

# The influence of a hyperbaric environment and increased oxygen partial pressure on the corrosion of dental alloys

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## Key words

Diving, hyperbaric oxygen, nitrox, dental, teeth, hyperbaric research

## Abstract

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**Objectives:** The purpose of this in-vitro study was to determine whether there is a correlation between a hyperbaric environment or increased oxygen partial pressure and the corrosion of dental alloys used for dental restorations in divers.

**Method and materials:** Samples of three commercially available dental alloys (palladium-based, reduced-gold-content and high-gold-content) were tested in the DIN EN ISO 1562 static immersion test and the amount of dissolved ions measured by atomic absorption spectrometry. The specimens were exposed to one of the following three conditions: normobaric and normoxic conditions ( $\text{PO}_2$  21 kPa); 608 kPa (6 bar,  $\text{PO}_2$  127 kPa) pressurised air in a pressure chamber or 506 kPa (5 bar,  $\text{PO}_2$  304 kPa) pressurised nitrox in a pressure chamber.

**Results:** None of the exposures suggested a correlation between increased ion solubility as a measure of corrosion and increased ambient pressure of the three alloys. The reduced-gold-content alloy released zinc ions at twice the weekly recommended dose. When the palladium-based alloy was exposed to a hyperbaric or hyperbaric/hyperoxic environment, ion solubility increased only slightly for gallium and silver.

**Conclusions:** Within the limited sample size of the current study it can be concluded that hyperbaric and/or hyperoxic conditions do not seem to be a risk for increased corrosion for any of the three tested alloys.

## Introduction

Around three million Europeans are thought to be recreational scuba divers, diving to depths up to around 40 meters' sea water (msw). Additionally, there are approximately 800 professional civilian and 700 military divers registered in Germany as well as some 500 compressed-air (caisson) workers, e.g., for tunnel or bridge construction work.<sup>1,2</sup> Military divers, who undergo regular fitness examinations at the Naval Medical Institute in Kiel, Germany, repeatedly complain about damaged dental restorations.<sup>2</sup> In a study conducted over a period of nine years, the overall dental appearances of divers were constantly significantly poorer than those of submariners.<sup>2</sup> These findings raise the question as to whether there is a correlation between dental health and diving. As the most important property of a dental alloy is its chemical stability, its degradation might result in adverse cytotoxic reactions to the host tissue and a release of metal ions into the gingival tissue, which can lead to additional aesthetic problems such as discoloration.<sup>3-5</sup> Previous studies have shown that certain cements are susceptible to a loss of retention and increased microleakage when diving.<sup>6,7</sup>

Irrespective of a suspected decreased personal oral hygiene and oral health negligence of naval personnel, the main reason for the poorer oral condition of divers in comparison to submariners could be from stress as a result of a hyperbaric environment.<sup>2</sup> This may be one of several factors influencing the dental health of divers.<sup>8</sup> Additional potential causes might be:

- increased partial pressures of the gases used in the

breathing mixture, in accordance with Dalton's law;

- changed ion composition and pH value of saliva as a result of occasional exposure of the oral cavity to sea water;
- increased evaporation and exsiccation of the oral cavity as a result of the relatively cold and dry air which is breathed, in accordance with Gay-Lussac's law.<sup>2</sup>

The purpose of this study was to test the null-hypotheses that exposure of dental alloys to hyperbaric pressure alone or a combination of hyperbaric and hyperoxic conditions does not lead to increased corrosion.

