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Active

Project #: E-18-633 Cost share #: Rev #: 2
Center # : 10/24-6-R7666-1A0 Center shr #: OCA file #:
Work type : RES
Contract#: 1 R55 DE09664-01A1 Mod #: EXTENSION Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA:
Main project #: PE #:

Project unit: MSE Unit code: 02.010.112
Project director(s):
MAREK M I MSE (404)894-2380

Sponsor/division names: DHHS/PHS/NIH / NATL INSTITUTES OF HEALTH
Sponsor/division codes: 108 / 001

Award period: 920930 to 950929 (performance) 951229 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	100,000.00
Funded	0.00	100,000.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: THE RELEASE OF METALLIC ELEMENTS FROM DENTAL ALLOYS

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NIH supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
GRANT BUDGET PERIOD EXTENDED FOR 12 MONTHS IN ACCORDANCE WITH EXPANDED AUTHORITIES.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/23/96

Project No. E-18-633 Center No. 10/24-6-R7666-1A0

Project Director MAREK M I School/Lab MSE

Sponsor DHHS/PHS/NIH/NATL INSTITUTES OF HEALTH

Contract/Grant No. 1 R55 DE09664-01A1 Contract Entity GTRC

Prime Contract No.

Title THE RELEASE OF METALLIC ELEMENTS FROM DENTAL ALLOYS

Effective Completion Date 950929 (Performance) 951229 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
NOTE USE DHHS FORM FOR PATENT

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

NOTE: Final Patent Questionnaire sent to PDPI.

E-18-633
#1
(new)

Final Report

THE RELEASE OF METALLIC ELEMENTS FROM DENTAL ALLOYS

By:
Miroslav Marek, Ph.D.
School of Materials Science and Engineering

Under:
Grant No. 1 R55 DE09664
DHHS/PHS/NIH/NIDR

Period of Performance:
09/30/92 - 09/29/95

December 30, 1995

TABLE OF CONTENTS

1. SPECIFIC AIMS

The main objective of the study was to reach an understanding of the kinetics of the metal ion release from dental alloys. While the original research proposal targeted palladium-based cast alloys, the reduced funding of this grant mandated a choice of a less expensive subject material. The release of nickel was chosen as a suitable subject because of the concerns regarding nickel release, especially in view of the high incidence of allergic reactions to nickel among the population. Nickel is one of the main constituents of a group of dental casting alloys, as well as orthodontic wires and some dental implants. The specific material selected for the study was a Ti-Ni intermetallic alloys (Nitinol), which suited the purpose of this study as a relatively simple system, in which the absence of many dissolving elements made feasible the methodology and a reliable interpretation of the results.

The study was performed *in vitro*. The following Specific Aims were pursued:

1. To characterize the electrochemical corrosion behavior of a specific Nitinol wire product in synthetic oral fluids.

2. To develop analytical techniques for nickel concentration determination in simulated body fluids with a ppb sensitivity.

3. To determine the nickel release kinetics in synthetic oral fluids.

4. To analyze the effect of nickel ion concentration in the test solution on the nickel release kinetics and reach conclusions regarding a methodology of metal ion release testing.

2. STUDIES AND RESULTS

2.1 ELECTROCHEMICAL CHARACTERIZATION
(Specific Aim No. 1)

2.1.1 Materials

Alloy: The material used in this study was a nickel-titanium alloy wire, 0.8 mm in diameter, supplied by Goodfellow Corporation, Malvern, PA, Cat. No. NI205100, in the as received conditions. The main physical and thermodynamic characteristics of this alloy are as follows:

Composition: Ni 45 at.%, Ti 45 at.%
Temperatures, austenite: 23°C, 37°C
Temperatures, martensite: 5°C, -8°C

This alloy provided a consistent sample material and was considered preferable to one or a few of the commercial products on the market for a fundamental study.

Electrolytes: The electrolyte used in this study was a modified Ringer's solution of the following composition: sodium chloride 9.00 g/L; calcium chloride 0.17 g/L; potassium chloride 0.40 g/L; sodium bicarbonate 2.1 g/L. This solution was used in preference to artificial saliva mainly to avoid interference in the solution analysis. Since nickel-containing alloys are used both in the oral cavity and for implantation the use of the extracellular body fluids substitute represents a more severe testing environment than saliva for oral cavity applications, but does not materially change the fundamental conclusions based on the test results.

Atmospheres: For tests simulating an exposure under spontaneous corrosion conditions, i.e., in the corrosion potential measurements, the atmosphere contained 10% oxygen, 5 % carbon dioxide, and balance nitrogen. This atmosphere simulates the average oxidation conditions in the body fluids, and the carbon dioxide content, in conjunction with the bicarbonate content of the electrolyte provides a buffering action at near-neutral pH value,

also simulating the body fluid conditions. For the polarization measurements the atmosphere contained 5 % carbon dioxide and balance nitrogen. The atmospheres were obtained as gas mixtures in compressed gas cylinders, and the test solutions were saturated with them.

2.1.2 Procedures

The electrochemical behavior of the tested material was characterized using corrosion potential, potentiodynamic anodic polarization, and repassivation measurements. The protocols for the tests are presented in Appendix I. Ten replicate tests of each type were performed. Mean values and standard deviations of the characteristic parameters were determined, and t-tests were performed for differences in the means at $p \leq 0.05$.

2.1.3 Results

Corrosion potential measurements: The long-term corrosion potential data are presented in Table 1. The extremes of the potential-time variation have been plotted in Fig. 1. The corrosion potential showed a slight increase initially with time, followed by a very slight decrease and an almost constant value at exposures longer than one day.

Potentiodynamic anodic polarization curves: Ten replicate anodic polarization tests have been performed. Typical anodic polarization curves, showing the range of the behavior are shown in Fig. 2-6. All potentiodynamic anodic polarization measurements yielded qualitatively similar results, i.e., a region of passivity (potential-independent current density region), which ended when the current density sharply increased (transpassivity region), indicating localized attack. The individual results varied in the current density in the passive state, and in the value of the critical potential for passivity breakdown (breakdown potential). The characteristic current density and critical potential data are presented in Table 1. A comparison of the anodic polarization results with those of the corrosion potential measurements show that under the spontaneous corrosion conditions the material was in the passive state. There was a statistically significant ($p \leq 0.05$) difference (difference of means 0.262 V) between the stabilized corrosion potential and

the breakdown potential. Nevertheless, the extremes of the corrosion potential and breakdown potential values overlapped indicating that for some specimens a relatively slight increase in the oxidation power of the solution would bring the potential into the transpassive state, i.e., cause localized corrosion in the form of pitting.

Repassivation measurements: In these tests the potentiodynamic anodic polarization scan in allowed to proceed to a predetermined anodic current density; the potential scan is then reversed and the potential-current density response if recorded until the current return to a low value indicating a passive condition. The potential at which this is achieved is the repassivation potential. While the breakdown potential is a measure of the susceptibility of the material to localized corrosion initiation due to an increase in the oxidation power of the solution, the repassivation potential is a measure of the material to resist localized corrosion caused, for instance, by crevice corrosion conditions. Also, the repassivation potential indicates the ability of the material to repair a damage caused by an occasional fluctuation of the oxidation power of the solution causing pitting initiation. For resistance to pitting initiation the corrosion potential must not exceed the breakdown potential; for an ability of repair of a pit initiated by an occasional pitting initiation the corrosion potential should not exceed the repassivation potential. Two typical scans showing repassivation is presented in Fig. 7. The repassivation potential data are presented in Table 1. While the breakdown potential varied substantially, the repassivation potential was very reproducible. The means of the repassivation potential were not significantly different ($p \leq 0.05$) from the means of the stabilized corrosion potential. These results indicate that the material had only a marginal ability to repassivate if localized corrosion was initiated.

2.2 ANALYTICAL TECHNIQUES FOR NICKEL ION DETERMINATION (Specific Aim No. 2)

Measurement of the nickel release rate requires an analytical techniques capable of determination nickel concentration in the ppb (part per billion) range. The most commonly used analytical technique for metal ions, Atomic Absorption

Spectrophotometry (AAS), was available in the laboratory and initial an attempt was made to use it for the purpose of this study. In AAS the liquid sample is atomized, and the absorption of light on a wavelength specific for the element of interest is measured and the absorbance is converted to concentration using known standards. While a flame atomization method of AAS lacks the required sensitivity, a flameless technique using carbon furnace atomization, has the sensitivity, albeit at the expense of substantial data dispersion. A substantial effort was made to use AAS to achieve the Specific Aims No. 2 and 3 of this study. However, the results have shown an unacceptably high interference at the nickel wavelength, which could not be adequately compensated even using a deuterium lamp.

Another analytical technique with sensitivity in the ppb range for many metallic elements is Stripping Voltammetry. In this technique the dissolved elements first are reduced on an electrode, in which they can be dissolved; for most elements a thin layer of mercury on a carbon rod serves this purpose, since most metallic elements dissolve in mercury as long as the concentration is low. The reduction is achieved by making the carbon/mercury electrode a cathode in an electrochemical cell. Following the reduction the polarity of the electrode is reversed to make in an anode, and its potential is scanned in a suitable range to ionize and dissolve the elements of interest. The dissolution current is measured and the current peak area at a potential characteristic for the element of interest is determined and converted to concentration using known standards.

The Stripping Voltammetry technique was investigated and found suitable for the purpose of this study. Radiometer Trace Lab 1 System (Radiometer Copenhagen), interfaced with an IBM 486/66 MHz Computer was used. While the original analytical for nickel procedure provided with the instrument was unsatisfactory, a modified procedure was developed in the course of this project. The modified procedure met the requirements of sensitivity and has shown adequate data dispersion. The procedure is described in Static Leaching Test Protocol in the Appendix 2.

2.3 NICKEL RELEASE DETERMINATION

(Specific Aims No. 3 and 4)

2.3.1 Materials

Alloy: The material used in this part of the study was the same as in Part A, Electrochemical characterization, i.e., a nickel-titanium alloy wire, 0.8 mm in diameter, in the as received conditions

Electrolytes: The electrolyte used in this part of the study was the same as in Part A, Electrochemical characterization, i.e., a modified Ringer's solution of the aforementioned composition.

Atmospheres: The atmosphere contained 10% oxygen, 5 % carbon dioxide, and balance nitrogen. The gas mixture was bubbled through the electrolyte in each test tube to saturate the solution.

2.3.2 Procedures

The nickel release rate was determined by analyzing samples of the solution, in which specimen of the test material was exposed for a specific period of time. The solution analysis was performed using a method of stripping voltammetry, described in Section B above and in the Test protocol in the Appendix 2.

In the first series of tests (Specific Aim No. 3) the solution was analyzed at the end of each specific 24-hour test period during a long-term exposure test. For each of these test periods a fresh solution was used; each specimen was exposed to the test electrolyte throughout the total test. The results of these tests thus provided the values of the average nickel release rate during 24 hour periods, each starting with a nickel-free solution, as a function of the overall exposure time. The longest exposure time in this series of tests was 49 days.

In the second series of tests (Specific Aim No. 4) the effect of the nickel ion concentration on the nickel release rate was determined. This series of tests was initiated

after the first series of tests, starting at a total exposure time of 89 days and ending at a total exposure time of 138 days. Thus the nickel release rate, as affected by the surface conditions of the specimens, was essentially stabilized. For this purpose the initial nickel concentration in the test solution was adjusted to 3 ppb. The test exposure was then varied from 1 hour to 72 hours.

2.3.3 Results

The results of the first series of tests are summarized in Fig. 8, which shows that the average 24-hour nickel release rate for the five tested specimens, determined using 24-hour test exposure periods, decreased with the total exposure time. After five weeks of exposure the average 24-hour nickel release rate was about 0.5 $\mu g.cm^{-2}.day^{-1}$.

The results of the second series of tests are summarized in Figs. 9-10, Fig. 9 shows the average nickel release rate as a function of the test exposure period for the five tested specimens, based on the assumption that the fundamental release rate was essentially stabilized. The result show that the average nickel release rate decreased with increasing test period. In Fig. 10 the results were normalized and averaged, the corrosion rate determined using a 24-hour test period made equal to one. The results show that the nickel release rate, as determined by the test, was higher by a factor of two when the test period was reduced to 2 hours, and by a factor of more than 8 when the test period was one hour. There was a slight decrease in the measured nickel release rate when the test period was longer than 24 hours.

3. SIGNIFICANCE

Nickel-containing alloys are one of the major groups of dental alloys. They are used as dental casting alloys for crowns and bridges, especially for PMF (Porcelain Fused to Metal) applications, as wires for orthodontic applications, and for dental implants. Although nickel-bearing dental alloys are passivating alloys exhibiting a good corrosion

resistance in oral and body fluids due to a thin, very protective surface oxide film, there is always some release of the elements from the alloy into the environment.

Although the nickel release from dental alloys has not been systematically studied, the release of nickel into the human body environment is of some concern in view of the well documented incidence of allergic reactions to nickel among the population. Gjerdet et al. (1987) found pronounced cytotoxicity for some nickel-containing wires. Altuna et al. (1991) reported skin reactions due to orthodontic materials. Bishara et al. (1993) found that orthodontic appliance might show an increased corrosion rate under some conditions, which would result in an increase in the nickel release. Bass et al. (1993) reported a higher rate of nickel hyper-sensitivity and suggested that a long term exposure to nickel-containing appliances might sensitize patients to nickel.

Nickel-titanium alloys of approximately equal atomic proportions of the two elements are one of the latest and very promising materials for orthodontic appliances and dental and other implants (Civjan et al., 1975). The alloy (usually called Nitinol) is basically a Ni-Ti intermetallic, although commercial alloys frequently contain smaller amounts of other elements, such as cobalt. The outstanding feature of this materials is its shape-memory effect and superelasticity, obtained with proper heat treatment. Both effects are related to the stress induced crystallographic transformation from austenite to martensite. The shape-memory effect occurs when the alloy is first deformed to a desired shape while undergoing a high-temperature heat treatment. After the wire has cooled below a transition temperature range it may be deformed to another shape. When heated then to the transition temperature range, it will return to the original shape. Since the transition temperature of these Ni-Ti alloys can be adjusted to be close to the body temperature by alloying and heat treatment, it is possible for this shape change to occur after the material is inserted into the human body environment. The superelasticity of this material, on the other hand, allows a high elastic deformation at relatively low stresses, which is especially attractive for orthodontic applications.

3.1 CORROSION BEHAVIOR OF Ni-Ti ALLOYS

The corrosion behavior of Nitinol in both dental and other biomedical applications has received limited attention. Sarkar and Schwanninger (1980) examined Nitinol after an *in vivo* exposure in the oral cavity for up to 5 months and reported an advent of pitting. Pitting of Nitinol orthodontic wires in the oral cavity also was reported by Kapila et al. (1991). The results of the in vitro studies have shown ambiguous results. Sarkar et al. (1979) reported a moderate breakdown potential, +0.15 V (SCE),but a substantial current in a reverse potential scan, indicating susceptibility to pitting, which also was observed in the SEM. Oda et al. (1988), reported a very high breakdown potential of 1.2 V (SCE) for a Ti 45 Ni 55 alloy. On the other hand, Lee and Kim (1994), who studied two commercially available orthodontic wires, reported a low breakdown potential of -0.1 V (SCE). Harris et al. (1988) reported a substantial decrease in specific mechanical properties of a nickel-titanium orthodontic wire as a result of an exposure to a simulated oral environment; Schwaninger et al. (1982), on the other hand, had reported an absence of such an effect. It is evident that the reported results for Ni-Ti alloys are contradictory.

