-2Mo-4W-N	−407	38.89	0.27(mV)	0.087(mV)
L605	−528	32.53	0.24(mV)	0.13(mV)

and W elements, which prevents the formation of brittle phases. The newly developed cobalt based Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy shows a higher strength than L605 alloy, allowing thinner struts while maintaining enough radial strength.

Though the content of C and W elements are reduced, N element is added. N (nitrogen) element has been additionally added. Nitrogen is known to be a strong austenite stabilizer, which can lead to solid solution strengthening [21,27,28] and improvement of the yield and ultimate tensile strengths of the alloy. Solid solution strengthening was obtained through the existence of N and C atoms in the form of interstitial atom [29]. Nitrogen is also known to reduce the Stacking Fault Energy (SFE) of austenitic stainless steels, especially at low temperature [21,28] resulting in a large number of beneficial effects on mechanical properties such as strength, impact and fracture toughness. Mn is also an alloy element substituting Ni, which also plays the role of enhancing the nitrogen content [30]. The complete absence of Ni in HNS with relatively low chromium and molybdenum contents leads to reduced manufacturing costs [31].

Table 4

Fitting results of EIS data for Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy and L605 alloy.

Material	$R_s/\Omega \text{ cm}^2$	$R_{ct}/\times 10^4 \Omega \text{ cm}^2$	$\text{CPE}/\mu \text{ cm}^{-2}$	n
Co-20Cr-12Fe-18Mn-2Mo-4W-N	6.68	8.91	0.96	0.89
L605	9.45	4.59	1.14	0.88

3.3. Electrochemical test

Potential dynamic polarization curves of Co-20Cr-12Fe-18Mn-2Mo-4W-N and L605 alloy are plotted in Fig. 4. The I_{corr} (corrosion current density), E_{corr} (corrosion potential), B_a (Tafel slope of the partial anodic processes) and B_c (Tafel slope of the partial cathodic processes) were determined using the curve-fitting routine of the corrosion software and listed in Table 3. The high value of B_a in comparison with the values of B_c for both of the alloys indicates an anodic control in the corrosion process [32]. It can be found that the corrosion current density (I_{corr}) of the both alloys is similar. However, the corrosion potential (E_{corr}) of the new Co based alloy is increased to −407 mV while that of L605 alloy is −528 mV, respectively.

The EIS spectra and fitting results of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy and L605 alloy measured in Hank's solution are presented in Nyquist and Bode plots in Fig. 5. One capacitance loop is observed in Nyquist plot indicating the existence of one time constant. The electrical equivalent circuits shown in Fig. 5b is used to fit the test data and the fitting results are shown in Table 4. From Fig. 5a, it can be observed that the change of impedance curve is not relative with that of frequency in the range of high frequency (10^4 – 10^5 Hz). The phase angle at high frequency is closed to 0° , which corresponds to the typical resistance reaction describing the resistance of the solution between the working electrode and SCE. In the low frequency range (10^1 – 10^3 Hz), impedance is linear with frequency. The phase angle is closed to -80° , which corresponds to the capacitance performance between the working electrode and electrolyte. The capacitance loop diameter and charge-transfer resistance (R_{ct}) of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy are larger than those of L605 alloy, reflecting the better corrosion resistance of this newly developed Ni free Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy.

The above results reveal the obvious improvement in the corrosion resistance of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy as compared to L605 alloy. Nitrogen is considered to be an important alloying addition to austenitic stainless steel in terms of corrosion resistance [21,33,34]. It was reported that the addition of nitrogen in stainless steels could considerably increase the resistance toward pitting, crevice, intergranular and stress corrosion cracking in some media, especially in environments containing chloride ions [34–40]. As for the N contained stainless steels, the empirical formulas of pitting corrosion is [41]: $\text{PREN} (\text{pitting resistance equivalent number}) \approx \% \text{Cr} + 3.3\% \text{Mo} + (13-37)\% \text{N} + 4.5(\% \text{Mo}) (\% \text{N})$, indicating that N element plays an important role in pitting corrosion resistance. Thus, the improvement in corrosion resistance properties of newly developed Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy is directly related to the 0.41% N.

