

A preliminary investigation into the microscopic depassivation of passive titanium implant materials *in vitro*

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A sensitive electrochemical technique has been used to examine the passive state of titanium-based materials in Ringer's physiological solution. At ambient temperature, the alloy Ti-6Al-4V shows transient microscopic breakdown of the passive state induced by the presence of chloride ions, and enhanced by increased acidity. These breakdown events involve highly localized depassivation of the passive surface followed by repassivation. Under similar experimental conditions no breakdown of passive titanium was detected.

1. Introduction

Titanium and the alloy Ti-6Al-4V are widely used in biomedical applications. Their good mechanical properties, high corrosion resistance and good compatibility with biological materials are the main properties required for their use as implant materials [1-4]. A further advantage lies in the fact that in skeletal replacements and fixtures, the bone can grow directly against the metallic implant surface (osseointegration) [5].

Titanium owes its corrosion resistance to its passivity. The metal is in fact a base metal but shows remarkably high passivity in aqueous solution. This passivity is derived from the formation of a very stable and tenacious oxide film which develops naturally over the surface [6]. The film reforms very rapidly if removed or mechanically damaged. These observations are consistent with the Pourbaix diagram for the metal [7] which shows that the oxide TiO_2 is the only stable reaction product under the conditions of pH that can be encountered *in vivo*. The actual composition of the passivating oxide has not been firmly established, although most investigators agree that the main constituent of the film displays the TiO_2 stoichiometry [8-16], accompanied by some Ti_2O_3 [8, 14, 16].

After implantation of titanium in the human body, the metal oxide layer undergoes some changes, namely thickening of the passivating film and some stoichiometric changes. Phosphorus, calcium and silicon are incorporated into the oxide surface from the local environment, and some metal dissolution also occurs [17-20]. Thus, despite the adherence of the film to its metal substrate, and its ability to reform readily when damaged, titanium has occasionally been observed in tissue adjacent to an implant prosthesis [17-22]. Al-

though titanium appears to be tolerated in the body in minute amounts [21, 23, 24], it accumulates in giant cells and is not excreted [21]. Moreover, concern is being expressed regarding the possibility of metallosis as a new cause for the failure of titanium-based implant prostheses [25]. Both passivation and metal dissolution are oxidation processes (accompanied by a suitable reduction reaction), electrochemical in nature. The two processes occur essentially in competition with each other. Thorough research must still be carried out in order to understand these processes fully, so as to minimize or prevent the occurrence of catastrophic failures.

At room temperature, the two-phase alloy Ti-6Al-4V develops a passivating oxide film which is very similar to that formed on pure titanium. The major component of the film is TiO_2 with Ti_2O_3 also present, but oxide films on the alloy have been found to be more amorphous and not unexpectedly, to incorporate alloy constituents [26-30]. The alloy is generally less corrosion resistant than titanium itself [1-4].

Although the passive film formed on titanium and its alloys is fairly unreactive and the metal is regarded as highly passive, our recent investigations have shown that the passive state is not entirely stable. In the presence of chloride, localized breakdown on a highly microscopic scale has been found to occur. The breakdown events which have been observed do not lead necessarily to growth of structurally damaging pits; nevertheless, they show an instability in the passive state which may have a bearing on the behaviour of the metal *in vivo*. Both stainless steel [31-36], and titanium-based materials [37] immersed in acidic aqueous chloride solutions exhibit transient microscopic breakdown. Such breakdown is thought to be

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the cause of the nucleation of corrosion pits that occurs at potentials well below the corresponding pitting potential for the respective metal in the solution. These breakdown events cannot be observed using conventional potentiostatic measurements on relatively large specimens: they are generally too small in amplitude and too fast. Their detection requires methods which are not adversely affected by extraneous electrical interference, and the use of very tiny specimens. These investigations have shown that the chloride ion is the aggressive agent responsible for breakdown of passivity.