## Methods and materials

The tests were conducted under conditions corresponding to the clinically relevant maximum levels of hyperbaric pressure (divers diving up to 50 msw) or maximum recommended levels of oxygen partial pressure (therapeutically breathing compressed oxygen in a pressure chamber at a partial pressure ( $\text{PO}_2$ ) of 304 kPa).<sup>9</sup>

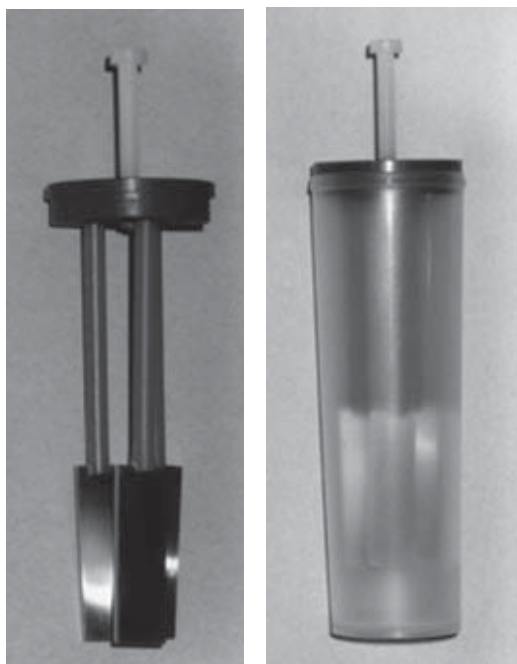
According to the procedures of DIN EN ISO 1562, 18 specimens per tested alloy were cast from a palladium-based alloy (*Reliance*, Jensen, Metzingen, Germany), a reduced-gold-content alloy (*Landmark*, Jensen) and a high-gold-content alloy (*JP-84*, Jensen), air-abraded (110  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  at 253 kPa) and polished with a 600-grit silicon carbide paper under water cooling.<sup>10</sup> The chemical composition of each of the three alloys is listed in Table 1. The specimens had dimensions of 32x10x1.5 mm, and were embedded

**Table 1**  
Composition of the tested alloys expressed as % weight (see Periodic Table for symbols)

|          | Au   | Pt | Pd   | Ag   | Zn  | Ga | In  | Others <1% |
|----------|------|----|------|------|-----|----|-----|------------|
| Reliance | -    | -  | 64.4 | 25   | 8.5 | 2  | -   | Rh, Ru     |
| Landmark | 59.3 | -  | 8    | 28.8 | 2   | -  | 1.5 | Fe, Ir     |
| JP-84    | 84.5 | 8  | 5    | -    | -   | -  | 2   | Re, Fe     |

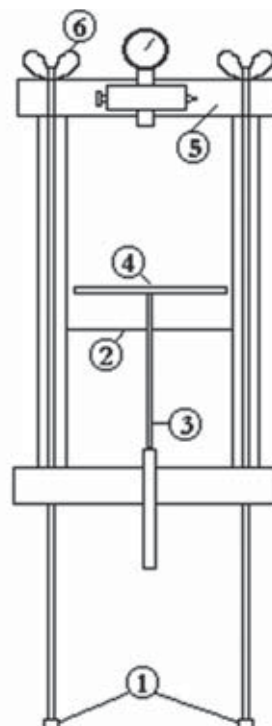
**Figure 1**

(Left) alloy plates fixed with slotted PE bars  
(Right) alloys immersed in PE-container in 26 ml saliva replacement solution



**Figure 2**

Pressure-chamber: 1 – rotatable feet, 2 – fluid level, 3 and 4 – height adjustable base for carrying specimens, 5 – Plexiglas lid, 6 – wing nuts



in prefabricated slots in polyethylene (PE) bars (Figure 1, left). All specimens were immersed in PE containers (27x32x9.5 mm, 30 ml, Figure 1, right) filled with 26 ml of a saliva substitute (0.1 mol L<sup>-1</sup> lactic acid, 0.1 mol L<sup>-1</sup> sodium chloride).<sup>10</sup> The lids of the PE containers were pierced with 1 mm holes to allow pressure equalization. A pressure chamber (IDE Power-test 110, International Diving Equipment, Rosenheim, Germany, Figure 2) without the specimens was put into the incubation room (TE1500\*2290\*80, LW1000\*2000 DIN, Vießmann, Hof, Germany) three days before immersing the specimens, to allow equilibrium to 37°C. After temperature equilibrium, the specimens were stored in the pressure chamber for the static immersion test. Before and after storage, the filled PE containers were weighed to ensure constant concentration of the saliva-replacement solution. Two containers per alloy and experimental subgroup with three specimens per container (overall 18 specimens per alloy) were filled with the saliva substitute and stored as follows according to the experimental subgroups:

- for each of the three tested alloys, two containers with

three castings each were put into an incubation room at 37°C for seven days in normobaric, normoxic conditions (control group);

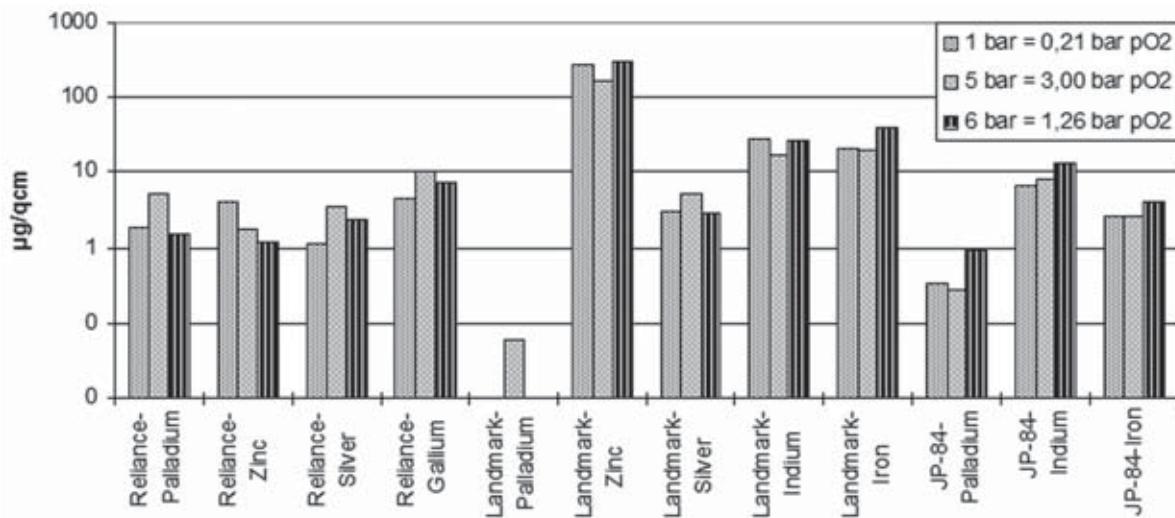
- for each of the three tested alloys, two containers with three castings each were put into the pressure chamber standing in the incubation room at 37°C for seven days in air at 608 kPa, PO<sub>2</sub> 127 kPa;
- for each of the three tested alloys, two containers with three castings each were put into a pressure chamber filled with commercially available nitrox (breathing gas mixture 60% oxygen 40% nitrogen) at 506 kPa, PO<sub>2</sub> 304 kPa.

After completion of seven days' storage time, the concentrations of the tested ions in the saliva-replacement solution were evaluated with an atomic absorption spectrometer (Perkin-Elmer, type 1100b), a graphite tube oven (PE HGA 700) and an auto-sampler (AS-70) for palladium (Pd), gallium (Ga) and indium (In) ions. An

