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Posted Date: 11 December 2025

doi: 10.20944/preprints202512.0895.v1

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Article

Electrochemical Interactions of Titanium and Cobalt-Chromium-Molybdenum Alloy in Different Solutions

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Abstract

Pure titanium (Ti) and its alloys are the "gold standard" for dental implants due to their stable titanium dioxide passive film providing excellent corrosion resistance in physiological environments. This study examined electrochemical interactions between Ti and cobalt-chromium-molybdenum alloy (CoCrMo), and between a novel Ti-Magnesium composite (BIACOM TiMg) and CoCrMo, when immersed in everyday solutions representing beverage or oral hygiene exposure. Test solutions included Coca-Cola®, lemon juice, Elmex® fluoride gel, Listerine® Cool Mint, and Sensodyne® fluoride paste. The immersion experiment paired Ti sticks with CoCrMo sticks, then BIACOM TiMg composite with CoCrMo sticks, with three measurements per configuration. Coca-Cola immersion increased electrochemical potential to ~983 mV for BIACOM TiMg and ~830 mV for CP4 titanium. Significant potential increases occurred in Elmex fluoride gel for both materials. Listerine Cool Mint and Sensodyne Fluoride exposures showed electrochemical interactions exceeding 200 mV. Marked differences in corrosion stability between CP4 titanium and BIACOM TiMg composite were confirmed. Findings indicate that material pairing and electrolyte environment significantly influence galvanic and corrosion behavior, with Ti-Mg composite showing higher susceptibility than CP4 titanium under tested conditions, impacting dental/biomedical material selection in oral environments.

Keywords: CoCrMo; CP4 titanium; BIACOM TiMg composite; electrochemical interaction

1. Introduction

Metals and their alloys have been used extensively in dentistry due to their favorable properties [1]. Titanium (Ti) is the most used material in implantoprosthodontics because of its superior osseointegration and passivation properties [2]. In prosthetic treatment, Ti is used for abutments, similar to the fixtures. However, the final restoration is crafted from a different metal that offers superior castability [3]. Galvanic corrosion commonly occurs in the oral cavity when a Ti dental implant is coupled with a suprastructure made of a different metal alloy, creating differing electrochemical potentials in the presence of an electrolyte, such as saliva or bodily fluids [4]. The acidic environment and high fluoride concentrations, commonly found in oral care products, such as toothpastes and fluoride gels, further exacerbate the risk of corrosion [5]. This process results in the formation of a galvanic cell, in which one metal acts as the anode and the other as the cathode [6]. A

significant challenge in the longevity and success of Ti-based dental implants is material corrosion, particularly galvanic and pitting corrosion [7].

Previous studies have shown a correlation between corrosion in a galvanic system composed of a Ti implant and a superstructure made of a different alloy and the subsequent failure of implantoprosthesis therapy [8]. The galvanic corrosion of implant-suprastructure systems may cause biological effects arising from the dissolution of alloy components, including local inflammatory responses, allergic reactions, or systemic toxicity [9]. Moreover, anodic materials corrode rapidly, leading to structural weakening over time, compromising the integrity of the dental implant system and affecting its durability and functionality [10]. In addition, the electrical current generated by the galvanic coupling can influence bone metabolism, potentially leading to bone resorption at the implant site [11]. In this context, the interaction between Ti-based materials and cobalt-chromium-molybdenum (CoCrMo) alloys, particularly when used in close proximity or as part of multi-component prosthetic systems, warrants careful investigation. The galvanic potential difference between different alloy pairings can influence the magnitude of electrochemical currents and dictate corrosion behavior. Previous studies have demonstrated that coupling Ti and CoCrMo may produce measurable galvanic currents under specific conditions [6].

In recent years, novel composite materials, such as Ti–Magnesium (Ti–Mg) composites (BIACOM TiMg), have emerged, seeking to combine favorable mechanical and biological properties with lower stiffness or improved bioactivity [12]. However, their electrochemical stability when immersed in everyday fluid environments, such as common beverages or oral hygiene solutions, remains unclear. Therefore, in this study, we aimed to examine whether electrochemical interactions occur between Ti and CoCrMo alloy, and between a Ti–Mg composite (BIACOM TiMg) and CoCrMo alloy, when immersed in a range of everyday solutions representing beverage or oral-hygiene exposure. We sought to quantify the galvanic and corrosion-related behavior of these material pairings and compare their relative stability by performing controlled immersion experiments and measuring electrical potentials in realistic fluid media (including Coca-Cola®, lemon juice, fluoride gel, mouth rinse, and fluoride dental paste). Our findings have implications for the selection of dental or biomedical material combinations in contact or proximity within the oral environment, by highlighting differences in corrosion susceptibility under conditions that mimic real-world exposure.