Chloride ions are a natural component of physiological environments. The present communication concerns a preliminary report on *in vitro* observations of localized instability of the passive state of titanium and the alloy Ti-6Al-4V specimens exposed to artificial physiological solutions. The work was carried out using Ringer's solution together with an acidic modification of the Ringer's solution at room temperature.

2. Experimental procedures

The experiments described below are aimed at detecting as sensitively as possible any possible breakdown events on the passive metal surface in simulated physiological solution (Ringer's solution). Microelectrodes were used as test specimens in order to reduce significantly the background current, which because it flows from the entire specimen surface, depends on the surface area. Reducing the area of the specimen raises the ratio of the current amplitude of any breakdown events to the passive current, thus making the breakdown events easier to detect.

Experiments were carried out on titanium and ELI (extra low interstitial) grade Ti-6Al-4V wires (Goodfellow Materials Ltd., Cambridge). The diameter of the titanium wire was 50 μm . The metal was not analysed, but typical impurity levels (in ppm) were cited by the supplier as: Al 1, Cr 30, Cu 10, Fe 90, Mg 10, Mn 400, Ni 50, Si 30, V 50, H 80, N 20, O 400. In the case of the alloy, wire of diameter 250 μm was employed, and typical analysis from the supplier gave Al 6%, V 4%, with impurity levels (in ppm): Fe 300, C 220, H 100, N 100, O 650. These analyses conform to ASTM standards for implant material [38, 39]. Both wires which were used in the as-drawn condition, were mounted into an epoxy resin sleeve, such that only the 50 μm or the 250 μm diameter circular end-surface was free, forming microelectrodes. The end-surfaces of the electrodes were finished to 4000 grit using silicon carbide paper and cleaned thoroughly in double-distilled water. Ideally, the two materials would have been the same size; however, the alloy was not available in 50 μm dia. wire. Note that the microstructure of these as-drawn wires is likely to be different from that of the cast, forged or wrought materials.

The experiments were performed at constant potential using a two-electrode cell powered by a battery and a voltage divider, the entire arrangement being housed in a double Faraday cage. The current was measured through a Keithley model 428 current amplifier (also in a Faraday cage), the output being fed

through a digital voltmeter into a computer. The counter electrode, which also functioned as a reference electrode, was a 22 cm^2 sheet of silver which had been anodised in chloride solution to produce a silver/silver chloride electrode. It was equilibrated with the working electrolyte, but held in a separate vessel, connected to the working cell by a tube. Because of the small sizes of the working electrodes and the consequently small currents involved, this relatively very large Ag/AgCl electrode was not polarized during the experiments; its dual role as reference and counter electrode is thus satisfied. In the chloride-free electrolyte (see below), a saturated calomel electrode (SCE), mounted in the side-arm to the working cell, was used as combined reference/counter electrode. This has been shown to function satisfactorily [33, 34]. The advantage of this type of measurement over the more conventional three-electrode potentiostatic system is the minimization of the background noise levels.

The working electrolytes used were based on Ringer's physiological solution [40]. All components were of analytical grade. Ringer's solution was made up using 0.147 M NaCl, 0.00432 M CaCl_2 , and 0.00404 M KCl in double-distilled water and this formed the main electrolyte. An acidic version of Ringer's solution was also made by adding HCl to Ringer's solution to bring the pH to 2.5. This addition caused only very small change in the concentrations of the other components. The acidic pH was chosen because the tissue adjacent to an implant under distress is considered to become acidic [17]. The more acidic pH also increases the frequency of occurrence of the de-passivation events, as shown below. In addition, a chloride-free analogue of Ringer's solution was prepared in order to see the effects of the chloride anion itself. This solution was made using the sulphate salts to replace the chloride salts in the recipe above whilst maintaining the same cation concentration. Thus the chloride-free analogue to Ringer's solution contained 0.0735 M Na_2SO_4 , 0.00432 M CaSO_4 , 0.00201 M K_2SO_4 . The electrolytes were not deaerated during use. Measurements were performed at room temperature ($18 \pm 3^\circ\text{C}$).