The results of this study have provided some insight into the reasons for the variability of the results reported in the literature. Even for the same material the electrochemical test result shave shown a high variable properties. The results of the polarization tests (Figs. 2-6 and Table 1) have shown a wide variation of the breakdown potential, indicating a variable resistance to pitting. Some of the breakdown potential values were close to the value of the open circuit corrosion potential (Table 1), indicating that a relatively small variation in the oxidation power of the environment may dramatically change the behavior from absence to occurrence of pitting, and *vice versa*. Moreover, the results of the repassivation tests (Fig. 7 and Table 1) show that the repassivation potential was close to the open circuit corrosion potential,. This means that when pits are initiated, perhaps by an occasional slight change in the oxidation power of the environment, they would be likely to continue growing, rather than repassivate.

Since the shape-memory effect and superelastic behavior is intimately related to the crystallographic change from martensite to austenite and back when the material is heat treated, stressed and deformed, it is also entirely possible that the observed corrosion behavior is different for the surface layer than for the internal structure. In other words, the corrosion behavior of the surface of a Nitinol product, including the wire tested in this study, may not be representative of the inherent electrochemical behavior of the material. This hypothesis will have to be examined in further studies.

3.2 NICKEL RELEASE FROM Ni-Ti ALLOYS

The results of this study have shown that there is a moderate release of nickel from Nitinol, when exposed to a simulated body fluid (Fig. 8). The release rate was relatively high initially, but decreased and stabilized after a few weeks of exposure. The release rate also varied from specimens to specimen, consistent with the results of the electrochemical measurements.

The decrease in the nickel release with time can be attributed to two main factors. One is the growth of the passive surface oxide film, which is the main barrier against corrosion of these thermodynamically unstable materials, and the morphological changes in the film with time. A decrease in the corrosion rate with time is quite typical for passivating alloys. The second factor is the possible selective dissolution of nickel from the alloy, which would result in the surface enrichment in titanium. Although nickel is thermodynamically more stable than titanium, the titanium oxide film is substantially more stable in an aqueous environment than a nickel oxide. It is thus conceivable that the titanium dissolution is substantially diminished by formation of a titanium oxide layer, while nickel migrates through the film and dissolves. This would deplete the layer of the alloy at the interface with the oxide film in nickel, and contribute to a reduction of the nickel dissolution rate with time. This hypothesis also requires future verification.

3.3 DETERMINATION OF THE METAL ION RELEASE *in vitro*

The *in vitro* metal ion release is determined by analyzing the solution to which a metal specimen had been exposed. Thus the concentration of the elements in the solution increases with time. Two basic approaches can be taken regarding the sampling. In the first approach the same solution is used for the entire test exposure. Small samples of the solution are then withdrawn from the bulk solution and analyzed, while most of the solution remains to the end of the test exposure for each metal specimen; alternatively, test exposures of variable length are used with different specimens. In both cases the metal ion release rate per unit time is obtained as a slope of the tangent of the concentration vs. exposure time curve, usually by numerical differentiation. When this approach is used the concentration of the dissolving element in the solution often varies by many orders of the magnitude with the exposure time. A decrease in the release rate with time obtained in this type of test has been commonly interpreted as due to surface changes of the electrode, while the effect of the metal ion concentration has been ignored.

The second approach to metal ions release testing also involves a long-term exposure, but a fresh solution is used after each sampling for the analysis. Thus the ion release rate per unit time is determined directly, without using a differentiation of the concentration vs. time curve. Even in this approach, however, only an average dissolution rate is determined, and the metal ion concentration varies during the test exposure. In most tests the initial concentration is virtually zero (except for background impurity), while the final concentration depends on the test exposure time, which must be long enough to allow a quantitative determination of the concentration.

The effect of the changes in the metal ion concentration during the test exposure, which have been ignored in virtually all reported studies, may have a profound effect on the results of the test. The driving force for dissolution fundamentally is a function of the concentration of the element in the solution. For metals in an active corrosion state the effect of the concentration on the driving force for dissolution can be theoretically predicted. This analysis has been performed by the author as a part of this projected and

presented at scientific meetings (Marek, 1993; Marek, 1995). The details of the analysis are shown in Appendix 3.

The effect of the metal ion concentration on the metal ion release rate for a passivating alloy has not been theoretically analyzed. In principle, the dissolution rate also should be a function of the dissolved element concentration. The dissolution in the passive state is essentially due to two factors: the dissolution of the oxide film (which is being continuously reformed), and migration of ions from the substrate through the film to the film/electrolyte interface, where they are dissolved. The rate of the oxide film dissolution would be affected by the metal ion concentration in the solution if the film was an oxide of the element. In the case of a Ni-Ti alloy is oxide film, however, is likely to be mostly titanium oxide, the dissolution rate of which would not be affected by nickel ion concentration. The migration rate of nickel through the oxide film, on the other hand, is expected to be a function of the concentration gradient and thus of the metal ion concentration in the electrolyte.

Results of this study, presented in Figs. 9-10, have shown that the length of the test exposure strongly affected the average dissolution rate per unit time. Since the tests were performed after a long total exposure, so that the fundamental dissolution conditions have stabilized, the differences in the average dissolution rate with the test exposure time can be attributed to the variation of the metal ion concentration in the solution. Figs. 9-10 show that the average dissolution rate per unit time decreased with increasing test exposure and thus with increasing final metal ion concentration, consistent with the theoretical predictions. A more detailed analysis of the effect of the metal ion concentration on the dissolution rate for passive alloys will be performed in future studies.

4. CONCLUSIONS

1. Nickel-titanium intermetallic (Nitinol) dental alloys exhibit corrosion behavior in simulated body fluids which is marginal with respect to the resistance to pitting. Large variation of the behavior are observed even for the same material.

2. The nickel release rate from nickel-titanium intermetallic (Nitinol) dental alloys is moderate, decreases with time and stabilized. Consistently with the results of the corrosion behavior measurements the nickel dissolution rate varies significantly from specimen to specimen.

3. A hypothesis has been proposed that the relatively low corrosion resistance of the Ni-Ti alloys is due to the structure of the surface of the specimens and products rather than being an inherent property of the alloy.

4. The results of the determination of the metal ion release rate have been shown to be strongly affected by the length of the test exposure. A hypothesis has been proposed that the effect is due to the changes in the metal ion concentration with the test exposure time, which change the driving force for dissolution.

5. REFERENCES

Altuna G, Lewis DW, Chao I, Rourke MA (1991). A statistical assessment of orthodontic practices, product usage, and the development of skin lesions. Am J Orthodon Dentofac Orthop 100:242.

Bass JK, Fine H, Cisneros GJ (1993). Nickel hypesensitivity in orthodontic patients. Am J Orthodon Dentofac Orthop 103:280.

Bishara SE, Barrett RD, Selim MI (1993). Biodegradation of orthodontic appliances. Part II. Changes in the blood level of nickel. Am J Orthodon Dentofac Orthop 103:115

Civjan S, Huget EF, DeSimon LB (1975). Potential applications of certain nickel-titanium (nitinol) alloys. J Dent Res 54:89-96.

Gjerdet NR, Kallus T, Hensen-Pettersen A (1987). Tissue reactions ro implanted ortyhodontic wires in rabbits. Acta Odontol Scand 45:173.

Harris EF Newman SM Nicholson JA (1988).Nitinol arch wire in a simulated oral environment: changes in mechanical properties. Am J Orthod Dentofacial Orthop 93:508-13.

Kapila S, Reichhold GW, Anderson S, Watanabe LG (1991) Effects of clinical recycling on mechanical properties of nickel-titanium alloy wires. Am J Orthodon Dentofac Orthop 100:428.

Lee YK, Kim CW (1994). Electrochemical corrosion behavior of dental orthodontic wires. Dent Mat J (SNU) 4:19-36.

Marek, M (1993). "Measurement of Ion Release from Dental Alloys," Transactions of the Second International Congress on Dental Materials, November 1-4, 1993, Honolulu, Hawaii. The Academy of Dental Materials, 117-127.

Marek M (1995). "Measurement of Metal Ion Release from Biomedical Implant Alloys," Proceedings of the Spring Meeting of The Electrochemical Society, Symposium on Compatibility of Biomedical Implants, May 23-25, 1994, San Francisco, CA. The Electrochemical Society, Pennington, NJ, 1995.

Oda Y, Matsuno S, Sumii T (1988). A study of corrosion of titanium alloys used in dental work. Bull Tokyo Dent Coll 29:59.

Sarkar NK, Redmond W, Schwaninger B, Goldberg JA (1979). The chloride corrosion behavior of four orthodontic wires. J Dent Res 58:A98.

Sarkar NK, Schwaninger B (1980). The in vitro corrosion of Nitinolwire. J Dent Res 59:628.

Schwaninger B Sarkar NK Foster BE (1982) Effect of long-term immersion corrosion on the flexural properties of nitinol. Am J Orthod 82:45-9.

Schwaninger B, Sarkar NK, Foster BE (1982). Effect of long-term immersion corrosion on the flexural properties of Nitinol. Am J Orthodont 82:45.

6. HUMAN SUBJECTS

None

7. VERTEBRATE ANIMALS

None

8. PUBLICATIONS

Marek, M. "Measurement of Ion Release from Dental Alloys," Transactions of the Second International Congress on Dental Materials, November 1-4, 1993, Honolulu, Hawaii. The Academy of Dental Materials, 117-127.

Marek M. "Measurement of Metal Ion Release from Biomedical Implant Alloys," Proceedings of the Spring Meeting of The Electrochemical Society, Symposium on Compatibility of Biomedical Implants, May 23-25, 1994, San Francisco, CA. The Electrochemical Society, Pennington, NJ, 1995.

Marek, M. "Nickel Ion Release from Ti-Ni Dental Alloys." Manuscript in preparation.

Marek, M. "Electrochemical Behavior of Ti-Ni Dental Alloys." Manuscript in preparation.

9. INVENTIONS AND PATENTS

None

Table 1

RESULTS OF THE ELECTROCHEMICAL CHARACTERIZATION TESTS

Parameter	Units	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	MEAN	S.D.
Corrosion potential (stabilized)	V (SCE)	-0.125	-0.098	-0.112	-0.086	-0.093	-0.137	-0.105	-0.121	-0.089	-0.098	-0.106	0.017
Breakdown potential	V (SCE)	0.130	0.056	0.250	0.265	0.140	0.090	0.123	0.187	0.088	0.232	0.156	0.073
Repassivation potential	V (SCE)	-0.138	-0.133	-0.135	-0.128	-0.139	-0.129	-0.131	-0.128	-0.138	-0.133	-0.133	0.004
Average current density in passive state	A/cm^2	3.3E-8	1.1E-8	8.7E-9	9.7E-9	1.1E-8	1.2E-8	7.8E-9	2.8E-8	3.2E-8	1.3E-8	1.7E-8	1.0E-8

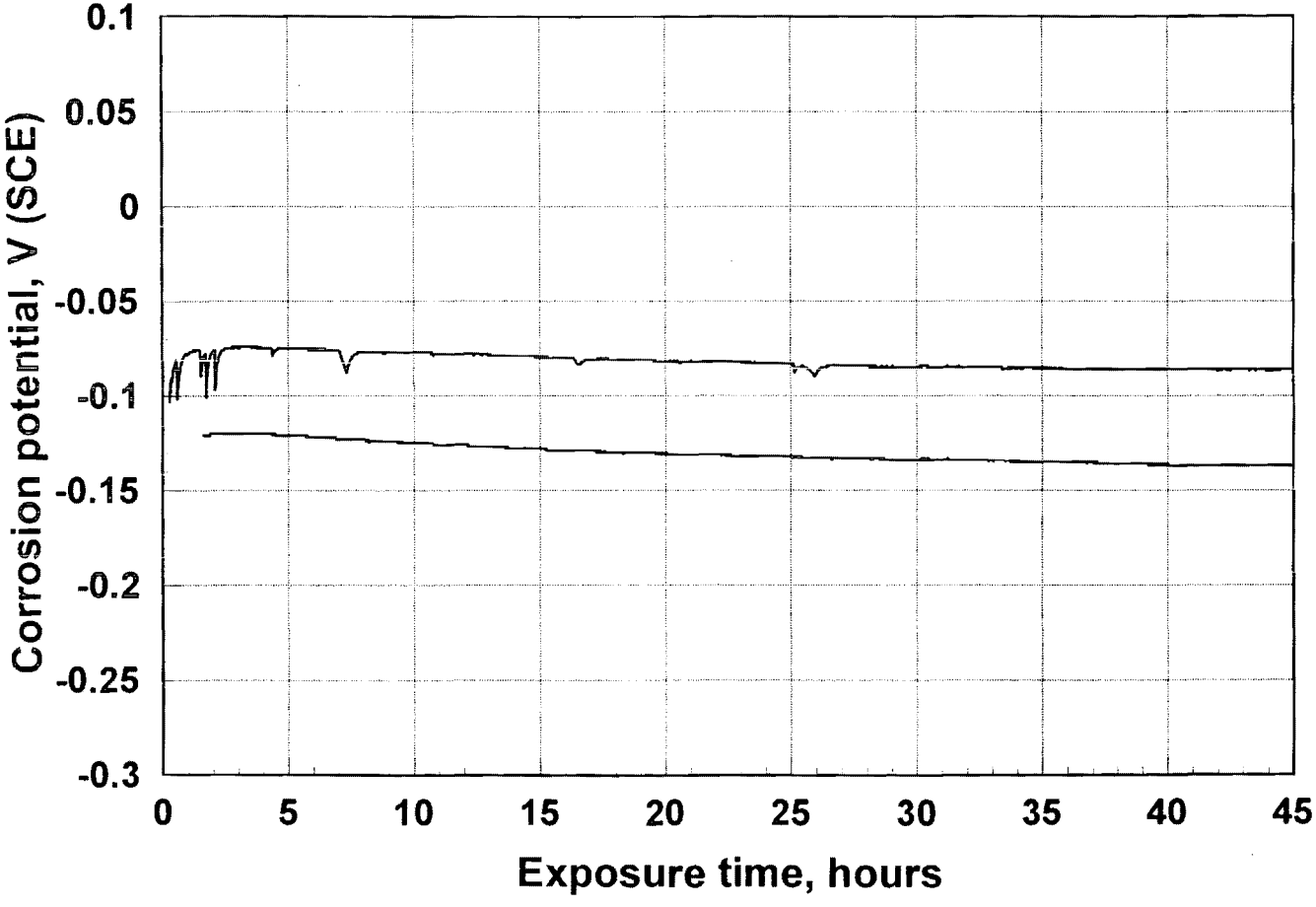

Fig. 1 Lowest and highest values of the corrosion potential in long-term tests.