The null hypothesis tested in this study was that there is no difference in the electrical potential between the tested materials when immersed in different fluid media.

2. Materials and Methods

2.1. Sample Preparation

The Research Ethics Committee of the Dental School, University of Zagreb, approved the study (approval number: 05-PA-30-X-9/2022).

In this study, three distinct specimen types were employed:

- A cast rod of the CoCrMo alloy (commercial product: Heraenium P, Kulzer Mitsui Chemicals Group, Hanau, Germany) with a diameter of 1 mm and a length of 18 mm. The chemical composition of the alloy was: 59.0 wt% Co, 25.0 wt% Cr, 4.0 wt% Mo, 10.0 wt% Tungsten, 1.0 wt% Silicon, 0.8 wt% Manganese, and 0.2 wt% Nitrogen.
- A rod of commercially pure Ti (CP4 grade) with dimensions 2 mm × 2 mm × 10 mm produced by laser-sintering powder metallurgy at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb.
- A metal composite of CP-Ti and magnesium (BIACOM TiMg) with a diameter of 5 mm and a length of 11 mm, manufactured by low-temperature cold extrusion of Ti and Mg powders at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb.

The chemical compositions of the investigated alloys were determined by X-ray fluorescence spectroscopy using an Olympus Innov-X system (Woburn, MA, USA).

2.2. Electrode Assembly

In the first measurement phase, the CP4 Ti rod served as one electrode while the CoCrMo rod served as the counter-electrode. In the second phase, the BIACOM TiMg composite rod functioned as one electrode, again paired with the CoCrMo rod as the counter-electrode. The electrodes were mounted within a silicone clamp made from addition-curing putty-consistency silicone (3M ESPE Express STD firmer set putty, 3M Deutschland, Neuss, Germany). The inter-electrode spacing was sealed with a low-viscosity addition-curing silicone (3M ESPE Express Light Body fast set, 3M ESPE, St. Paul, MN, USA) to isolate the exposed surfaces and define the electrolyte interface (Figure 1).

After each immersion measurement, the electrodes were rinsed in tap water, dried, then immersed in a hypotonic solution (Aqua pro injectione, HZTM, Zagreb, Croatia), and dried with isopropanol (Kontakt IPA plus, AG Termopasty, Sokoły, Poland). Finally, the rods were allowed to air-dry completely before the next measurement series.

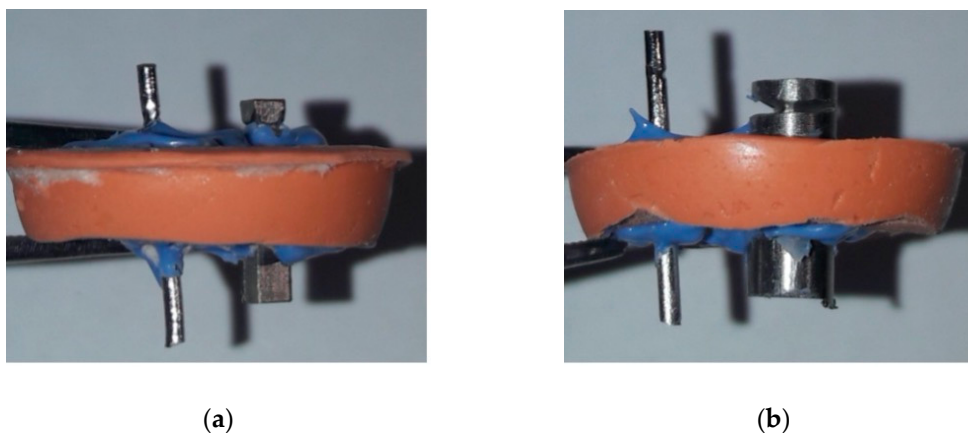


Figure 1. The electrodes were secured using a silicone holder made of additional silicone, and the gap was additionally sealed with a very low-viscosity addition silicone: (a) CoCrMo alloy and Ti rod (b) CoCrMo alloy and Ti alloy.