3.4. Biocompatibility studies

3.4.1. Cytotoxicity test

Table 5 shows the optical density of L-929 cells in the extraction medium of the test samples measured by CCK-8 assay. The OD value of the three groups increased gradually with the culture time, reflecting that the cells grew well and had good proliferative capacity. The relative growth rate (RGR) of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy groups was assessed. The cell toxicity grade (CTG) was obtained by the relationship between RGR and CTG. RGR is calculated as follows: $\text{RGR} = \text{OD}_e / \text{OD}_c \times 100\%$, where OD_e is the average OD value of the experimental, and OD_c is the average OD value of the negative control group. The RGR and CTG results are listed in Table 6. After 24 h incubation, the

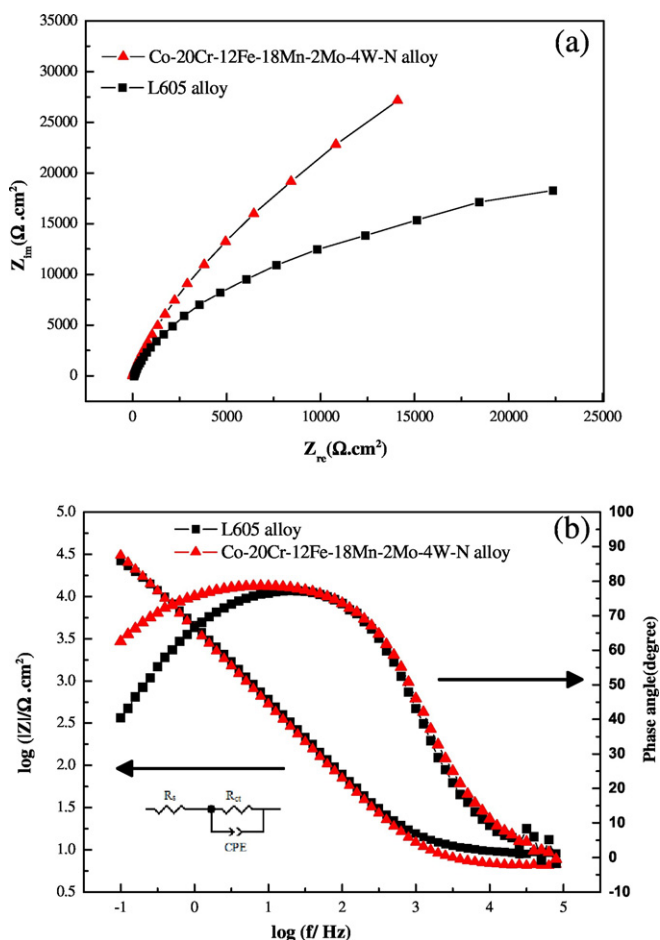


Fig. 5. EIS of new cobalt-base alloy Co-20Cr-12Fe-18Mn-2Mo-4W-N and L605 alloy: (a) Nyquist plots and (b) Bode plots.

Table 5The optical density of L929 cells in extraction solution at different time points by the CCK8 test, $n = 9$; $P < 0.05$.

Culture time	Negative control group	L605	Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy
24 h	0.359 ± 0.000158	0.350 ± 0.000501	0.373 ± 0.000181
48 h	0.521 ± 0.000279	0.505 ± 0.000692	0.519 ± 0.000635
72 h	0.975 ± 0.00317	0.916 ± 0.00268	0.888 ± 0.00177

results show that CTG of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy is grade 0, which is demonstrated as non-cytotoxic according to the regulation in Table 6. The CTG of Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy is grade 1 at 48 h and 72 h, which displays non-cytotoxicity. According to the evaluation criteria of cytotoxicity from The United States Pharmacopeia, the new Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy has non-cytotoxic effects.

Fig. 6 shows the morphology of L929 cells cultured on L605, Co-20Cr-12Fe-18Mn-2Mo-4W-N and pure titanium samples for 3 days. For all the samples, the cells grew well in shape of spindle. Cells cultured on all the samples were observed to exhibit spreading stacked with a well-developed cytoskeleton. No significant difference was found for the three different samples in case of cell adhesion.