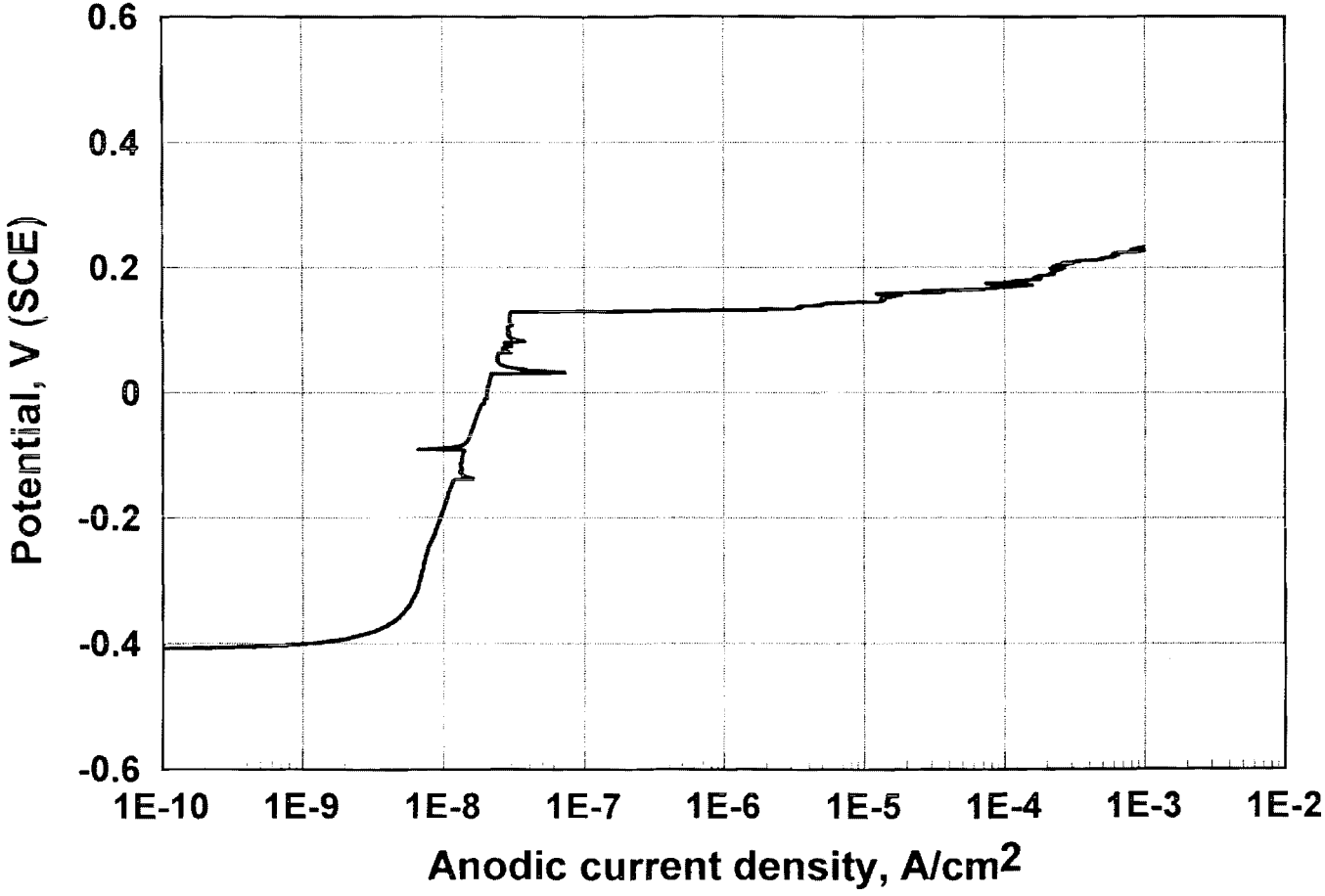

Fig. 2 Potentiodynamic anodic polarization curve.

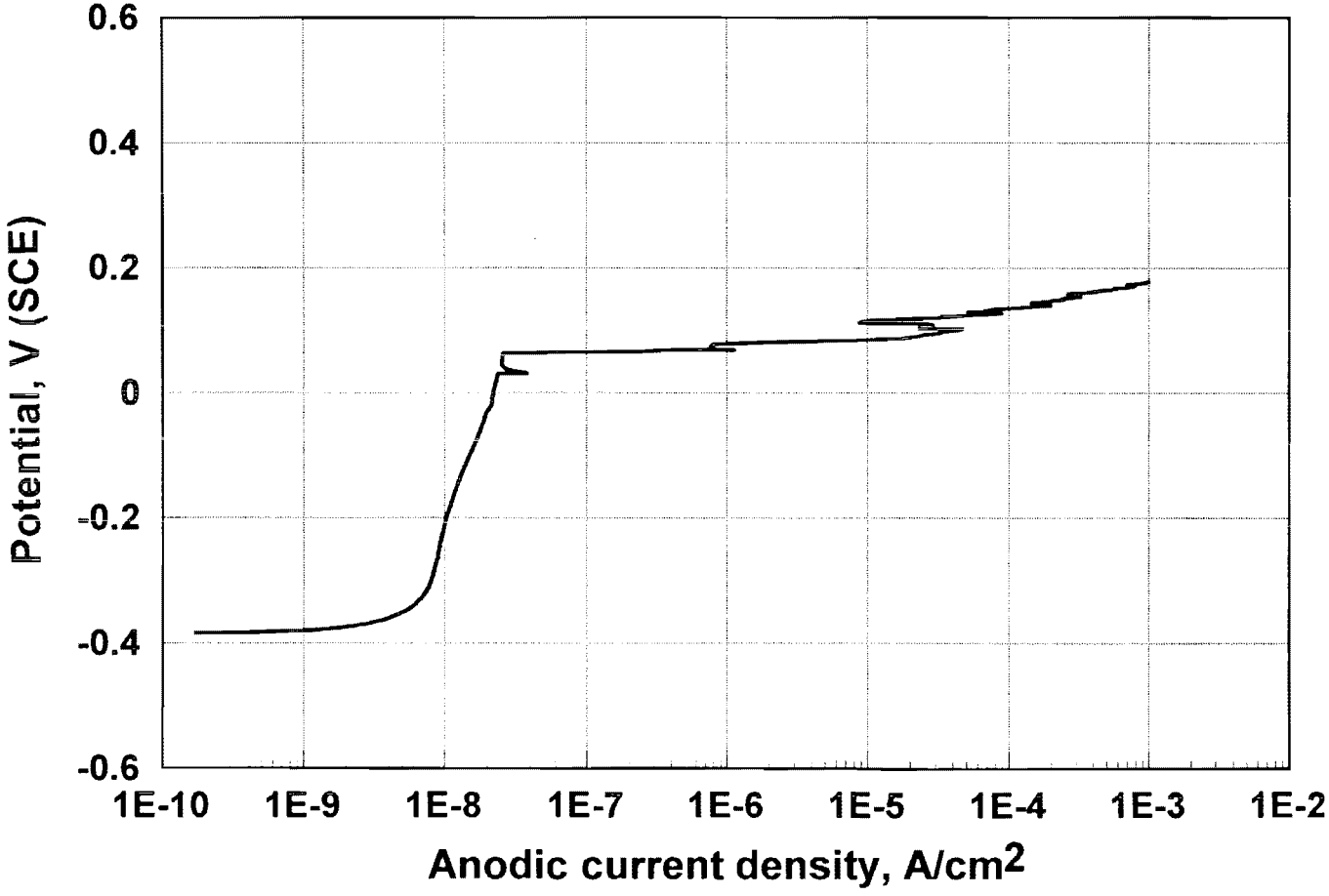

Fig. 3 Potentiodynamic anodic polarization curve.

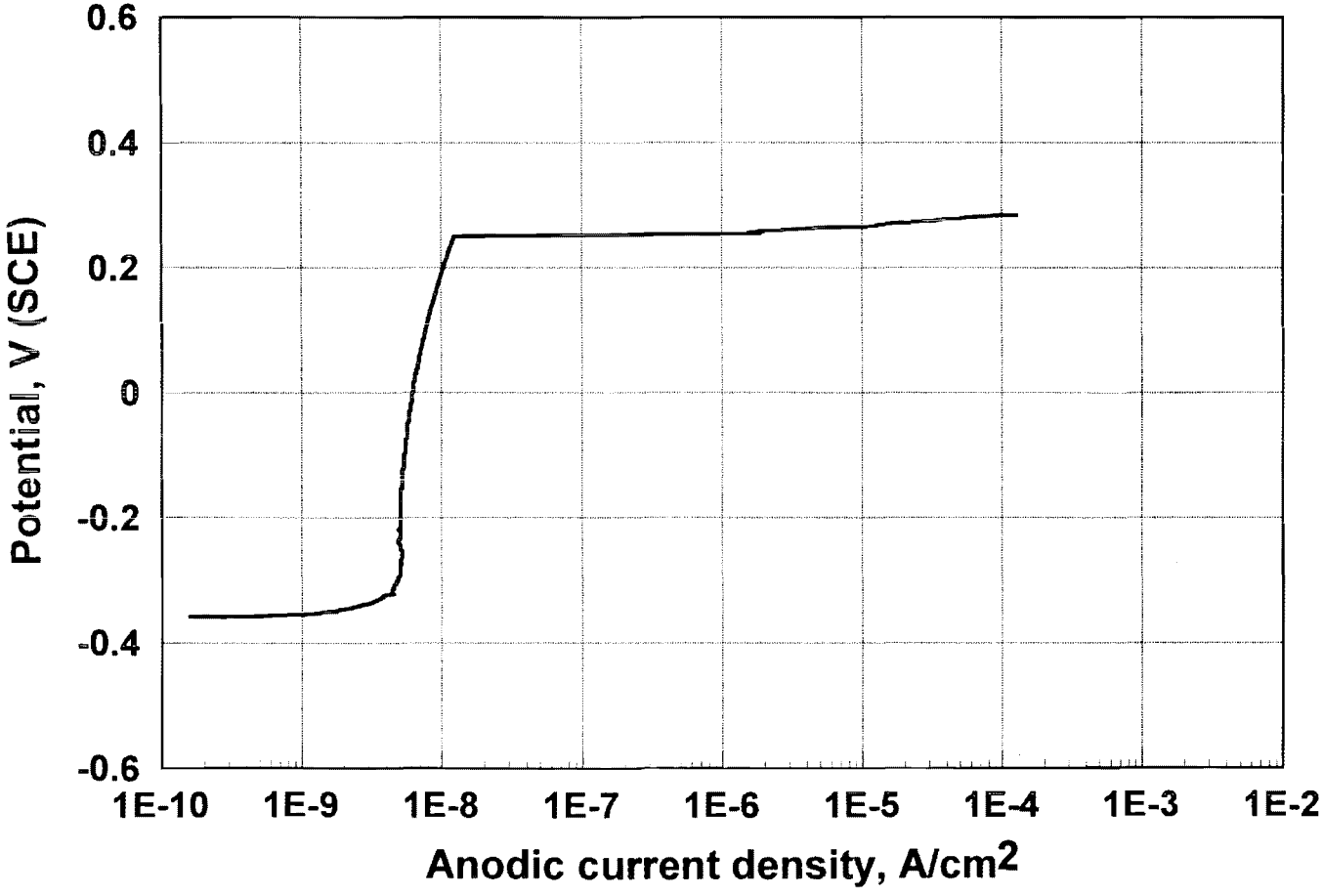

Fig. 4 Potentiodynamic anodic polarization curve.

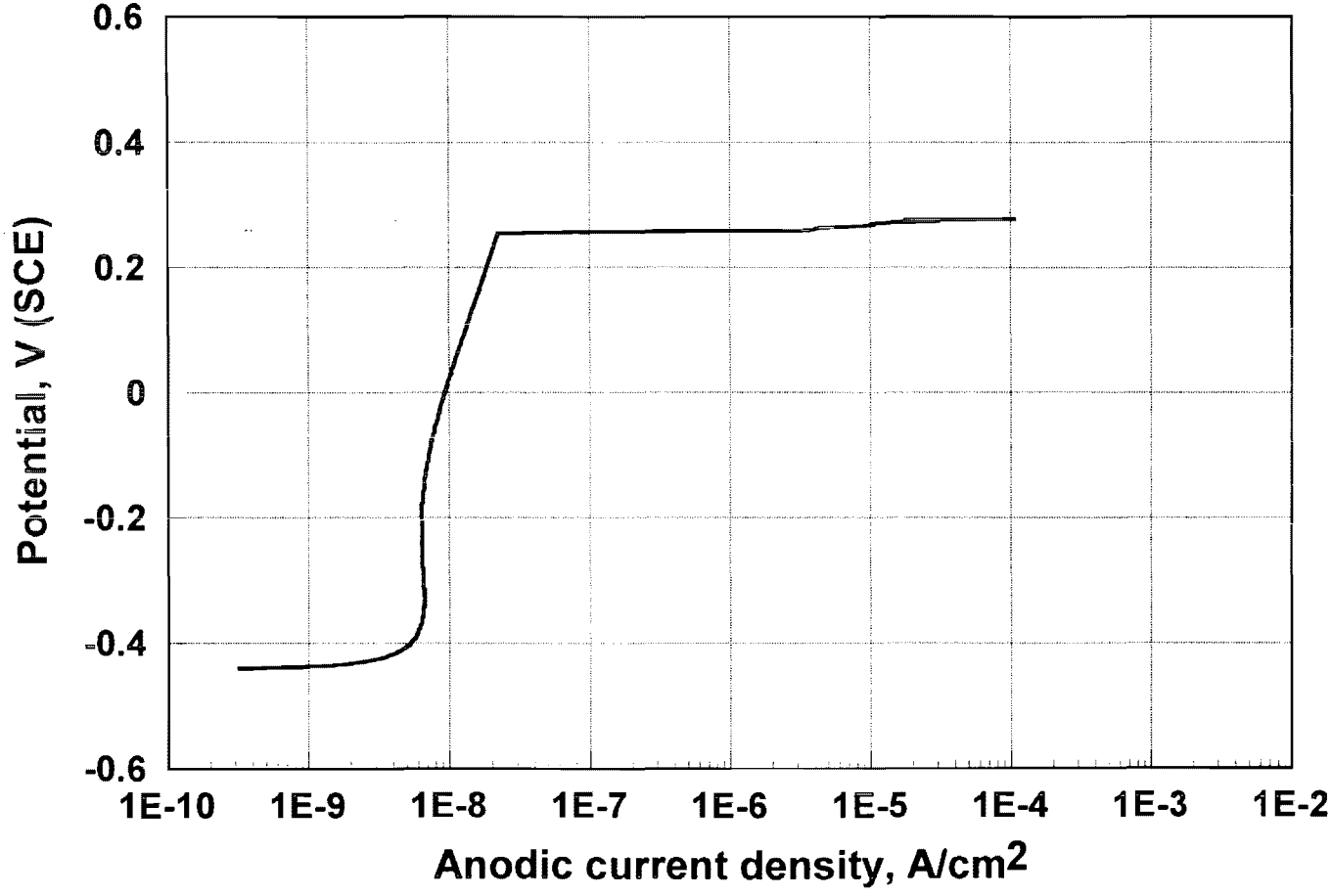

Fig. 5 Potentiodynamic anodic polarization curve.