2.3. Solutions

The solutions used in the immersion experiments were (Figure 2):

- Coca-Cola® (Coca-Cola Hrvatska, Zagreb, Croatia)
- Freshly squeezed lemon juice
- Elmex® fluoride gel (CP GABA GmbH, Hamburg, Germany)
- Listerine® Cool Mint mouth-rinse (Johnson & Johnson, New Brunswick, NJ, USA)
- Sensodyne® Fluoride toothpaste (GSK, London, UK)

Each solution was placed in surplus quantities into a silicone vessel to ensure that the entire sample was fully submerged during measurement.



Figure 2. The different test solutions used in the immersion experiments: Coca-Cola®, freshly squeezed lemon juice, Elmex® fluoride gel, Listerine® Cool Mint mouth rinse, and Sensodyne® Fluoride toothpaste.

2.4. Measurement of Electrochemical Potentials

All measurements were conducted at the Department of Electronic Systems and Information Processing, Faculty of Electrical Engineering and Computing, University of Zagreb. For each immersion solution, three independent measurements, each lasting 3 min were performed. The experiment was performed in two phases: in the first phase, one electrode consisted of a commercially pure Ti (CP4) rod and the other electrode of a CoCrMo alloy rod; in the second phase, one electrode was the BIACOM TiMg composite rod, and the other was the CoCrMo alloy rod. The electrodes were connected via electrical clamps to a digital multimeter (Fluke 45, Fluke Europe, Eindhoven, The Netherlands), which transferred sampled data to a personal computer (Figure 3). A custom graphical interface developed in MATLAB was used to visualize, analyze, and process the recorded potential signals.

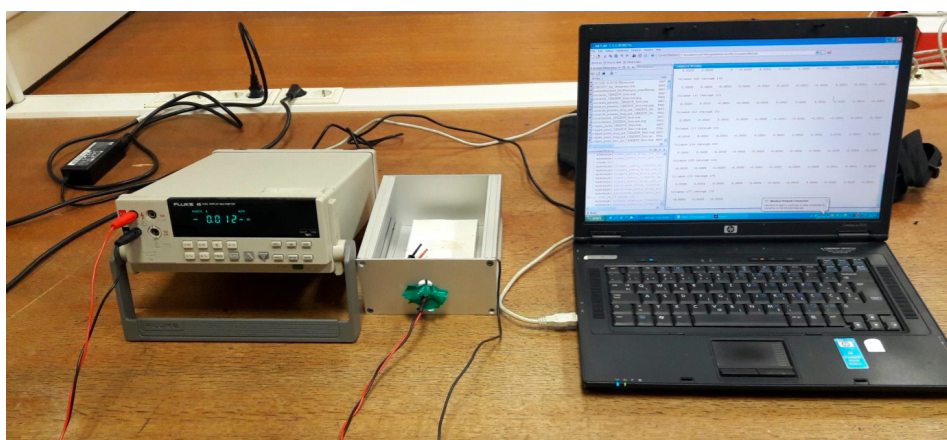


Figure 3. Experimental setup and measurement procedure. The electrodes (Ti or TiMg composite vs. CoCrMo) were immersed in different solutions, and their potentials were recorded over three independent 3-minute runs using a Fluke 45 multimeter connected to a computer.

2.5. Statistical Data Processing

Voltage levels were recorded every second and the values were saved in a .mat file using a script written in MATLAB. The maximum and minimum values were selected from the 180 collected data points. When selecting the minimum value, the first few seconds were ignored while the electrodes were still being immersed in the electrolyte. The range was calculated as the difference between the maximum and minimum values to describe the dynamics of the electrolyte behavior.

$$\Delta U = U_{max} - U_{min}$$

The geometric mean was calculated for all three parameters to obtain an average value characteristic of each electrolyte and electrode pair. The geometric mean was calculated using the following formula:

$$U = \sqrt[3]{U_1 * U_2 * U_3}$$

3. Results

3.1. X-Ray Fluorescence Spectroscopy

The chemical compositions of the investigated alloys were determined by X-ray fluorescence spectroscopy (Olympus Innov-X system). The Ti-based material consisted predominantly of Ti with aluminium (Al) and vanadium (V) as the principal alloying elements, corresponding to a Ti-6Al-4V-type alloy, with iron present as a minor impurity (Table 1). The cobalt-based alloy was composed primarily of Co and Cr, with additions of Mo and tungsten, characteristic of a CoCrMo-based alloy commonly employed for biomedical and dental applications (Table 2).