3.4.2. Apoptosis rates of L929 cells

The scatter plot charts show that there are little early apoptotic cells, as shown in the lower right quadrants in Fig. 7, in the three groups. The early apoptosis rate of the negative group (a), Co-20Cr-12Fe-18Mn-2Mo-4W-N group (b) and L605 group is 0.0%, 3.0%, 3.2%, respectively. There is no significant difference between Co-20Cr-12Fe-18Mn-2Mo-4W-N group and L605 group ($P > 0.05$). Flow cytometry is now a widely used method for analyzing expression of cell surface and intracellular molecules [42–44]. It is performed to detect the apoptosis of L-929 cells. Programmed cell death is called apoptosis which is one kind of self ordered death. The process of apoptosis is controlled by genes, which is important to keep the stability of intracellular environment [45,46]. The results revealed that Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy is as safe as the conventional L605 alloy to be used for coronary stent.

The newly developed nickel-free Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy has a high Fe and Mn content, but low W and a negligible Ni (0.10%) content while 0.4% N element is added to substitute C element. Menghua Li et al. showed that the high nitrogen nickel-free austenitic stainless steel is a promising new biomedical material for coronary stent development [47]. It was demonstrated that divalent manganese (Mn^{2+}) ions substantially increased the affinity of integrins for binding to a bioactive surface, as transmembrane adhesion receptors connected the actin cytoskeleton to the extracellular matrix, and thus promoted a better functionalization of the prosthetic surface [48]. Mn-doped β -TCP showed higher potential for proliferation and better viability when tested in osteoprogenitor cell culture than those with a lower Mn content [49]. In vitro bioactivity test in simulated body fluid demonstrated a good osteoblast proliferation and spreading on Mn-doped glasses and most of all that the Mn-doping can promote the expression of alkaline phosphatase (ALP) and some bone morphogenetic proteins (BMPs) [50].

Table 6

The RGR and CTG results of L929 cells at different time points.

Group	24 h		48 h		72 h	
	RGR(%)	CTG	RGR(%)	CTG	RGR(%)	CTG
Negative control group	100	0	100	0	100	0
L605	97.5	1	96.9	1	93.9	1
Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy	103	0	99.6	1	91.1	1

4. Conclusion

A new nickel-free cobalt-base alloy for intravascular stent was designed and characterized. The nickel free austenitic stainless steel contains both N and Mn elements to stabilize the austenitic