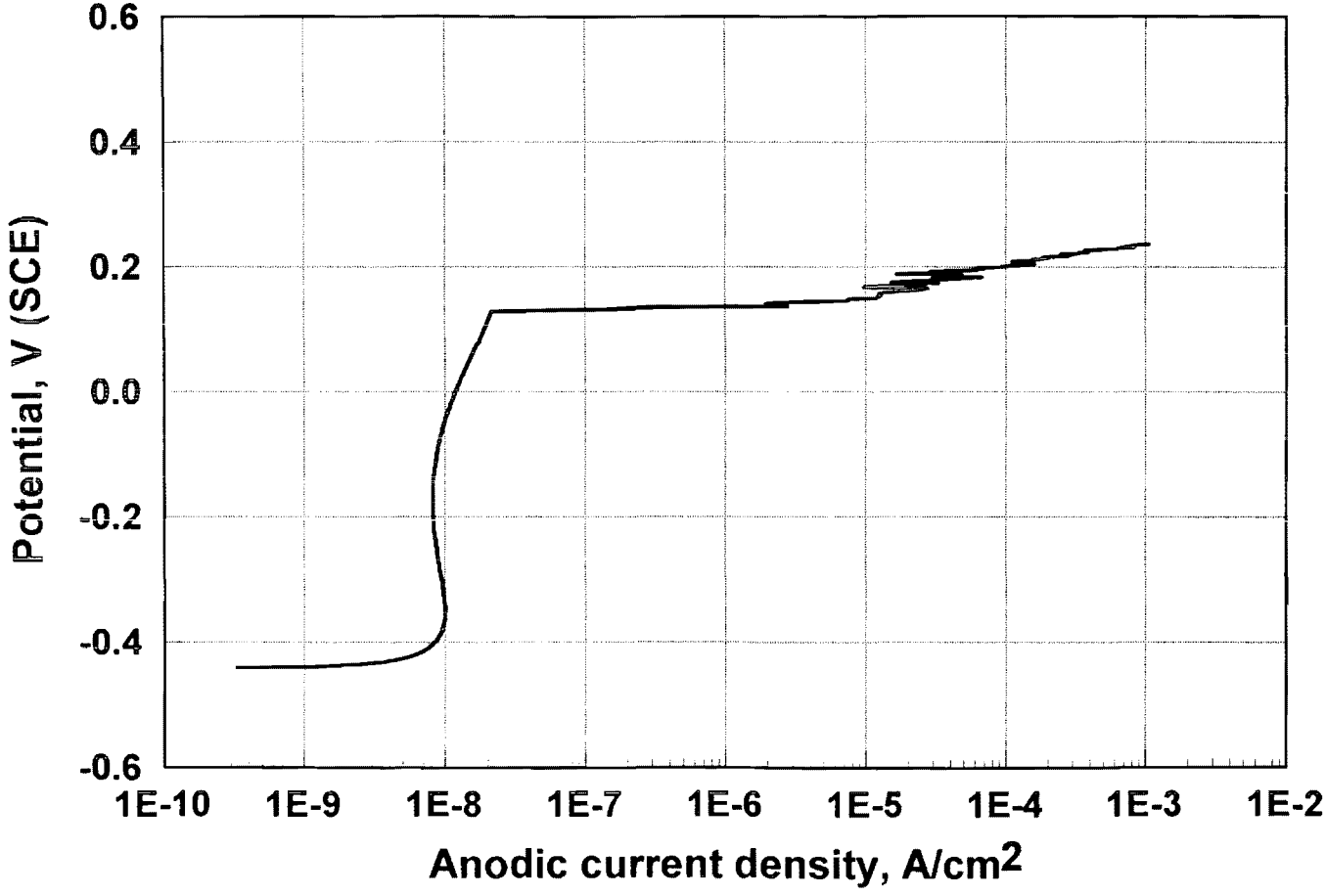

Fig. 6 Potentiodynamic anodic polarization curve.

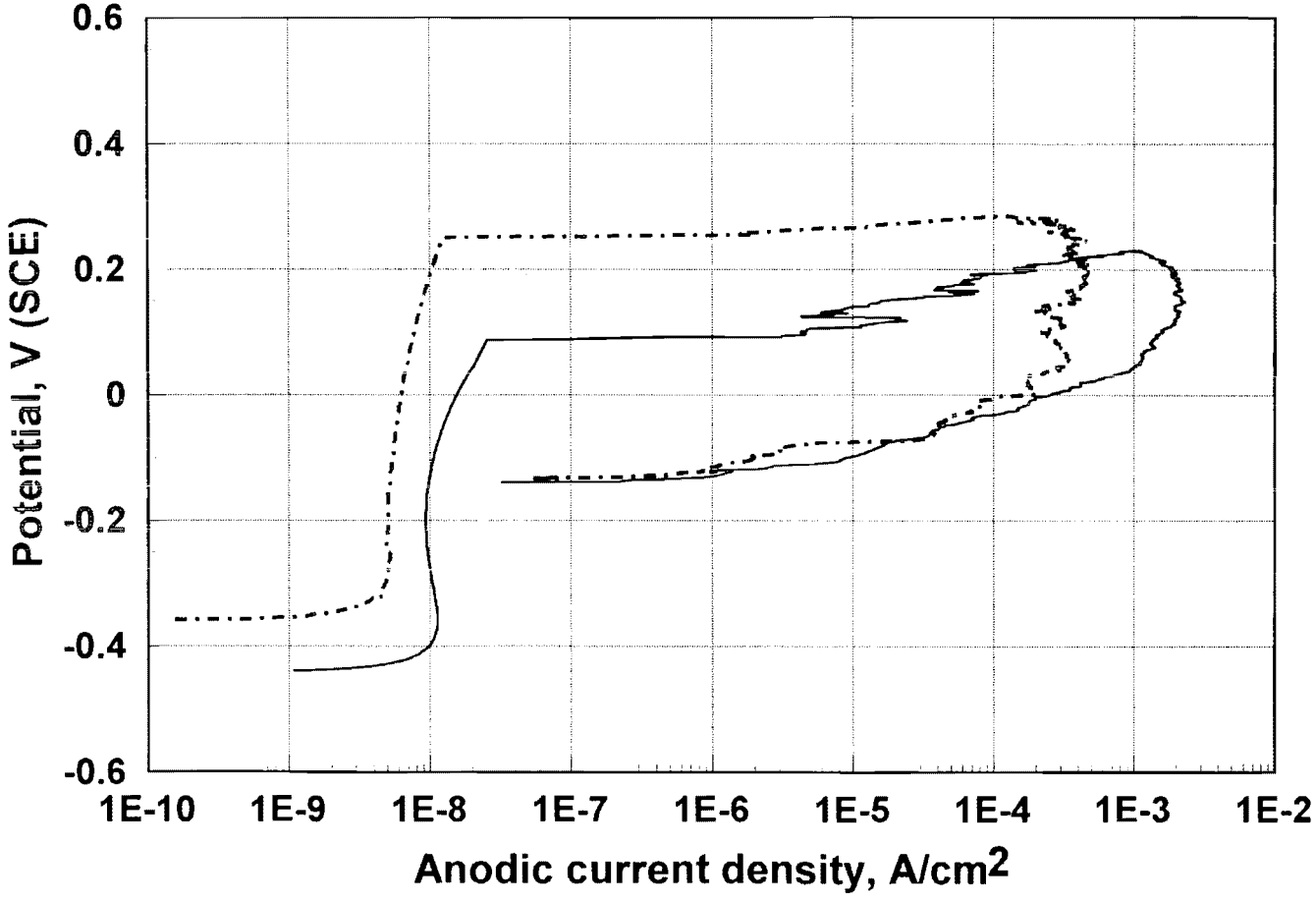

Fig. 7 Typical results of a potentiodynamic repassivation test.

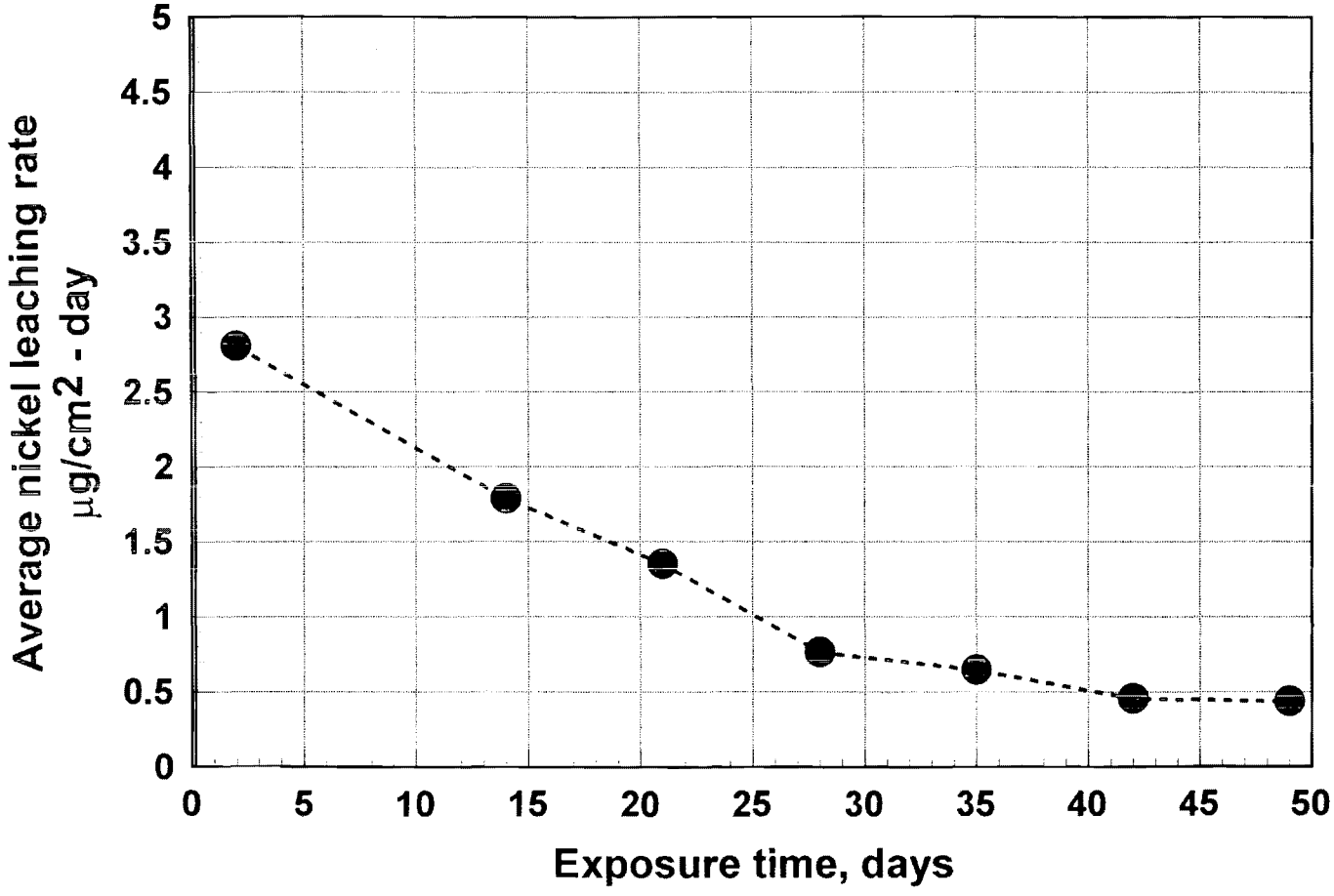

Fig. 8 Nickel release rate as a function of the exposure time, measured using 24-hour test periods.

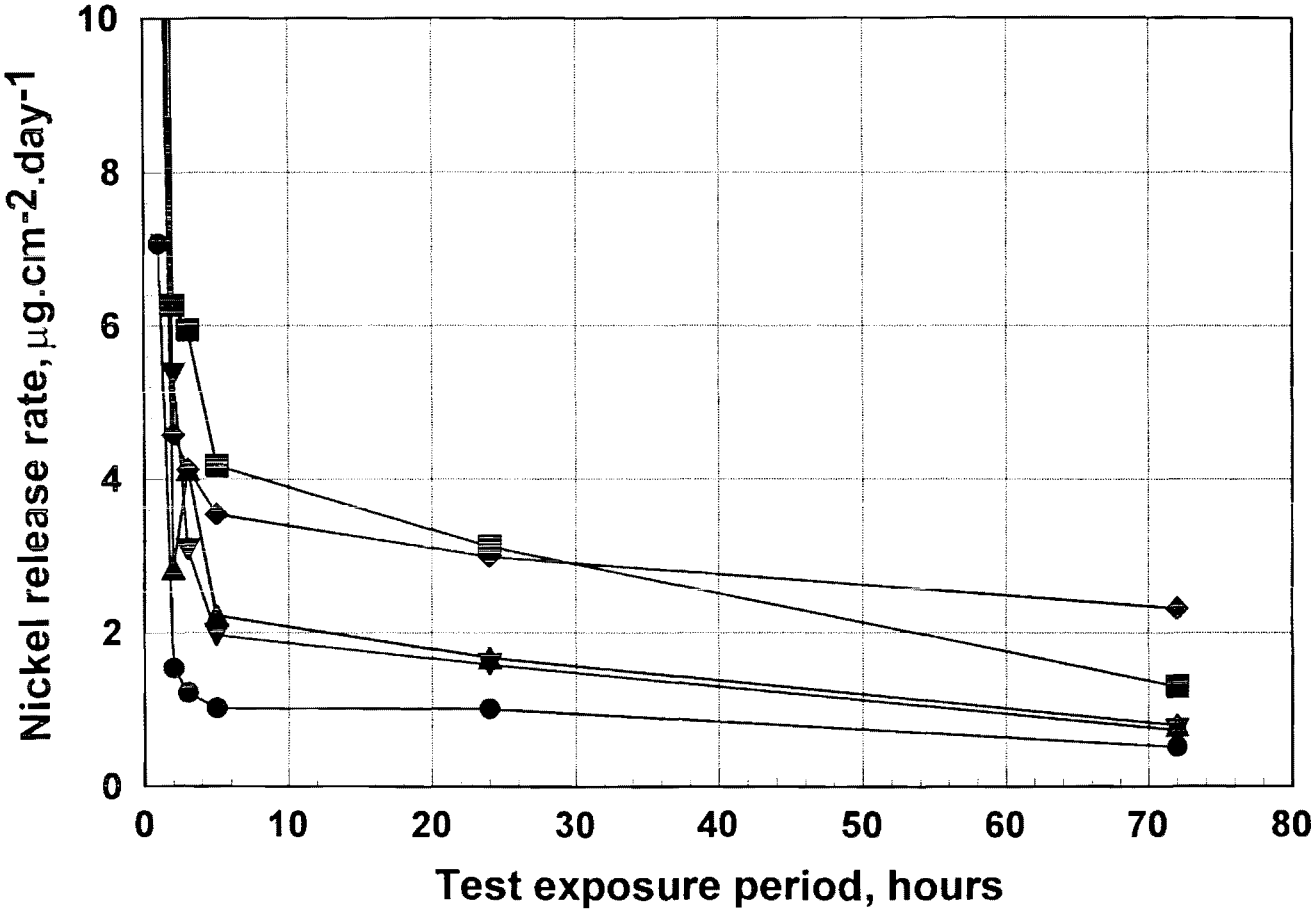

Fig. 9 Nickel release rate as a function of the test period, for a stabilized release condition.