Table 1. Elemental composition of the Ti-based alloy determined by X-ray fluorescence spectroscopy (wt %).

Element	wt %
Ti	90.34
Al	5.29
V	4.20
Fe	0.18

Table 2. Elemental composition of the CoCrMo alloy determined by X-ray fluorescence spectroscopy (wt%)

Element	wt %
Co	60.50
Cr	23.21
Mo	4.69
W	4.97
Al	6.62
P	0.02

3.2. Open-Circuit Potential Measurements

Open-circuit potential (OCP) measurements were performed to establish the intrinsic electrochemical nobility of each alloy before galvanic coupling and to assess the thermodynamic driving force for electrochemical interaction between Ti-based implants and CoCrMo alloys in oral-relevant environments (Figure 4). The OCP of individual Ti and CoCrMo specimens was recorded using a potentiostat controlled by SoftCorr III software, with the potential measured relative to a reference electrode under open-circuit conditions. Measurements were conducted for 1000 s to ensure stabilization of the surface passive films, particularly the TiO₂ layer on Ti and the Cr-rich oxide on CoCrMo. The stabilized OCP values obtained for the Ti-based and CoCrMo alloys served as a baseline for interpreting subsequent galvanic coupling experiments and corrosion behavior in the tested electrolytes (Table 4).

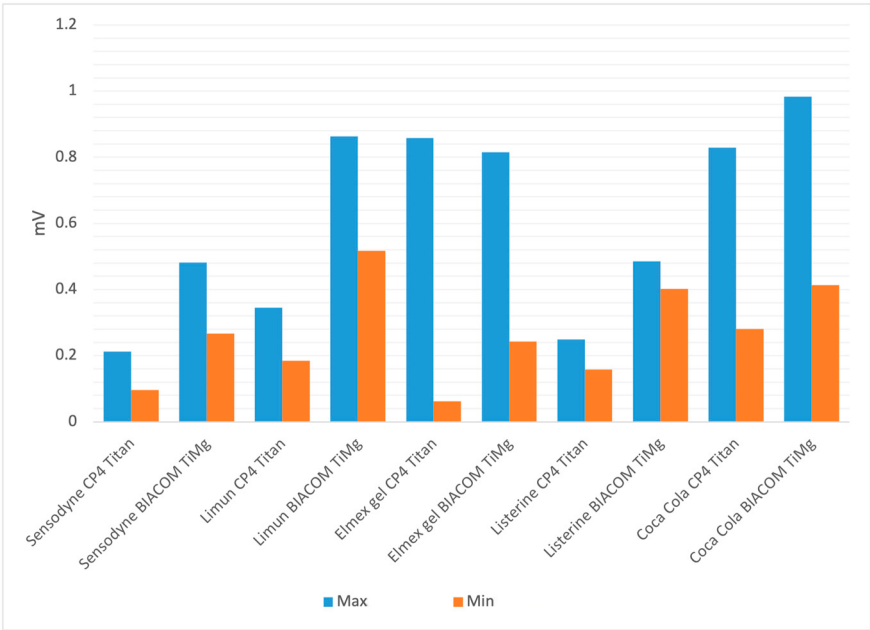


Figure 4. Graphical representation of the average minimum and maximum values, expressed in millivolts, for each experimental group.

Table 4. Average of the minimum to maximum range.

	Sensodyne CP4 Titan	Sensodyne BIACOM TiMg	Lemon juice CP4 Titan	Lemon juice BIACOM TiMg	Elmex gel CP4 Titan	Elmex gel BIACOM TiMg	Listerine CP4 Titan	Listerine BIACOM TiMg	Coca Cola CP4 Titan	Coca Cola BIACOM TiMg
Range	0.104	0.206	0.141	0.328	0.736	0.566	0.09	0.078	0.501	0.57

4. Discussion

This study demonstrates that the electrochemical behavior of Ti-based materials in contact with CoCrMo strongly depends on the surrounding electrolyte environment. Across all tested solutions, CP4 Ti and the BIACOM TiMg composite exhibited measurable galvanic interactions with CoCrMo, with the most pronounced potential increases occurring in Coca-Cola and Elmex fluoride gels.