**Table 2**  
Ion concentration in  $\mu\text{g cm}^{-3}$  of the tested solutions after storage

|                                   | Control group<br>(normobaric air) | Hyperbaric/hyperoxic condition<br>(506 kPa, PO <sub>2</sub> 304 kPa) | Hyperbaric air condition<br>(608 kPa, PO <sub>2</sub> 127 kPa) |
|-----------------------------------|-----------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------|
| <b>Palladium-based alloy</b>      |                                   |                                                                      |                                                                |
| Reliance-palladium                | 1.88                              | 5.09                                                                 | 1.57                                                           |
| Reliance-zinc                     | 3.86                              | 1.70                                                                 | 1.20                                                           |
| Reliance-silver                   | 1.13                              | 3.56                                                                 | 2.40                                                           |
| Reliance-gallium                  | 4.39                              | 10.01                                                                | 7.36                                                           |
| <b>Reduced-gold-content alloy</b> |                                   |                                                                      |                                                                |
| Landmark-palladium                | 0.01                              | 0.06                                                                 | 0.01                                                           |
| Landmark-zinc                     | 282.51                            | 173.11                                                               | 297.65                                                         |
| Landmark-silver                   | 3.15                              | 4.95                                                                 | 2.80                                                           |
| Landmark-indium                   | 28.41                             | 16.74                                                                | 27.36                                                          |
| Landmark-iron                     | 21.10                             | 19.46                                                                | 38.22                                                          |
| <b>High-gold-content alloy</b>    |                                   |                                                                      |                                                                |
| JP-84-palladium                   | 0.34                              | 0.28                                                                 | 0.91                                                           |
| JP-84-indium                      | 6.68                              | 7.81                                                                 | 13.01                                                          |
| JP-84-iron                        | 2.49                              | 2.49                                                                 | 3.85                                                           |

**Figure 3**  
The concentration ( $\mu\text{g cm}^{-3}$ ) of dissolved ions for each dental alloy shown in a logarithmic scale to eliminate the high peak of dissolved zinc ions by specimens of "Landmark"



atomic absorption spectrometer (Perkin-Elmer, type 5100 PC) with an auto-sampler (AS-90) was used for detection and evaluation of the concentration of zinc (Zn), iron (Fe), copper (Cu) and silver (Ag) ions. Gold (Au) and platinum (Pt) ions were not evaluated, since several studies have found minimal concentrations only of those ions after static immersion tests and other studies categorise them as inert metals.<sup>11-14</sup> The evaluation of the results was conducted using descriptive statistics, since three specimens were stored in one PE container, thus already resulting in a mean concentration for each alloy, leaving the sample size for each alloy and experimental group as 2 ( $n = 6/3$  per 2 containers).

## Results

The concentrations of dissolved ions of the three alloys after the seven-day period of static immersion depending on ambient pressure and oxygen partial pressure are shown in Table 2 and Figure 3. None of the three tested alloys suggested a correlation between increased ion solubility as a measure of corrosion and increased ambient pressure. When the Pd-based alloy was exposed to a hyperbaric or hyperbaric/hyperoxic environment, ion solubility increased only slightly for Ga from  $4.4 \mu\text{g cm}^{-3}$  to 7.4 or  $10 \mu\text{g cm}^{-3}$  and Ag from  $1.1 \mu\text{g cm}^{-3}$  to 4 or  $2.4 \mu\text{g cm}^{-3}$ , respectively.

Pd-ion solubility only showed an increase when subjected to a hyperbaric/hyperoxic environment. The reduced-gold-content alloy showed a high Zn release between  $173 \mu\text{g cm}^{-3}$  and  $298 \mu\text{g cm}^{-3}$  and to a lesser extent, but still higher than the other two alloys, a higher In and Fe release. In contrast, the high-gold-content alloy released negligible amounts of ions, with only In release slightly increasing from  $6.7 \mu\text{g cm}^{-3}$  to  $7.8$  or  $13 \mu\text{g cm}^{-3}$ . No Cu ions could be detected in the solution.

## Discussion

Increasing pressure and, therefore, increasing  $\text{PO}_2$  are two changing conditions whilst diving. The current study aimed to investigate the hypotheses of Goethe et al. that these two factors could potentially influence the corrosion of dental alloys.<sup>2</sup> The static immersion test is a well-established procedure to evaluate corrosion resistance of dental alloys.<sup>10,15</sup> It accelerates testing time by using a saliva substitute with a pH of 2.3, while the in-vivo saliva pH normal range is between 6–7.5, and using a constant temperature of  $37^\circ\text{C}$ , compared to a temperature of about  $35^\circ\text{C}$  in the mouth, which varies breath-by-breath.<sup>16–18</sup>