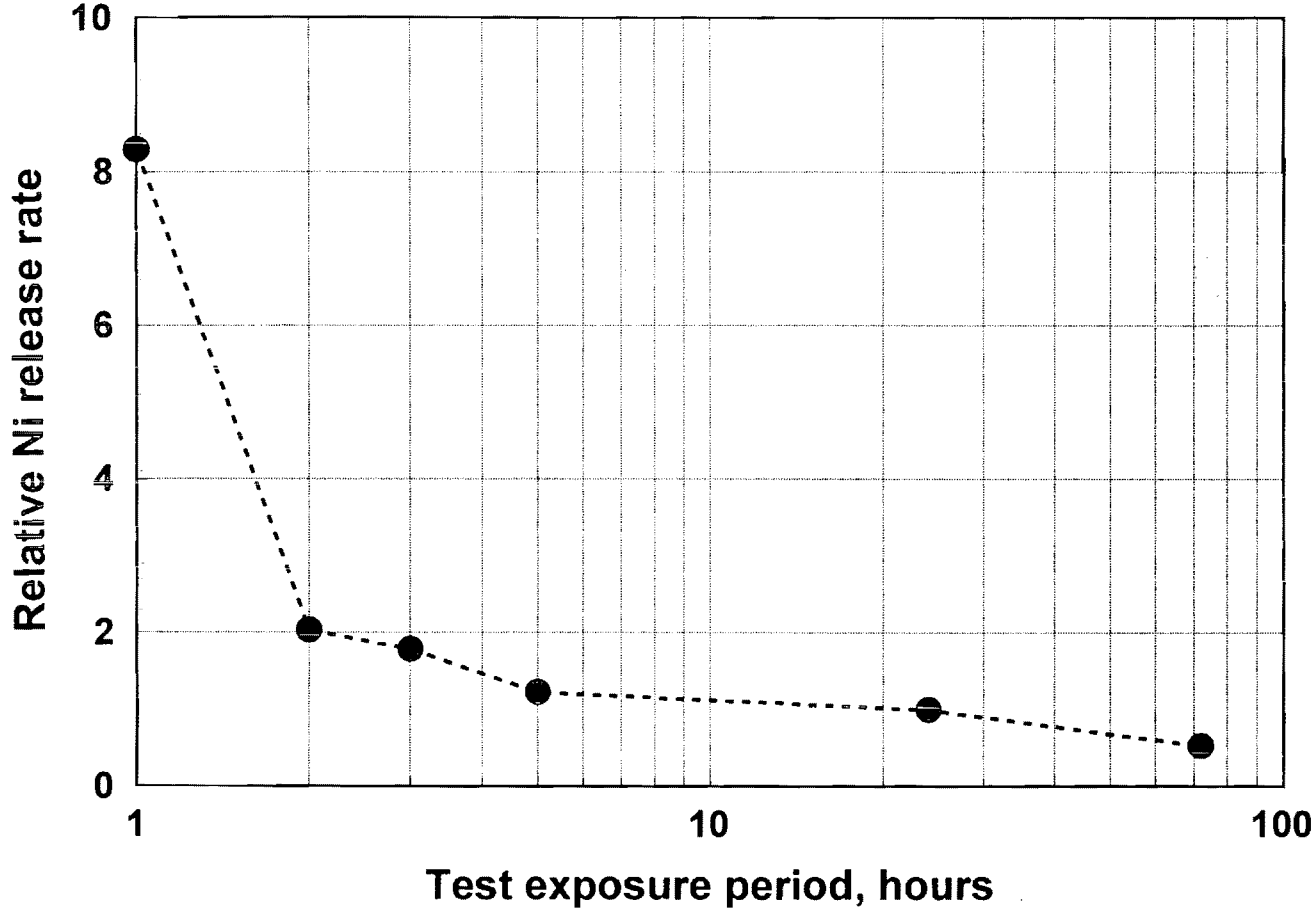

Fig. 9 Nickel release rate as a function of the test period, normalized for a 24-hour test period.

APPENDIX 1

General protocol

Electrochemical Characterization of Dental Alloys

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Appendix 1

I. PURPOSE

The purpose of the electrochemical tests covered by this protocol is to determine the corrosion behavior and corrosion rate of a given material or device when exposed to simulated body fluids.

II. BACKGROUND

Corrosion of metals in aqueous electrolytes, such as body fluids, is an electrochemical process. A metal exposed to an electrolyte establishes a corrosion potential (open circuit electrode potential), which depends on the properties of the electrode as well as the chemistry of the electrolyte. Generally, the corrosion potential varies with time, but may reach a stabilized value after a period of time. Since the chemistry of the actual environment may vary and the laboratory simulation is not perfect, the corrosion behavior of the electrode in a realistic range of potentials must be examined. In the battery of tests covered by this protocol, the open circuit corrosion potential is determined as a function of the exposure time, providing a rough idea of the potentials of interest; the potential-time variation also may reveal changes in the surface condition with time.

The anodic polarization measurements are performed to examine the corrosion behavior of the electrode in a range of potentials. The results are polarization curves, which show the current density, which is proportional to the reaction rate, as a function of the electrode potential. Most metals and alloys used in the human body (except for noble metals) rely on the formation of an oxide surface film (passive film) for protection against corrosion. The anodic polarization measurements reveal the presence or absence of passivity, and the extent (potential range) of the passive condition. The relative values of the current density in the passive region give an indication of the protectiveness of the passive film. If the polarization curves shows an increase in the corrosion rate above a certain potential, the value of this critical potential with respect to the open circuit potential and to the theoretical potential maxima gives an indication of the safety margin for maintaining the passive state.

III. EQUIPMENT

□ Potentiostat EG&G Model 272 (modified) or Model 273

□ 486/66 MHz Computer with National Instruments GPIB IIA interface card, loaded with EG&G Model 352 corrosion test software

□ Printer, H-P Laserjet IIP

□ Three-electrode glass corrosion test cell with jacket for temperature control, custom-made

□ Constant temperature circulator, Fisher Scientific

□ Standard Saturated Calomel Electrode, Fisher Scientific

□ Magnetic stirrer, Fisher Scientific

□ Barnstead Glass Distillation Still, Fisher Scientific Cat. No. 09-028-11

□ Digital Ionalyzer, Orion Research Model 801A

□ Combination pH Electrode, Fisher Scientific Cat. No. 13-620-97

□ Two stage gas pressure regulators with gas flow control valves

IV. MATERIALS:

□ Sodium Chloride NaCl; Puratronic 99.999% Johnson Matthey Cat. No.10862

□ Calcium Chloride $CaCl_2.2H_20$; Certified A.C.S. Fisher Cat. No. C-79

□ Sodium Bicarbonate $NaHCO_3$; Certified A.C.S. Fisher Cat. No. S233-500

□ Potassium Chloride KCl; Certified A.C.S. Fisher Cat. No. P217-500

□ Anaerobic gas mixture, 5 % carbon dioxide, balance nitrogen (compressed gas cylinder)

□ Aerobic gas mixture, 10% oxygen, 5 % carbon dioxide, balance nitrogen (compressed gas cylinder

□ Aerobic gas mixture, 6% oxygen, 5 % carbon dioxide, balance nitrogen (compressed gas cylinder

V. ELECTROLYTE AND ATMOSPHERE

Electrolyte: For simulation of the environment of an implant in human body tissues fluids, modified Ringer's solution is prepared as follows:

In a 1000 mL beaker dissolve the following reagents in about 900 mL of distilled water:

sodium chloride	9.00 g
calcium chloride	0.17 g
potassium chloride	0.40 g
sodium bicarbonate	2.1 g

Transfer to a 1000 mL volumetric flask and make up to volume.

Atmosphere: For simulation of the chemistry of extracellular body tissue fluids use a gas mixture containing 6% oxygen, 5% carbon dioxide, balance nitrogen (aerobic mixture), or 5% carbon dioxide, balance nitrogen (unaerobic mixture).

VI. SPECIMEN PREPARATION:

The preparation depends on the shape and size of the specimen. A typical procedure for wire material, or for devices made of a wi re or similar material is as follows. The wire specimen or device is attached to one end of a stainless steel wire 1 mm dia., 17 cm long, by welding using a capacitor spot welder. The wire has been degreased in trichlorethylene before welding, and the specimen either also has been degreased, or is touched only using clean stainless steel tools. The stainless steel wire is inserted into a glass tube, 6 mm O.D. 1.5 mm I.D., 15 cm long, so that the welded joint is next to the end of the glass tube. A piece of Teflon tubing, slightly less than 6 mm. I.D. and 12 mm long is slipped over the glass tube at the end where the joint with the specimen is located. The Teflon tubing extends over the end of the glass tube to a distance needed to surround the wire/specimen joint. The tube is placed vertically in a rack with the specimen on top, and the end of the Teflon tubing is filled with fresh mixture of metallographic epoxy resin and

hardener. When the epoxy resin hardens the specimen is ready for testing. The glass tube holder fits in the central port in the top of the corrosion cell where it is sealed with a fitting and an "O" ring; the specimen extends into the jacketed part of the cell, filled with the electrolyte.

VII. POLARIZATION CELL

A three-electrode corrosion test cell is prepared as follows. Wash the interior of the cell three times with distilled water. Place a magnetic stirring bar on the bottom of the cell. Insert the Luggin capillary of the salt bridge through the spherical joint in the side of the cell and secure the salt bridge with a clamp. Pour 400 mL of Ringer's solution in the cell. Place the cell on the top of the magnetic stirrer and adjust the stirrer for moderate stirring speed. Fill the bottom part of the salt bridge with Ringer's solution and attach it to the top part. Insert the external end of the salt bride, equipped with the glass frit junction, into the reference electrode reservoir, half-filled with Ringer's solution. Insert the Saturated Calomel Electrode in the other opening of the reservoir. Attach the hoses of the Constant Temperature Circulator to the inlet and outlet of the cell jacket using quick-connects. Place an "O" ring on the cell flange.

Insert the glass tube specimen holder in the central port in the cell top and secure it with an "O" ring and a fitting. Adjust the platinum electrode wire to surround the specimen. Place the cell top on the flange of the cell bottom and secure it with a clamp. Insert the thermometer in the port on the cell top with a fitting and an "O" ring. Insert the gas dispersion tube in the ground joint on the cell top, and the outlet tubing into a flask filled with distilled water.

Start the Constant Temperature Circulator. If necessary, adjust the temperature to 37°C. Turn on the gas cylinder valve and adjust the flow of the gas to medium-fast bubbling from the gas dispersion tube (type of gas depends on the test to be performed - see specific test section).

Appendix 1

Test protocol

Potentiodynamic Anodic Polarization Measurements

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Appendix 1

Potentiodynamic Anodic Polarization Measurements

The test procedure generally follows the ASTM G-5 Standard Recommended Peactice for Standard Refer4ence Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements.

I. OBJECTIVE

The purpose of the test is to record the anodic polarization curves for the submitted material or device. The anodic polarization curves show how the anodic (corrosion) current density varies with the electrode potential. In combination with the data for the open circuit potential the anodic polarization curves show whether the electrode is active or passive in the given electrolyte, provide a relative indication of the activity of the electrode, indicate susceptibility to pitting, etc.

II. PRINCIPLE

In the potentiodynamic polarization measurement the electrode potential is controlled by the electronic potentiostat and varied at a predetermined rate and in the desired potential range, so that the behavior at various potentials can be examined. The mpore commonly measured anodic polarization curves, which show the corrosion (anodic) current, are generated by scanning the potential from the open circuit potential, or a potential slightly negative to the open circuit potential, in the positive direction. For electrolytes naturally containing dissolved oxygen the solution usually is deaerated (the dissolved oxygen removed) before the test by saturating it with an inert has, such as nitrogen. Since only the difference between the anodic and cathodic current can be measured, deaeration, by reducing the cathodic (reduction) current, makes possible examination of the anodic (corrosion) behavior at a potential the electrode would maintain in the presence of dissolved oxygen.

III. TEST PROCEDURE

Prepare the three-electrode corrosion test cell as described in the General Protocol. Start deaeration by bubbling the anaerobic gas mixture through the solution in the cell. Connect the corrosion cell to the terminals of the potentiostat: the specimen to the working electrode terminal, the platinum electrode to the counter-electrode terminal, and the reference electrode (Saturated Calomel Electrode) to the reference electrode terminal. Start the EG&G Model 352 corrosion test program, select potentiodynamic polarization and enter the specimen data: Specimen identification, type of electrolyte and atmosphere, test temperature; exposed surface area of the specimen. If necessary enter the test parameters: potential scanning rate 0.1667 mV/s (10 mV/min), potential step 1 mV, starting potential -0.15 V with respect to the open circuit potential. Enter the end potential either on the basis of previous results, or use 0.8 V with respect to the reference electrode (0.8 V, SCE). Save the setup in a file with an appropriate file name and .DAT extension.

Engage the Cell Enable Switch. Enter the RUN command. When the test terminates automatically or by command save the results under the previously entered file name with the .DAT extension.

XII. DATA PROCESSING

For preliminary evaluation of the results examine the polarization curveon the screen or print a hard copy using the EG&G Model 352 software and a Laserjet printer. For formal reports export the data (file name with .TXT extension) and import the file in the Stanford Graphics data analysis software program. Plot the curve or curves using scaling that allows a fair comparison of test results for different specimens.

Appendix 1

Test protocol

Corrosion Potential Measurements

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Corrosion Potential Measurements

I. OBJECTIVE

The purpose of the test is to measure the value and variation of the open circuit corrosion potential with time. The potential of the specimen actually is a potential difference with respect to the reference electrode (Saturated Calomel Electrode).

II. PRINCIPLE

The open circuit potential is established spontaneously as the potential, at which the rates of the anodic and cathodic reactions are equal. It depends on the properties of the electrode as well as the chemistry of the electrolyte. The corrosion potential generally varies with time. For passivating metals the corrosion typically increases with the time of the exposure and approaches a stabilized value after a period of time. If the passive film is broken or corosion in any of the active forms takes place the corrosion potential shifts in the negative direction.

The corrosion potential can be measured using an stand-alone electrometer and recorded using a suitable recorded. Since an electronic potentiostat also containes an electrometer it is often convenient to use the potentiostatic setup to record the potentil-time variation. Only long-term corrosion potential measurements will be performed using a stand-alone electrometer to free the potentiostatic setup for other tests.