Galvanic corrosion may occur when two metals with different electrode potentials are present in the oral cavity [13]. The presence of an electrolyte is required for electrochemical action, and in the oral environment this role is performed by saliva and the soft and hard tissues. A spontaneous flow of electrons occurs from the anode to the cathode. A potential difference arises at the interface between the metal and electrolyte. The metal is positive with respect to the electrolyte; therefore, the metal with the lower electrode potential is consumed. A metal that is less resistant to corrosion serves as the anode, while the more noble metal serves as the cathode. Oxidation (also called the anodic reaction) occurs at the anode; in this process, metal atoms change into ions and electrons. Concurrently, reduction (the cathodic reaction) occurs at the cathode, signifying consumption of electrons [14].

Corrosion dynamics depend on several factors. Beyond the intrinsic properties of the metal, they depend on its interaction with the surrounding environment [6]. In addition, the conditions in the oral cavity vary. When eating, the temperature may increase from 0 °C to 70 °C, the pH may vary from about 2 to 11, and electrolyte concentration can also change [15]. Saliva is in constant contact with air, and gas diffusion may lead to atmospheric-type corrosion. Aside from corrosion, dissolution of the material is also possible, which is the intended design of the BIACOM TiMg composite [16].

Our results indicate that upon immersion of the samples in Coca-Cola, a marked increase in electrochemical potential was observed, thereby rejecting the null hypothesis of no interaction. Coca-Cola induced pronounced electrochemical instability of the samples, with maximum values of ~829 mV for CP4 Ti and ~982 mV for BIACOM TiMg. The pH of Coca-Cola was approximately 2.37. A similar maximum potential of ~863 mV was reached for the BIACOM TiMg sample immersed in freshly squeezed lemon juice. Numerous studies measuring potential differences between Ti implants and overlying suprastructures in artificial saliva confirm that pH variability and temperature oscillations further accelerate corrosion [17,18].

Likewise, the results demonstrate increased electrochemical interaction when using the Elmex fluoridation gel (12 500 ppm F⁻, pH ~4.8) as the electrolyte. Fluoride prophylaxis, although clinically beneficial, has been shown to cause corrosion instability in Ti when the pH is below neutral [19]. High fluoride concentrations and low pH values have been identified as detrimental to Ti corrosion resistance ability; for instance, the threshold pH values found previously were ~4.0 at 0.05% NaF and ~4.3 at 0.1 % NaF [20].

The negative impact of fluoride on Ti passivity demonstrated in our work using Elmex fluoride gel is corroborated by recent research on fluoride-containing oral care products. Slama et al. performed electrochemical assessments of innovative Ti-based high-entropy alloys in artificial saliva with fluoride and directly investigated the environmental conditions relevant to dental applications [21]. Their findings indicated that fluoride ions markedly influenced the corrosion characteristics of Ti-based materials in saliva-like electrolytes, with the degree of passivity destabilization contingent on both the fluoride concentration and alloy composition. Their findings also highlighted that fluoride could undermine the protective TiO₂ layer through complexation processes that generate soluble Ti-fluoride species, especially in acidic environments where the passive film is already compromised. This method elucidates the significant potential increases found with the Elmex fluoride gel (12,500 ppm F⁻, pH ~4.8), since the synergy of elevated fluoride concentration and acidic pH fosters ideal circumstances for passive film degradation.

Fluoride-induced corrosion has clinical consequences that go beyond damaging materials. When Ti implants are combined with different metals, such as CoCrMo in the presence of fluoride, the weakened passive coating on Ti might accelerate galvanic corrosion and cause more ions to be released from both materials. The potential shift of 800 mV observed in our investigation with fluoride-containing medium are a strong electrochemical force that can cause metals to dissolve. These results indicate that individuals with Ti implants associated with CoCrMo prosthetic components should receive guidance regarding the choice of oral care products, especially those with elevated fluoride concentrations or low pH levels. Fluoride delivery methods with a neutral pH or lower fluoride concentrations may be better for maintaining the electrochemical stability of multi-material implant systems.

Electrochemical interactions exceeding 200 mV were recorded with the use of the Listerine Cool Mint rinse and the Sensodyne Fluoride toothpaste. The BIACOM TiMg specimen developed almost twice the potential compared to the CP4 Ti in identical solutions. The potential values in the same solutions were considerably lower when pure Ti was used. Many Ti-based alloys exhibit superior mechanical properties compared with pure Ti; however, they often demonstrate reduced chemical stability compared with pure Ti [22]. Furthermore, given the designed solubility of Mg in the metal composite, increased electrochemical activity of the BIACOM TiMg sample is plausible [6].