Corrosion was tested for under extreme but, for humans, tolerable conditions.<sup>9</sup> Using compressed air at 608 kPa represents the situation of someone diving to 50 msw. This pressure was chosen in order to test the upper end of conditions divers, particularly commercial and military ones, might normally encounter.<sup>19</sup> Likewise, the current study tested the highest  $\text{PO}_2$  used in hyperbaric oxygen therapy (e.g., Boerema's scheme/TS 300-90), but which a diver would never have to experience.<sup>8,9</sup> The seven days of immersion represent around 300 to 600 dives, depending on the depths of the dives. Professional military divers accomplish around 5,000 dives in their lifetime. Thus, this represents a reasonable exposure time of the dental alloys.<sup>1,20</sup>

The corrosion of dental alloys can be measured as the sum of all dissolved ions.<sup>21,22</sup> Although none of the three tested alloys showed a correlation between increased ion solubility and increased ambient pressure, the Pd-based alloy showed slightly higher ion solubility for Ga and Ag when subjected to hyperbaric and/or hyperbaric/hyperoxic conditions. Pd-ion solubility only showed an increase when subjected to a hyperbaric/hyperoxic environment. With the high-gold-content alloy releasing only a minimal amount of ions as well, the ion release for these two alloys seems to be clinically negligible since the overall sum of ion release should be less than  $100 \mu\text{g cm}^{-3}$ , but ideally less than  $10 \mu\text{g cm}^{-2}$  in a week.<sup>10,23</sup>

In contrast, the reduced-gold-content alloy showed a high Zn release, more than twice the recommended limit of  $100 \mu\text{g cm}^{-3}$ , independent of surrounding pressure or  $\text{PO}_2$  conditions and regardless of a potential increase of corrosion due to

salty sea water. Since even small concentrations of certain ions can cause toxicity, allergic reactions or other diseases, the additional Fe and In release of this alloy suggests its cautious use as a dental restoration material, in general.<sup>3</sup> With regards to the components with the highest ion release by the Pd-based alloy, Ga has shown cytotoxic effects, with soft tissue responses and cell necrosis in guinea pigs and sarcomas in rats.<sup>24,25</sup> When evaluating ions released in higher concentrations by the reduced-gold-content alloy, severe cytotoxic effects for Zn are known, whereas Ag was found to be intermediate in cytotoxic effects and iron the least cytotoxic element.<sup>26–28</sup> As Cu is known for causing inflammation, allergic reactions and cytotoxicity and with Zn being found in so-called 'Zn-free' alloys, the current study tested all experimental alloys for Cu traces and excluded contamination.<sup>11,12</sup>

A limitation of the current study is the small sample size of six specimens per experimental subgroup, being further diluted by the storage of three specimens in one container, thus building a mean of the ion release and only allowing a descriptive analysis of the results. Subsequent research in this particular area is desirable since the current study did not test amalgam samples. Subsequent studies should include amalgam testing, examine effects of changing ion concentrations and temperature in saliva and the effects of multiple pressure changes while diving. An additional factor to be tested should include the dilution of the saliva replacement solution with sea water and, therefore, an increased salt concentration.

## Conclusions

Within the limitations of the current study with special regard to the small sample size, it can be concluded that hyperbaric and/or hyperoxic conditions do not seem to pose a risk for increased corrosion to any of the tested alloys. Because of a potential toxicity of the dissolved Zn ions released by the reduced-gold-content alloy, this particular alloy should be used with caution. The Ga release of the Pd-based alloy did not seem to be clinically important. As the high-gold-content alloy showed the lowest combined ion solubility it could be preferentially used for divers with many hours of diving, if metal alloy is the restorative material of choice.

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The database of randomised controlled trials in hyperbaric medicine maintained by  
Dr Michael Bennett and colleagues at the Prince of Wales Hospital  
Diving and Hyperbaric Medicine Unit is at:  
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