Two-hour corrosion potential measurements provide a rough idea of the short-term open circuit potential behavior, but the potential in most cases still changes with time. A 15 hour potential-time measurement is a good compromise between short-term (one ot two hours) and truly long-term (2-4 weeks) measurement.

III. TEST PROCEDURE

Prepare the three-electrode corrosion test cell as described in the General Protocol. Start aeration by bubbling the aerobic gas mixture through the solution in the cell. Connect the corrosion cell to the terminals of the potentiostat: the specimen to the working electrode terminal, and the reference electrode (Saturated Calomel Electrode) to the reference electrode terminal; the platinum electrode does not have to be connected. Start the EG&G Model 352 corrosion test program, select corrosion potential vs. time program and enter the specimen data: Specimen identification, type of electrolyte and atmosphere, test temperature; exposed surface area of the specimen (not required but useful). Enter the test parameters: Total exposure time, and step time; the maximum number of data points per test is 3000. Save the setup in a file with an appropriate file name and .DAT extension.

Engage the Cell Enable Switch. Enter the RUN command. When the test terminates automatically or by command save the results under the previously entered file name with the .DAT extension.

XII. DATA PROCESSING

For preliminary evaluation of the results examine the potential-time curve on the screen or print a hard copy using the EG&G Model 352 software and a Laserjet printer. For formal reports export the data (file name with .TXT extension) and import the file in the Stanford Graphics data analysis software program. Plot the curve or curves using scaling that allows a fair comparison of test results for different specimens. For plotting of multiple polarization curves it is useful to delete the cathodic data points to improve clarity.

APPENDIX 2

Test protocol

Static Nickel Leaching Test

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Static Nickel Leaching Test

I. PURPOSE

The purpose of the test is to determine the rate of dissolution of nickel from the tested material or device.

II. BACKGROUND

Elements leaching from metallic implants are of potential concern. Since the physiological responses generally are dose related, the rate of release is of primary importance. The daily dose or release from a device, based on the release per unit area of the wire, can be compared with an allowable daily intake of each elements. The release rate also has been related to the local tissue response. The release of nickel from medical implant has been of particular concern because of the high incidence of allergic reaction to nickel among the population.

Most implant alloys (stainless steel, titanium, etc.) are passivating metals, and their high corrosion resistance is due to the presence of a very protective, thin oxide film on the surface. The film forms by reaction with the environment and its thickness increases with time, reducing the dissolution rate. Therefore, it is necessary to determine the changes in the dissolution rate as a function of time. However, since the rate of growth slow down with time and the dissolution rate generally approaches a steady state, exposure time of weeks to months generally is sufficient for determination of the leaching behavior.

III. SCOPE

This test will determine the leaching rate of nickel as a function of time in synthetic body fluids at body temperature. In the test covered by this protocol the test coupon is exposed to the solution for an extended period of time, but a fresh solution is used for each 24-hour test exposure. This procedure prevents a large accumulation of the dissolved ions, which would decrease the driving force for dissolution and reduce the dissolution rate.. The test thus simulates the condition of an implant which is exposed to circulating or flowing body fluids, such as blood, urine or bile. For implants that are to be implanted in the tissues which slow

down the transport of ions away from the implant and thus allow a possibly substantial increase in the metal ion concentration in the vicinity of the implant this test serves as the near-worst case test condition by reducing the concentration effect.

IV. EQUIPMENT

- Barnstead Glass Distillation Still, Fisher Scientific Cat. No. 09-028-11
- Radiometer Trace Lab 1 System (Radiometer Copenhagen)
- IBM 486/66 MHz Computer
- Constant Temperature Water Bath, Fisher Scientific
- Digital Ionalyzer, Orion Research Model 801A
- Test Tubes, Fisher Scientific Cat. No. 14-957G
- Test Tube Rack, Fisher Scientific Cat. No. 14-810-11B
- Bacti-Capall Stoppers, Fisher Scientific Cat. No. 14-127-28B
- Graduated Cylinder 1000 mL, Fisher Scientific Cat. No. 08-550H
- Volumetric Flask 100 mL, Pyrex No. 5641
- Volumetric Flask 500 mL, Pyrex No. 5600
- Volumetric Flask 1000 mL, Pyrex No. 5650
- Beaker 1000 mL, Pyrex No. 1000
- Fisher Scientific Pipette 10 mL, Cat. No. 13-650-2L
- Fisher Scientific Pipette 20 mL, Cat. No. 13-650-2N
- Eppendorf Pipette 10 µL, Fisher Scientific Cat. No. 21-370B
- Eppendorf Pipette Tips, Fisher Scientific Cat. No. 21-379-76
- Gas regulator, Fisher Scientific Cat. No. 10-572D
- Gas manifold, custom-made
- Combination pH Electrode, Fisher Scientific Cat. No. 13-620-97

V. MATERIALS

- Aerobic gas mixture, 10% oxygen, 5 % carbon dioxide, balance nitrogen (compressed gas cylinder
- Aerobic gas mixture, 6% oxygen, 5 % carbon dioxide, balance nitrogen (compressed gas cylinder
- Sodium Chloride NaCl; Puratronic 99.999% Johnson Matthey Cat. No.10862
- Calcium Chloride $CaCl_2.2H_20$; Certified A.C.S. Fisher Cat. No. C-79
- Sodium Bicarbonate $NaHCO_3$; Certified A.C.S. Fisher Cat. No. S233-500
- Potassium Chloride KCl; Certified A.C.S. Fisher Cat. No. P217-500
- Nickel Reference Standard 1,000 ppm; Fisher Cat. No.SN70
- Dimethylglyoxime Sodium Salt Hydrate; SIGMA Cat. No. D-1540
- Ammonium Chloride; Suprapure, EM Science Cat. No.1143-1
- Ammonia Solution Min. 25% Suprapure, EM Science Cat. No.5428-1
- Hydrochloric Acid, Fisher Cat. No. A144C-212
- Electrode Plating Solution, Radiometer 2201.

VI. SPECIMEN PREPARATION

The materials specifications and fabrication of the test coupons, and determination of the exposed surface area are covered in specific protocols.

VII. ELECTROLYTES AND ATMOSPHERES

Electrolyte: For simulation of the environment of an implant exposed to human body tissues fluid (extracellular fluid) or arterial blood, modified Ringer's solution is prepared as follows:

In a 1000 mL beaker dissolve the following reagents in about 900 mL of distilled water:

sodium chloride	9.00 g
calcium chloride	0.17 g
potassium chloride	0.40 g
sodium bicarbonate	2.1 g

Transfer to a 1000 mL volumetric flask and make up to volume.

Atmosphere: For simulation of the chemistry of extracellular body tissue fluids use a gas mixture containing 6% oxygen, 5% carbon dioxide, balance nitrogen (aerobic mixture), or 5% carbon dioxide, balance nitrogen (anaerobic mixture). For simulation of the arterial blood chemistry use a gas mixture containing 10% oxygen, 5% carbon dioxide, balance nitrogen (aerobic mixture), or 5% carbon dioxide, balance nitrogen (anaerobic mixture).

Other environments: For simulation of the environments other than extracellular fluid or blood, such as urine or bile, see specific protocols.

VIII. TEST TUBE PREPARATION

Drill and a hole using a 1/8" drill bit in the plastic Bacti-Capall Stoppers for test tubes. Wash the test tubes and the stoppers thoroughly using deionized water. Set the test tube rack in the

controlled temperature water bath, set at 37°C. Use a plastic water bath cover, in which holes had been drilled for the 1/8" Teflon tubing carrying the gas mixture from the manifold.

IX. TEST INITIATION

Place test coupons in the test tubes and pipette the test solution in each test tube. The amount of the solution depends on the size and surface area of the test coupon. For coupons smaller than 2 cm^2 use 10 mL per test tube, unless a larger volume is necessary to cover the coupon with the solution. For larger coupons use 20 mL per test tube. Pipette 20 mL of the test solution in an empty test tube as a blank. Put the plastic stoppers on the test tubes and place the test tubes in the rack in the water bath.

Push the 1/8" Teflon tubes from the manifold through the holes in the plastic cover and through the holes in the plastic stopper. Insert the tubes to within 5-10 mm from the bottom of each test tube. Lower the plastic cover of the water bath. Check the position of the tubing in the test tubes.

Turn on the valve on the compressed gas cylinder and adjust a pressure of 10-15 psi. Use the appropriate gas mixture (see Section VII). Turn on the manifold valves to bubble the gas through the solution at a rate of about 2 bubbles par second.

X. TEST EXPOSURE

One day before the selected total exposure time open the cover of the water bath, pull the 1/8" Teflon tubing from the test tubes, open each test tube and discard the solution, fill the test tube with deionized water, and discard the washing. Repeat two more times. Refill the test tubes with a fresh test solution. Assemble the test tubes, the gas lines and the cover as described in Section IV.

XI. SOLUTION SAMPLING

At the end of the 24-hour test exposure pull the gas lines from the test tubes, open the cover of the water bath and remove the caps from the test tubes Transfer the 20 mL solution

samples into 100 mL volumetric flasks and the 10 mL solution samples into 50 mL volumetric flasks; fill the test tubes with deionized water; insert the caps on the appropriate test tubes to wash the specimen with water, and remove again. Process the test tube containing the blank the same way. Add the washings to the flasks. Repeat two more times. Make up the volume in the flasks (100 mL or 50 mL) with distilled water. Pipette new test solution into the test tubes and assemble the setup as described above.

XII. SOLUTION ANALYSIS BY STRIPPING VOLTAMMETRY

1. Prepare ammonia buffer by dissolving 26.8 g of ammonium chloride in 500 mL volumetric flask half-filled with distilled water. Add 75 mL of 25% ammonia solution and make up to volume.
2. Prepare a 0.1 moles/L DMG solution by dissolving 3.04 g of a dimethylglyoxime sodium salt in distilled water in a 100 mL volumetric flask; make up to volume.
3. Prepare 1 ppm nickel standard solution by diluting 1 mL of 1000 ppm Nickel reference Solution (Fisher Scientific SN 70-500) in 1L volumetric flask with distilled water and make up to volume. Fill the AUTOBURETTE with the solution.
4. If necessary, based on experience or previous results, dilute solutions from the specimen test tubes to lower the nickel concentration into a range suitable for analysis. Record the dilution factor on the test sheet.
5. Turn on the Radiometer Trace Lab equipment and start the TAP2 program. Plate the glassy carbon electrode of the Trace Lab cell as follows: Lower the electrode into a beaker containing the plating solution. Select F2 on the main menu to start the plating procedure. Perform the Electrode Test.
6. Load the "Nickel in water, Ni-ABU3 method and perform the basic calibration as follows: Use the solutions from the blank test tube as blank. Deaerate with nitrogen for 1 minute. Select F2 on the main menu to start calibration.
7. Perform the analysis of the solutions from the specimen test tubes as follows: Pipette 20 mL of the solution from the volumetric flask, add 2 mL ammonia buffer and 0.1 mL 0.1

moles/L DMG solution into the beaker. Deaerate with nitrogen for 1 minute. Select F1 on the main menu to start the analysis.

8. Print and store the analytical data. Record the result of the analysis provided by the analytical software of the Radiometer Trace Lab in a data sheet. If a dilution factor was used, calculate the concentration in each volumetric flask (100 mL or 50 mL) containing the sample solution by multiplying the analytical result by the dilution factor and record it on the data sheet.

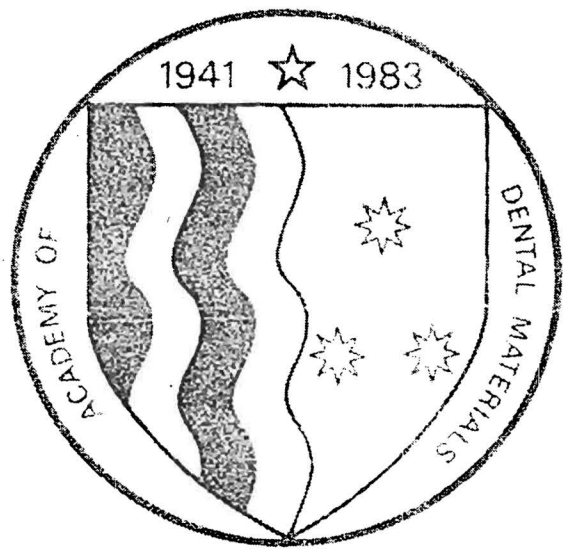
XIII. DATA PROCESSING

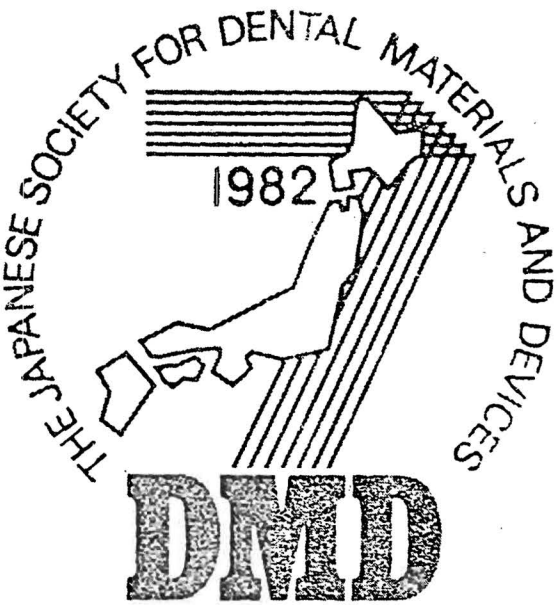
Enter the concentration data for each volumetric flask in a spreadsheet for each specimen and total exposure time. In Sheet 1 of a linked spreadsheet calculate the concentration in each test tube by multiplying the concentration in the volumetric flask by the ratio of the volume of the volumetric flask to the volume of the solution in the test tube. In Sheet 2 of the linked spreadsheet calculate the total amount of nickel [μg] dissolved in a 24 hour test period from a specimen (device) by multiplying the concentration in the volumetric flask [ppb = 10^{-9} g/mL] by the volume of the solution [mL], and dividing by 1,000 and by the number of the specimens in the test tube (if different from one), for each specimen and total exposure time. In Sheet 3 of the linked spreadsheet calculate the amount of nickel dissolved per unit area [μg /cm^2] in a 24 hour test period by dividing the values in the data cells of Sheet 2 by the surface areas of the specimens, for each specimen and total exposure time.

Transfer the data from the spreadsheet into the plotting program and plot the results as required.