The distinct electrochemical reaction observed between CP4 Ti and the BIACOM TiMg composite in our investigation corresponds with previous research regarding alloy-dependent corrosion behavior in oral settings. Turkina et al. examined the influence of widely available dry-mouth products on the corrosion resistance of prevalent dental alloys, such as Ti-6Al-4V and CoCr [23]. Their research showed that different types of dental care products changed the OCPs, corrosion potentials, and corrosion currents in a manner that was distinct to each material. They observed that CoCr alloys were corroded by pitting, which released Co and Cr ions into some products. In contrast, Ti alloys were more passive. The behavior of this product and alloy supports our finding that the

electrochemical stability of Ti-based materials varies greatly depending on the composition of the material and the unique electrolyte environment found in clinical practice.

The improved electrochemical activity of the BIACOM TiMg composite relative to that of CP4 Ti may potentially be affected by the composition and stability of the passive oxide layer. Recent research on innovative Ti alloys has demonstrated that alloying elements profoundly influence passive film properties and repassivation kinetics. Teixeira et al. assessed Ti-15Zr and Ti-15Zr-5Mo biomaterial alloys in phosphate-buffered saline and discovered that these innovative alloys had enhanced passive behavior and superior passive film recovery post-perturbation relative to commercially pure Ti Grade 4 [24]. Their electrochemical impedance spectroscopy findings indicated enhanced polarization resistance and increased stability of passive films of the alloyed materials. Adding Mg to the BIACOM composite serves a different purpose: controlled biodegradation. However, the idea that alloying metals change the stability of passive films and the electrochemical response is still true. The engineered solubility of Mg probably weakens the protective ability of the oxide layer, which is why we observed higher potentials in our galvanic coupling tests.

Ti and its alloys are highly reactive when in contact with biological media and metallic structures; a protective link forms that halts further surface oxidation. With the formation of a titanium dioxide (TiO₂) layer, the surface becomes passivated, which enables biocompatibility and bio-inert behavior even in highly active and corrosive environments [25]. The thickness of the oxide film, rather than the alloy composition, is crucial in protecting surrounding tissue cells from toxic constituents [26]. The passive layer serves to slow, though not prevent, the corrosion process [27].

The passive film made of TiO₂ is very sensitive to changes in the environment and surface treatments. Recent studies have elucidated the impact of manufacturing techniques and ambient conditions on the properties of TiO₂ layers, hence affecting their corrosion resistance. Igual-Muñoz et al. examined the effects of various sterilization techniques on the surface chemistry and electrochemical properties of biomedical alloys, specifically Ti and CoCrMo [28]. They discovered that autoclave sterilization elevated the Cr concentration in the passive coating of CoCrMo alloys, hence augmenting their corrosion resistance. In contrast, using both an autoclave and ultraviolet light sped up the corrosion kinetics in Ti alloys by speeding up the oxygen reduction kinetics at the surface. This finding is particularly relevant to our study, as it demonstrates that even routine clinical processing can alter passive film properties and modify the electrochemical response of Ti-based materials upon subsequent exposure to oral fluids.

The phase composition of the TiO₂ layer also affects the release of ions and stability of the layer over time. Javadi et al. investigated the release of metal ions from a plasma electrolytic oxidation (PEO)-coated Ti-6Al-4V alloy fabricated using direct metal laser sintering [29]. Their study showed that PEO coatings made of anatase and rutile phases kept about 98–99% of oxidized Ti in the passive layer when the circumstances were normal. However, when coatings were present, they could become the primary source of ion release, with the coating composition and microstructure determining whether the oxide layer functioned as a protective barrier or a source of soluble species. The fact that oxide layers can act as both protective coatings and possible sources of ions makes it more difficult to predict how corrosion would progress over time in clinical settings. In the context of our study, differences in the quality of the native oxide layer between CP4 Ti and the BIACOM TiMg composite may explain why they reacted differently when combined with CoCrMo.

A correctly processed surface is a prerequisite for the formation of a stable passive film [30].