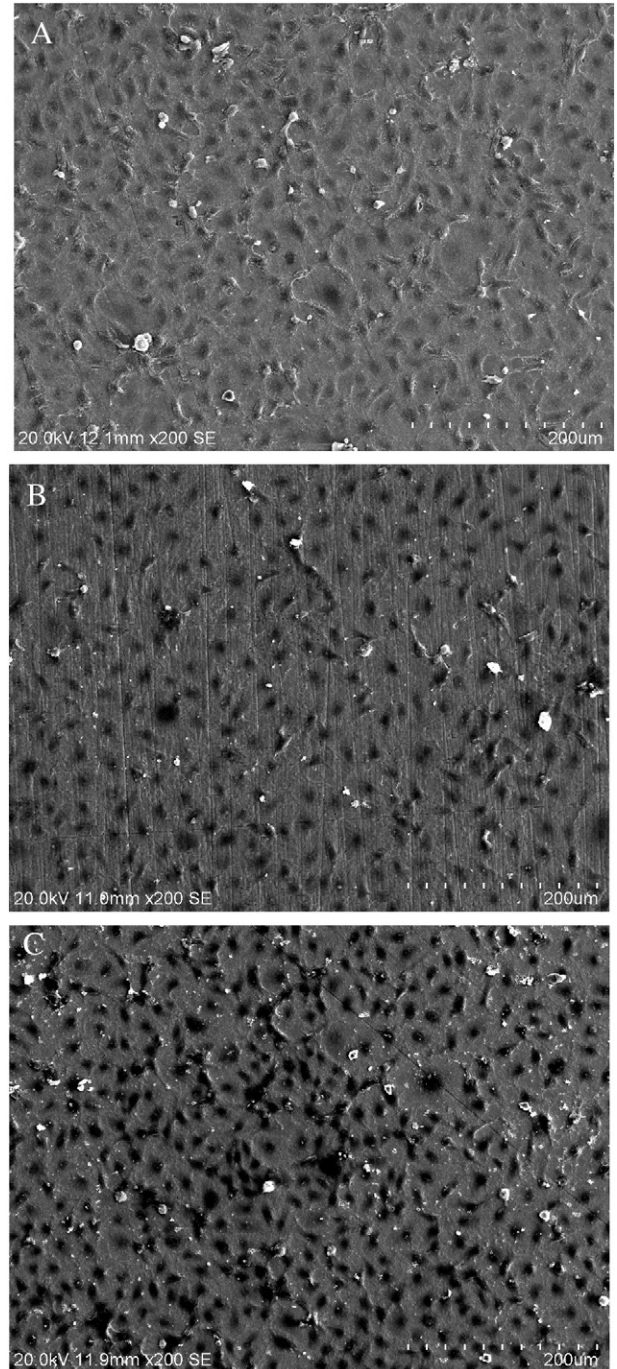


Fig. 6. Cell morphology on different samples after 3 days' culture. A: L605; B: Co-20Cr-12Fe-18Mn-2Mo-4W-N; C: pure titanium.

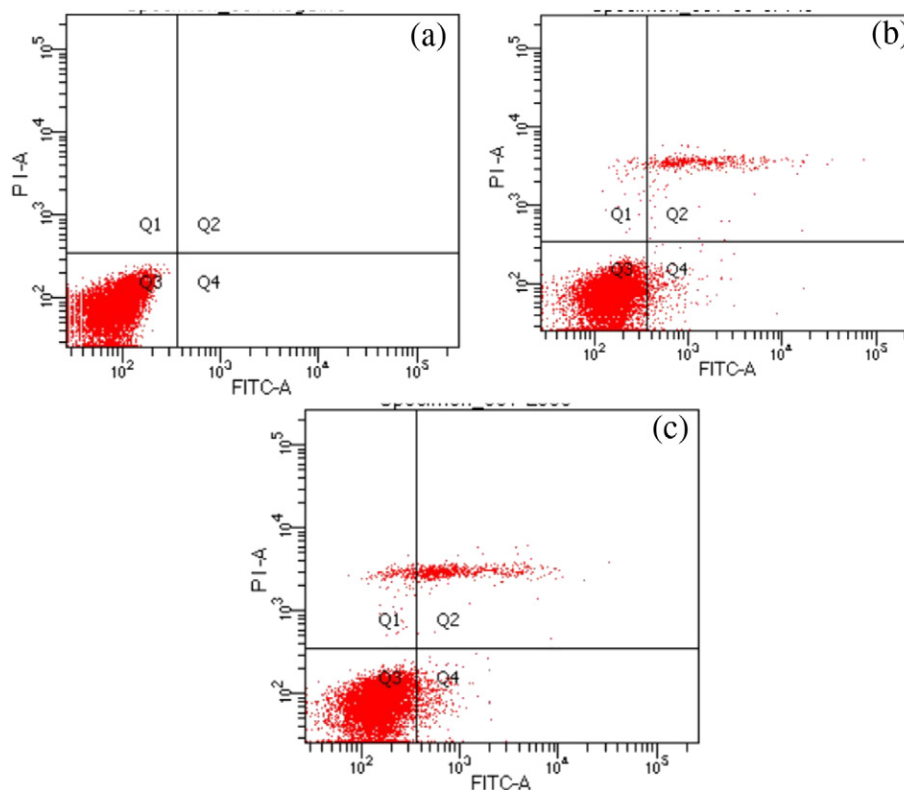


Fig. 7. Flow cytometric analysis of early apoptosis rates detected by Annexin V-FITC/PI apoptosis detection method: (a) the negative group; (b) Co-20Cr-12Fe-18Mn-2Mo-4W-N group; (c) L605 group.

microstructure. The N element was added to improve the strength and corrosion resistance of newly developed alloy. Fe and Mn elements were added in the alloy to substitute part of Co element to reduce manufacturing costs. New cobalt-base Co-20Cr-12Fe-18Mn-2Mo-4W-N alloy demonstrated excellent mechanical, corrosion resistance and biological properties, showing a promise as a novel biomedical material for intravascular stents.

Acknowledgments

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