TRANSACTIONS

SECOND INTERNATIONAL CONGRESS ON DENTAL MATERIALS





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Edited by: Dr. Toru Okabe
Dr. Shigeo Takahashi

Appendix 3

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MEASUREMENT OF ION RELEASE FROM DENTAL ALLOYS

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ABSTRACT

Dissolution measurements provide information on the identity of elements released from dental alloys and rates of their release. Laboratory tests are performed using simulated oral or tissue fluids; after periods of exposure, the solution is analyzed for dissolved ions. Solid corrosion products can be included in the determination or analyzed separately. In most clinical tests, saliva is analyzed after a period of collection in the mouth. Various analytical techniques are available for a quantitative determination of metal ions in liquid samples including Atomic Absorption Spectrophotometry, Inductively-coupled Plasma Emission Spectroscopy, Anodic Stripping Voltammetry, Nuclear Activation Analysis, and Radioactive Tracer Analysis. Detection limits of parts per billion (ppb) or even parts per trillion (ppt) are achievable. The increasing dissolved ion concentration during the test tends to decrease the dissolution rate and may cause error in the interpretation of the data. In tests of metal ion release from galvanic couples, and in controlled potential tests, plating of the dissolved ions on the cathode should be taken into account.

INTRODUCTION

When a solid object is exposed to any environment containing few or no atoms or ions of the material, a release of some these species into the immediate vicinity of the solid almost inevitably occurs. Once some accumulation of the released species takes place near the surface, however, continuation of the release depends on the thermodynamic tendency for dissolution. When placed in the oral cavity or implanted in body tissues, most metals used in dentistry are likely to continue to release metallic ions. Physiological reactions to the released metallic species have become a matter of increasing concern.

While systemic toxicity may be rare or nonexistent for most accepted dental alloys, allergic reactions, which require a relatively low eliciting threshold, and local tissue reactions are of some concern; more data on the rates of the release are needed. The biocompatibility, toxicity, and hypersensitivity of dental alloys were discussed at an

International Workshop (Lang *et al.*, 1986), and the techniques and reported release data were reviewed by Brune (1986).

A measurement of the release of metallic species from dental alloys may be performed with any of the following objectives: (a) To evaluate the danger of adverse physiological reactions; (b) To contribute to the understanding of the mechanism and kinetics of the interaction between the alloy and the environment; (c) To determine the corrosion susceptibility of the alloy. Of these objectives, (c) is least justifiable as a sole purpose of metal ion release tests because it requires determination of absolute values of the release and comprehensive results for all elements in all forms. As discussed below, this condition is very difficult to achieve in all but the simplest systems. As a complement to other corrosion rate measurements, such as those performed by electrochemical techniques, solution analysis can provide very useful additional information and assist in the interpretation of the data (Muller *et al.*, 1990).

With the exception of mercury, the transfer of the metallic species from a dental alloy into the oral or tissue fluids is almost exclusively an electrochemical process, and the released species are positive ions (cations), often in a complexed form. Further chemical or electrochemical transformations may follow in the environment. As shown elsewhere (Marek, 1990), mercury from dental amalgam is more likely released in atomic form. Since atomic mercury dissolved in a liquid environment is easily oxidized to one of the ionic form, the measurement of mercury release into liquids has nevertheless been included. Electrochemical techniques of determination of dissolution current density, which do not provide specific information on the elements released, will not be discussed in this review.

In principle, measurement of the metal ion release, especially *in vitro*, is deceptively simple. The alloy specimen is exposed to a liquid in a simple container; after an exposure allowing the concentration of the metal ions of interest to exceed the detection limit of the analytical technique, the solution is analyzed, and the concentration or the rate of release (or both) are reported. In practice, however, each step involves making choices and is a potential source of errors and misinterpretation.

TEST CONDITIONS AND PROCEDURES

LABORATORY TEST MEDIA. The exposure should simulate as much as possible the conditions in the human body. Thus, the test solution should have a chemistry approximating the chemistry of oral or tissue fluids, including the concentration of dissolved gases, and the temperature should be controlled at body temperature. The alloy specimen should be prepared in the same way the alloy would be processed during the preparation of the dental device. Naturally, these rules are altered when the effect of a particular variable on the ion release is to be examined.

In practice, because of the complexity of the oral environment and tissue fluids, *in vitro* tests are performed using synthetic electrolytes of much simpler chemistry. Synthetic salivas of various formulas (Marek, 1983), and various body fluid replacement solutions are commonly used in dissolution tests. Ideally, the electrolyte should contain in proper concentrations all the components which play significant roles in the dissolution process, and lacking those, should contain components that do not affect the interaction, in an effort to minimize possible interferences in the analysis. Since this information generally is not available, results of *in vitro* tests truly represent only the ion release in the test solution. Ranking of alloys of similar type on the basis of such tests can be justified,

assuming that the test medium has been intelligently chosen. Predictions of absolute release rate on the basis of *in vitro* tests seldom are appropriate.

The solutions may be open to air to allow natural aeration, but the dissolution vessels should be loosely covered to minimize evaporation. Evaporated water should be replaced. If vessels are sealed, depletion of dissolved oxygen by the reduction reaction may substantially change the interaction. In mercury dissolution tests, however, since mercury dissolves in atomic form and as such can escape by vaporization, open-to-air tests generally measure the rate of mercury oxidation in the solution, rather than the total rate of mercury release (Marek, 1990). Unless the vaporized mercury is separately analyzed, the only way to avoid this error is to use completely filled, closed dissolution vessels.

EXPOSURE PERIOD. The exposure period should be carefully chosen. Since some analytical techniques require only small amounts of solution, it is often possible to sample the bulk solution periodically with or even without solution replacement. Whether the solution is periodically replaced or not, the effect of its solution changes with time should be taken into account, as discussed later.

There are several solution chemistry changes with time that may affect the dissolution results, but which are relatively easily dealt with. The cathodic reactions, which normally are either reduction of dissolved oxygen or reduction of hydrogen ions, tend to cause a pH increase with time. Since biological fluids are effectively buffered, it is appropriate to use buffered test solutions and keep pH constant. If the bicarbonate/carbon dioxide system is used in the electrolyte, an atmosphere containing CO_2 is required (Wald and Cocks, 1971). Buffering also may prevent acidification by hydrolysis of metal ions when the solubility product is exceeded and solid corrosion products precipitate. Changes in the dissolved oxygen concentration may be prevented by continuous saturation of the solution with an inert gas containing an appropriate oxygen content. Some organic-containing solutions provide nutrients for bacterial growth, and sterilization or the use of a bactericide may be necessary in long-term exposures.

OTHER EXPOSURE CONDITIONS. The corrosive medium should be gently stirred, if possible. Since most dental alloys corrode at a very low rate, mass transport control of the corrosion reactions is unlikely, however. Vigorous shaking is inadvisable, especially for brittle materials such as dental amalgam, since it may cause a release of metallic debris and substantially increase the surface area of the solid and thus, total dissolution. Metal ion release rates determined under dynamic conditions, such as under variable stress, abrasion, etc., provide unique information on the studied effects.

The geometry and positioning of a specimen in the dissolution vessel may be critical. Corrosion at sharp edges usually is faster than on flat surfaces, and results for sharp-edged specimens may be difficult to compare with data for flat specimens. Perhaps most important is to avoid creation of crevices, such as between the specimen and the vessel or under gaskets, unless the objective of the study is to measure the metal ion release under crevice corrosion conditions.

SOLID CORROSION PRODUCTS. In many cases, reactions of a dental alloy with the environment result in a formation of solid corrosion products. Loose corrosion products should be considered a form of metal ion release; when formed in the oral cavity, they would enter the digestive tract and possibly dissolve in the acidic gastric juices (Brune *et al.*, 1983). Results of some of the analytical techniques include solid corrosion products which have separated from the metal in the total release. In some other techniques, solid products may be dissolved before the analysis (Berge *et al.*, 1982; Moberg 1985). Solid corrosion products also may be separated by filtration or other

techniques and analyzed separately (Brune, 1986). Tightly adherent products, and those forming within the structure, usually are excluded from the ion release determination.

ANALYTICAL TECHNIQUES. A variety of techniques can be used for the analysis of liquid samples and solid corrosion products. Their choice depends on the availability of the facilities, the detection limit, cost, convenience, etc. Following is a brief characterization of the most useful techniques; several other techniques are available but less popular.

Atomic Absorption Spectrophotometry (AAS). The most commonly employed technique by far for metal ion determination in liquids (e.g., recently, Gjerdet and Herø, 1987; Lappalainen and Yli-Urpo, 1987; Schwickerath, 1988; Moberg and Johansson, 1991; Torgersen and Gjerdet, 1992; Wataha *et al.* 1991, 1992), AAS involves atomization of the sample either in a flame, or by electrothermal means (most commonly, electrically heated graphite furnace). The presence of a metallic element is detected by absorption of a light beam at a characteristic wavelength, the absorbance being a function of the amount of the element in the vapor. Samples normally are stabilized by acidification; those containing organic substances such as proteins often are first digested using a combination of acids and heat. Interferences are minimized by comparing the absorbance at the characteristic wavelength and at the wavelength of a deuterium lamp.

AAS is fast, and modern spectrophotometers often are highly automated; the instruments are moderately expensive and available in many laboratories. Only one element is determined at one wavelength setting, however. Some instruments are capable of automated sequential multi-element determination. Detection limits in flame AAS are in the ppm (μg/mL) to ppb (ng/mL) range, depending on the element. With graphite furnace atomization, the required sample volume is on the order of microliters, and sensitivity is very high, but precision and reproducibility are lower than in flame AAS; detection limits are in the ppb to ppt (pg/mL) range. Dynamic range of AAS is relatively low, and interferences are often serious, especially in graphite furnace atomization.

For dissolved mercury analysis, a cold-vapor procedure is used instead of high temperature atomization. The stabilized solution (in which all mercury has been oxidized to an ionic state) is treated with a highly reducing substance such as stannous chloride or boron hydride. This converts ionic mercury to atomic mercury which is then driven out of the solution by inert gas, and the gas/mercury vapor mixture flows through a transparent cell placed in the optical path of the spectrophotometer. The technique is highly sensitive (detection limit about 0.1 ppb of Hg in the sample), and the detection limit can be further lowered by a factor of 10 or more by using preconcentration, in which the mercury vapor is first adsorbed on a gold foil, and then released by heating the foil.

Inductively Coupled Plasma Emission Spectroscopy (ICP-ES). In ICP-ES, a sample is nebulized, carried in a stream of argon, and injected in a plasma torch, operated in an intense RF magnetic field. A high-temperature plasma is formed as the argon gas is ionized in the RF field, generating characteristic atomic emission of the elements in the sample. The spectrum is analyzed and spectral intensities are converted to concentration. Muller *et al.* (1990) used ICP-ES to study metal ion release from nickel-based dental alloys.

ICP-ES allows true simultaneous multi-element analysis; for high precision, however, it is usually operated in a sequential mode. Detection limits are similar or better than in flame AAS, precision and reproducibility are similar, and interferences are less serious. The equipment is more expensive by a factor of two or more than the AAS instruments.

Anodic Stripping Voltammetry (ASV). Although several polarographic techniques can be used for metal ion determination, ASV is most commonly employed for a quantitative analysis at trace element levels. For this procedure, the polarographic cell includes a stationary working electrode rather than a dropping mercury electrode. The most common types are a hanging mercury electrode and a glassy graphite electrode. The working electrode first is made a cathode in the analyzed solution (using a platinum counter-electrode and a reference electrode), to reduce dissolved ions to the metallic state. The electrode potential is then scanned in the anodic direction and the "stripping current" is recorded. Since different elements oxidize at different potentials, the presence of an element is revealed by a peak on the current vs. potential chart, the peak area being proportional to the concentration.

The test is usually performed in a Differential Pulse mode. A standard potentiodynamic setup or specialized equipment can be used. The detection limits are in the ppm to ppb range, and some elements can be analyzed simultaneously; overlapping of peaks for elements with similar oxidation/reduction potentials occasionally is a problem. Dynamic range and reproducibility are high, but the technique is more laborious and time-consuming than AAS or ICP-ES.

Neutron Activation Analysis (NAA). The sample is neutron-irradiated in a nuclear reactor which creates unstable isotopes of the metallic elements in the sample. The radioactive decay of the isotopes is monitored, using suitable detectors and counters. From the radiation intensity and characteristics, the identities and amounts of the elements are determined. Since activation involves the atomic nucleus rather than the electron shell, the results are independent of the oxidation state or chemical form.

NAA determines absolute amounts of elements in the sample, and the concentration detection limit depends on the size of the sample, the counting time and the element. In routine analyses, the detected amounts are on the order of nanograms. Few researchers have easy access to the needed facilities; commercial analytical services are available, but the cost per analysis is relatively high.

Radioactive Tracer Analysis. As opposed to NAA, the radioactive isotope is present in the dissolving alloy during the exposure; the radioactivity of the solution is then measured, usually by gamma radiation spectroscopy, to determine the quantity of the dissolved element. The isotope can be included during the alloy preparation, but more commonly is formed by neutron irradiation of the alloy specimen.

Application of this technique to corrosion has been called Nuclear Corrosion Monitoring (NCM), and it has been used in studies of dental alloys (Brune *et al.*, 1982, 1984; Brune, 1988). In principle, it could be used to monitor dissolution continuously by circulating the solution from the dissolution vessel under the detector. Also it can be used to analyze different elements simultaneously. Sensitivity varies widely from element to element. The equipment for multi-element analysis is moderately expensive, but the expense of irradiation increases the cost per analysis. The procedure involves handling radioactive materials and thus requires special facilities and precautions.

Gold Film Mercury Detection. Well known among dental researchers, this technique is based on measurement of the electrical resistance of a gold foil which changes significantly upon adsorption of mercury vapor. Although only dry gaseous sample can be analyzed, mercury vapor can be generated from liquid or solid samples by procedures similar to those used in cold-vapor AAS. The equipment is much less expensive than the facilities for AAS, and is easily portable; it has been used frequently for *in situ* determination of mercury vapor in the oral atmosphere. The available

instruments can detect about 0.2 ng of Hg; this allows detection of about 3 $\mu g/m^3$ in air, and a detection limit approaching values achieved by AAS in liquid sample analysis.

DATA PROCESSING AND INTERPRETATION

THE RELEASE RATE CALCULATION. If the metal concentration in the sample is determined, data processing is straightforward. For analyses after relatively long exposure periods, the average dissolution rate R_{avg} [$kg.m^{-2}.s$; $\mu g/cm^{-2}.d$; etc.] can be calculated,

$$R_{avg} = \Delta C.V/\Delta t.A \qquad (1)$$

where ΔC is the concentration change [kg/L; μg/mL, etc.], V is the original volume of the electrolyte [L; mL], Δt is the time difference [s; d], and A is the exposed area of the alloy [m^{-2}; cm^{-2}]. If the concentration is determined frequently and a curve can be fitted through the points or dissolution is monitored continuously, the rate of dissolution at time t, R_t, is proportional to the slope of a tangent to the concentration vs. time curve,

$$R_t = (dC/dt).(V/A) \qquad (2)$$

Thus the dissolution rate vs. time curve can be obtained by differentiation of the concentration vs. time relationship either analytically, graphically or numerically.

THE EFFECT OF IONIC METAL CONCENTRATION. The dissolution rate may be affected by the metal ion concentration, as it increases with exposure time. Fig. 1 shows a schematic polarization diagram, illustrating this effect for a corrosion system under activation (Tafel) control. Fig. 2 is an example of the theoretical relationship between the metal ion concentration and the relative dissolution rate for such a process. An example of the resulting variation of the concentration and dissolution rate with time is shown in Fig. 3. Figs. 1-3 show that even in the absence of such effects as film formation or surface enrichment in the more noble components of the alloy, the dissolution rate into a solution of fixed volume would decrease with time.