In our study, we concentrated on potential measurements; however, subsequent investigations into the behavior of CoCrMo alloy offer a mechanistic framework for the observed galvanic interactions. Yilmazer et al. examined the corrosion and tribocorrosion characteristics of CoCrMo alloys subjected to various processing techniques, including high-pressure torsion and solution treatment [31]. Their research showed that CoCrMo is generally resistant to corrosion when immersed in phosphate-buffered saline, but it is quite prone to tribocorrosion when it is sliding against anything. This mechanical-electrochemical synergy is especially important in the mouth, where prosthetic parts can move slightly, be loaded with occlusal pressure, and come in contact with

food particles and other teeth in an abrasive manner. When CoCrMo is mechanically disturbed, its passive layer can break down in certain areas. This can momentarily increase its anodic activity and, when combined with Ti, may make galvanic reactions stronger.

The electrochemical behavior of CoCrMo components in galvanic couples is also affected by how they were made and their microstructure. The same study showed that CoCrMo samples that had been treated with a solution lost more material during tribocorrosion conditions compared to cast or high-pressure torsion-processed materials, even though they had the same static corrosion resistance [31]. This result shows that static immersion tests alone cannot adequately predict the electrochemical stability of CoCrMo in multi-material dental systems. In clinical situations with Ti-CoCrMo couples, mechanical considerations, including how well the prosthetic fits, how much weight it can hold, and how much micromotion occurs at the interfaces, can have a big impact on the amount and effects of galvanic corrosion. Future research should integrate tribocorrosion testing techniques that replicate the intricate mechanical-electrochemical milieu of operational dental implant systems to yield more therapeutically pertinent forecasts of material deterioration and ion release.

Corrosion may also lead to implant failure by compromising the mechanical stability and integrity of the surrounding tissue. Release of metal ions or electrochemical by-products can result in aseptic loosening, bone resorption (osteolysis), or trigger inflammatory responses through macrophage activation, and rarely, potential neoplastic developments [32]. In one study, galvanic potentials above 100 mV were observed in 84% of patients presenting oral pathological changes and symptoms; the most common pathological change was lichen planus, and confirmed symptoms included xerostomia and dysgeusia [30]. Normal oral electrical potentials between two metals or between a metal and the mucosa was approximately 100 mV; potentials up to 200 mV typically should not provoke symptoms [33]. If patients report subjective symptoms, such as burning or tingling upon contact with metals within the oral cavity (for example, during eating), this is accepted as evidence of a galvanic cell [34]. In these cases, potentials exceeding 200 mV indicate the need to remove the metal from the oral cavity.

This study has some limitations that should be acknowledged. First, the experiments were conducted under static laboratory conditions that do not fully reproduce the complexity of the oral environment, where factors such as saliva composition, temperature fluctuations, enzymatic activity, and mechanical loading can influence corrosion behavior. Second, only short-term immersion tests were performed. Therefore, long-term degradation kinetics and the stability of passive films over extended periods remain uncertain. Third, this study focused solely on potential measurements; complementary techniques such as electrochemical impedance spectroscopy, surface morphology assessment, or ion-release analysis were not performed and would provide a more comprehensive understanding of corrosion mechanisms. Finally, the sample size for each configuration was limited, which restricts the statistical power of the findings.

5. Conclusions

This study's findings indicate that common beverages and oral hygiene products can substantially alter the galvanic behavior of Ti-CoCrMo and TiMg-CoCrMo pairs by affecting the stability of their passive films. The pronounced potential shifts observed in low-pH and fluoride environments suggest that these media can compromise corrosion resistance, particularly for the Ti-Mg composite. Overall, CP4 Ti demonstrated greater electrochemical stability than the BIACOM TiMg material, underscoring the need to carefully evaluate emerging alloys intended for multi-material implant systems.

Author Contributions: Conceptualization, J.M.; methodology, T.K. and M.C.; software, T.K. and M.C.; validation, A.I. and I.P.; formal analysis, A.I., M.N., M.R. and T.K.; investigation, M.N. and M.R.; resources, J.M. and I.P.; data curation, J.M.; writing—original draft preparation, A.I.; writing—review and editing, I.P., J.M. and

T.K.; visualization, A.I., M.N. and M.R.; supervision, J.M. and M.C.; project administration, J.M.; funding acquisition, J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Croatian Science Foundation under the project number HRZZ-IP-2022-10-6065.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Ti	Titanium
CoCrMo	Cobalt-chromium-molybdenum alloy
TiO ₂	Titanium dioxide
OCP	Open-circuit potential measurements

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