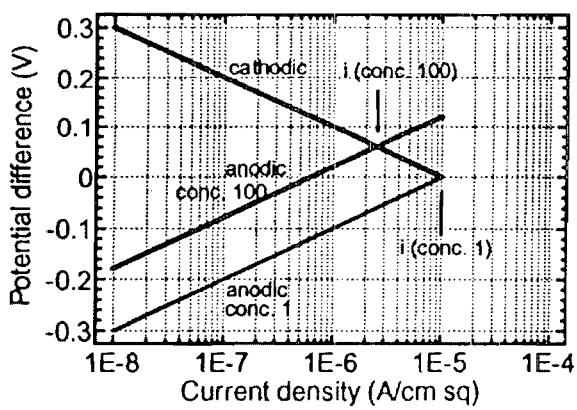

Fig. 1. Schematic polarization diagram showing the effect of a change in the concentration of dissolved metal ions on the dissolution rate.

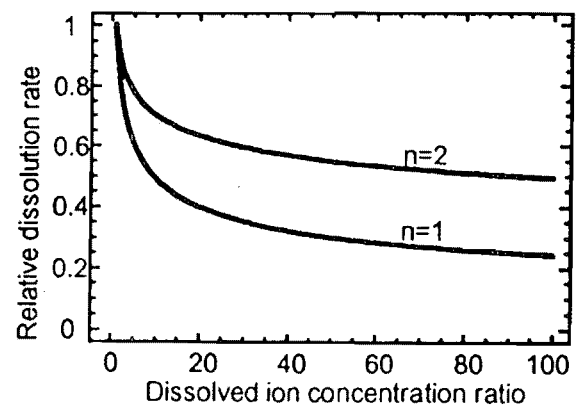

Fig. 2 Calculated effect of dissolved ion concentration on the dissolution rate (n is oxidation state of the ions).

Results showing dissolution rate decreasing with time have been reported (e.g., Brune, 1988; Geis-Gerstorfer *et al.*, 1991; Wataha *et al.*,1992), but the effect of metal concentration has not been considered. In tests not involving solution analysis, the problem can be avoided by using a large volume of the solution, possibly containing a suitable initial concentration of the ions. In dissolution tests, however, the requirement of sufficient concentration of metal ions for the analysis and sufficient change in the concentration for determination of the rate of dissolution are in an inherent conflict with the effect of the concentration on the dissolution rate. Solution replacements change the conditions, but do not eliminate the effect. If the effect of concentration is ignored, the experimental results may grossly underestimate the dissolution rate under conditions in which the ions are carried away from the metal, e.g., by the saliva flow or by food or drinks.

Dissolution of alloys in passive state apparently is less affected by the changes in the metal ion concentration but is not immune to it. The dissolution rate in the passive state is equal either to the rate of chemical dissolution of the film or to the electrochemical reaction controlled by the mass transport through the film. The rates of both processes are fundamentally solution concentration-dependent, but the magnitude of the effect is difficult to predict.

THE EFFECT OF ATOMIC METAL CONCENTRATION. A more complex problem exists in the dissolution of mercury. Since mercury is thermodynamically very stable with respect to electrochemical dissolution (De Zoubov and Pourbaix, 1974), the most likely process is dissolution in the form of mercury atoms. If the atoms are not consumed in any way, the rate of dissolution severely decreases as soon as the concentration approaches the solubility limit in the solution which is less than 100 ppb in pure water and likely to be lower in ionic solutions. The rate of dissolution is proportional to the rate of increase in concentration C with time t, which is proportional to the difference between the solubility limit Co and concentration C according to the following relationship (Epstein, 1957):

$$dC/dt = (\alpha A/V).(C_o - C) \qquad (3)$$

where α is a dissolution rate constant, V is the volume of the solution, and A is the surface area of the metal. Fig. 4 shows an example of results of a calculation for specific values of initial rate of mercury dissolution and volume of solution. In practice, however, dissolved atomic mercury usually is partially consumed by evaporation or oxidation to mercury ions, or both. The rates of both processes increase with increasing concentration of atomic mercury, altering the concentration and mercury release rate vs. time relationship. It is apparent that laboratory mercury dissolution tests provide a very distorted picture of mercury dissolution if the atomic mercury concentration is allowed to approach the solubility limit. Since the solution analysis usually yields total dissolved mercury, and the partitioning into the atomic and ionic forms is not known, the results are reliable only if the total mercury concentration is well below the solubility limit, and evaporation of mercury either is prevented or monitored.

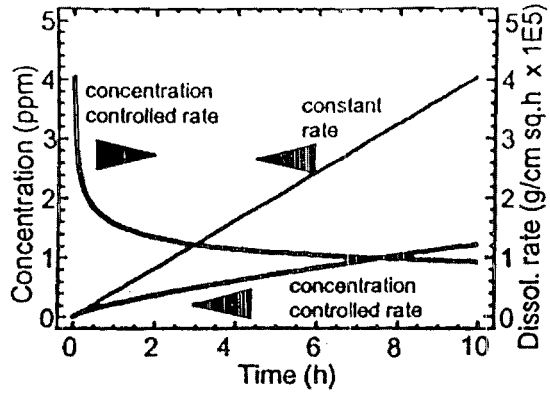

Fig. 3 Calculated effect of dissolution on concentration and dissolution rate vs. time (Ag, conditions as in Fig. 1, V=100 mL, A=1 cm sq).

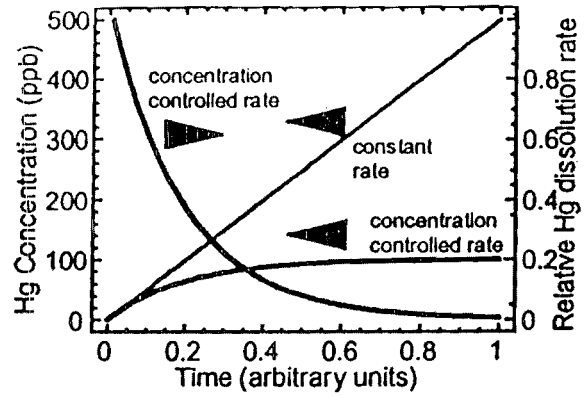

Fig. 4 Calculated effect of atomic Hg solubility limit (100 ppb) on concentration and dissolution rate vs. time.

SPECIAL ION RELEASE CONDITIONS

METAL ION RELEASE AT CONSTANT POTENTIAL. Metal ion release at the open circuit potential truly represents only dissolution under the conditions of the laboratory test. Since the potential *in vivo* may vary (Ewers and Greener, 1985), it may be useful to determine the metal release rate as a function of the potential. Ultimately, a complete anodic polarization curve can be constructed on the basis of the dissolution results ("Faradaic polarization curve"), providing information on the dissolution behavior under a wide variety of conditions.

In constant potential (potentiostatic) experiments, the potential is controlled by an electronic potentiostat, and the dissolution cell contains a reference electrode and a counter-electrode (usually Pt or graphite). If the specimen is polarized anodically, the counter-electrode is the cathode of the cell and some of the dissolved ions may plate out on it. To account for the reduced metals they must be dissolved after the test (usually in an acid) and their amount added to the amount of the metal in the solution. Alternatively, a conductive membrane may be used to separate the counter-electrode from the electrolyte, stopping the flow of the metal ions.

METAL ION RELEASE FROM GALVANIC COUPLES. Since galvanic coupling with more noble alloys may accelerate the metal ion release, this information may be of interest for dental alloys. In a simple test, the two metals are joined together and exposed to the electrolyte in a dissolution vessel. Such tests, however, provide limited information and are subject to substantial error. Since the noble alloy is a cathode of the cell, some of the dissolved metal ions may be reduced on it and plate out, which is similar to the situation in a potentiostatic test. Noble dental alloys, however, generally are not as inert as the platinum counter-electrode, and acid washing may result in a substantial contamination of the sample with dissolved components of the noble alloy. Further, since the severity of the galvanic interaction depends on the area ratio of the electrodes, results for one area ratio provide narrowly limited information. Therefore, it is more useful to obtain the dissolution vs. electrode potential data, which, in conjunction with easily measured values of the corrosion potential as a function of the area ratio, allow a reliable prediction of the dissolution rate from galvanic couples.

DETERMINATION OF METAL ION RELEASE *IN VIVO*. Clinical measurements of the metal ion release are both important and difficult. As usual, the *in vivo* data should be the ultimate test of the predictions based on *in vitro* results. Because of the variability of the conditions, however, the difficulty of performing the number of tests needed for representative results often is prohibitive.

Clinical measurements of the metal ion release from dental alloys used in the oral cavity usually are performed by analyzing saliva which has been collected after several minutes of accumulation in the mouth of the patient (De Melo *et al.*, 1983; Nilner, 1981; Stenberg, 1982; Gjerdet *et al.*, 1991). Because of the short exposure time, the concentration of metal ions, except from freshly installed devices or very corrosion-susceptible alloys, is very low, albeit within the capabilities of modern analytical techniques. For example, for a nickel-chromium alloy corroding at a current density on the order of 10^{-7} A/cm^2, assuming dissolution of nickel only, the amount dissolved in 5 minutes from one cm^2 area of the alloy is on the order of nanograms, well above the detection limit of some of the modern techniques such as AAS with electrothermal atomization. However, the background of metal ions naturally present in body fluids may make the determination difficult for very slowly dissolving alloys. Few clinical data have been reported, and more effort should be made in this direction. Metallic elements released into soft and hard tissues can be determined by various techniques of analysis of solids, including AAS, ICP-ES, NAA, x-ray techniques, etc. Because of the uncertainties regarding the transport of different species away from the sites and the relatively long intervals between insertion and analysis, the results, while important and interesting, are only semiquantitative and provide little information on the actual release rates.

SUMMARY

The effects of man-made materials on the human body, including the release of metallic species from dental alloys have become a matter of increasing concern. Dissolution tests provide important information on the identity of released metal ions and rates of the release. Laboratory tests are performed under controlled conditions and should yield reliable data. To achieve this goal, test conditions such as sample geometry and positioning, chemistry and volume of the medium, and time of exposure must be carefully chosen. The effects of the increasing metal ion concentration on the dissolution rate should not be ignored. A variety of analytical techniques, some of them highly sensitive, are available for metal ion determination. Special attention should be paid to the design of experiments in which some of the released metals may be lost during or after the test, such as controlled potential tests, galvanic tests, and mercury dissolution tests. More effort should be made to obtain statistically significant data for metal ion release *in vivo.*

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Appendix 3

REFERENCES

Berge M, Gjerdet NR, Erichsen E (1982). Corrosion of silver soldered orthodontic wires. *Acta Odontol Scand* 40:75-79.

Brune D (1986). Metal release from dental biomaterials. *Biomaterials* 7:163-176.

Brune D (1988). Mechanism and kinetics of metal release from dental alloys. *Int Endod J* 21:135-142.

Brune D, Evje D, Melsom S (1982). Corrosion of gold alloys and titanium in artificial saliva. *Scand J Dent Res* 90:168-171.

Brune D, Gjerdet NR, Paulsen G (1983). Gastrointestinal and *in vitro* release of copper, cadmium, indium, mercury and zinc from conventional and copper-rich amalgams. *Scand J Dent Res* 91:66-71.

Brune D, Hultquist G, Leygraf C (1984). Corrosion resistance of passivated and nonpassivated cobalt-chromium alloy. *Scand J Dent Res* 92:262-267.

De Melo JF, Gjerdet NR, Erichsen ES (1983). Metal release from cobalt-chromium partial dentures in the mouth. *Acta Odontol Scand* 41:71-74.

De Zoubov N, Pourbaix M (1974). Mercury. In: Pourbaix M, editor. Atlas of Electrochemical Equilibria in Aqueous Solutions. Houston, TX: NACE, 421-427.

Epstein LF (1957). Static and dynamic corrosion and mass transfer in liquid metal systems. In: Van Antwerpen FJ,ed. Liquid Metals Technology-Part I. New York: AICE, 67-81.

Ewers GJ, Greener EH (1985). The electrochemical activity of the oral cavity - a new approach. *J Oral Rehabil* 12:469-476.

Geis-Gerstorfer J, Sauer KH, Pässler K (1991). Ion release from Ni-Cr-Mo and Co-Cr-Mo casting alloys. *Int J Prosthodont* 4:152-158.

Gjerdet NR, Herø H (1987). Metal release from heat-treated orthodontic archwires. *Acta Odontol Scand* 45:409-414.

Gjerdet NR, Erichsen ES, Remlo HE, Evjen G (1991). Nickel and iron in saliva of patients with fixed orthodontic appliances. *Acta Odontol Scand* 49:73-78.

Lang BR, Morris HF, Razzoog ME, eds. (1986). Biocompatibility, Toxicity and Hypersensitivity to Alloy Systems Used in Dentistry. U. of Michigan School of Dentistry.

Lappalainen R, Yli-Urpo A (1987). Release of elements from some gold alloys and amalgam in corrosion. *Scand J Dent Res* 95:364-368.

Marek M (1983). Corrosion of dental materials. In: Scully JC, editor. Aqueous Corrosion and Passive Films. Treatise on Materials Science and Technology Vol. 23, London: Academic Press, 331-394.

Marek M (1990). The release of mercury from dental amalgam: mechanism and *in vitro* testing. *J Dent Res* 69:1167-1174.

Moberg L-E (1985). Corrosion products from dental alloys and effects of mercuric and cupric ions on a neuroffector system. *Swed Dent J Supplement* 29:1-51.

Moberg L-E, Johansson C (1991). Release of corrosion products from amalgam in phosphate containing solutions. *Scand J Dent Res* 99:431-439.

Muller AWJ, Maessen FJM, Davidson CL (1990). The corrosion rates of five dental Ni-Cr-Mo alloys determined by chemical analysis of the medium using ICP-AES, and by the potentiostatic deaeration method. *Corr Sci* 30:583-601.

Nilner K (1981). Studies of electrochemical action in the oral cavity. *Swed Dent J Supplement* 9:1-42.

Schwickerath H (1988). Zur Löslichkeit von Dentallegierungen. *Dtsch Zahnärztl Z* 43:339-342.

Stenberg T (1982). Release of cobalt from cobalt chromium alloy constructions in the oral cavity of man. Scand *J Dent Res* 90:472-479.

Torgersen S, Gjerdet NR (1992). Metal release from arch bars used in maxillofacial surgery. *Acta Odontol Scand* 50:83-89.

Wald FV, Cocks FH (1971). Investigation of copper-manganese-nickel alloys for dental purposes. *J Dent Res* 50:48-59.

Wataha JC, Craig RG, Hanks CT (1991). The release of elements of dental casting alloys into cell-culture medium. *J Dent Res* 70:1014-1018.

Wataha JC, Craig RG, Hanks CT (1992). The effects of cleaning on the kinetics of *in vitro* metal release from dental casting alloys. *J Dent Res* 71:1417-1422.