Data were collected at a preset electrode potential: 0.50 V (SCE) using a data acquisition rate of 13.5 Hz (74 ms per data point). The recording instrumentation was set to record 32 000 data points (39.5 min) continuously; these were stored as a single data file. Further recordings were then made if desired by rearming the recording for a further 39.5 min. This data acquisition rate may not have been ideal as shown below: many observed events were not resolved fully at this rate, and events which may have occurred within times significantly shorter than 74 ms may not have been observed at all. Nevertheless, this data acquisition rate provided a manageable quantity of data recorded over lengthy periods, as required for the present experiments. In addition, a faster data acquisition rate, while able to detect faster events, also gives a higher background noise level, making events of small amplitude more difficult to read [36]. The potential of 0.50 V(SCE) is below the water/oxygen equilibrium potential at the pH of the working electrolytes

used [7]. It is also below the pitting potential of titanium and Ti-6Al-4V in these electrolytes [41]: both titanium and Ti-6Al-4V are passive under these conditions.

3. Results

Polarization of the titanium and Ti-6Al-4V micro-electrodes in all the solutions described above results in flow of current through the electrochemical cell. At 0.50 V(SCE) both metals passivate with time, and this characteristic passivation is demonstrated by all the current/time traces recorded. Fig. 1 shows the first 39.5 min polarization of Ti-6Al-4V in neutral Ringer's solution. After an initial period of current overload (the overload limit for this larger electrode was 3 nA), the current shows an overall decay with time, and this describes passivation of the metal. Some breakdown events are observed as small current transients in the anodic direction during passivation. Although small, they are readily identifiable above the background noise level.

Fig. 2a shows the first 39.5 min polarization of Ti-6Al-4V in the acidified Ringer's solution (pH = 2.5). The form of the overall current decay is similar to that seen in Fig. 1, with the metal passivating throughout. The superimposed anodic current transients are now very much bigger in amplitude than in the neutral Ringer's solution, and there are more of them (i.e. their frequency of occurrence is greater). These transient breakdown events are thus rendered more facile for the more acidic solution. Whether the observed greater frequency of events in the acidic solution is due to the fact that the event amplitude is greater (enabling more events to be detected above the background noise) or due to a greater number of events *per se* is not at this stage known. After 18.6 h polarization, the overall current plotted in Fig. 2b still shows a continuing decay. Thus passivation is still not complete after 19 h, although the rate of current decay is very small. Note that the anodic current to 0.093 nA recorded at the end of Fig. 2b represents a current density of 1.9 mA m^{-2} (the area of the specimen is $5 \times 10^{-8} \text{ m}^2$),

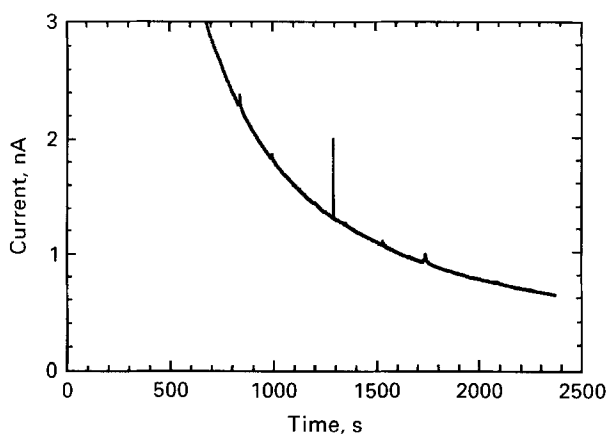


Figure 1 Decay of current due to passivation of Ti-6Al-4V in Ringer's solution, pH 6.7, at 0.50 V(SCE) showing the occurrence of transient breakdown events as the metal passivates. Specimen diameter 250 μm .

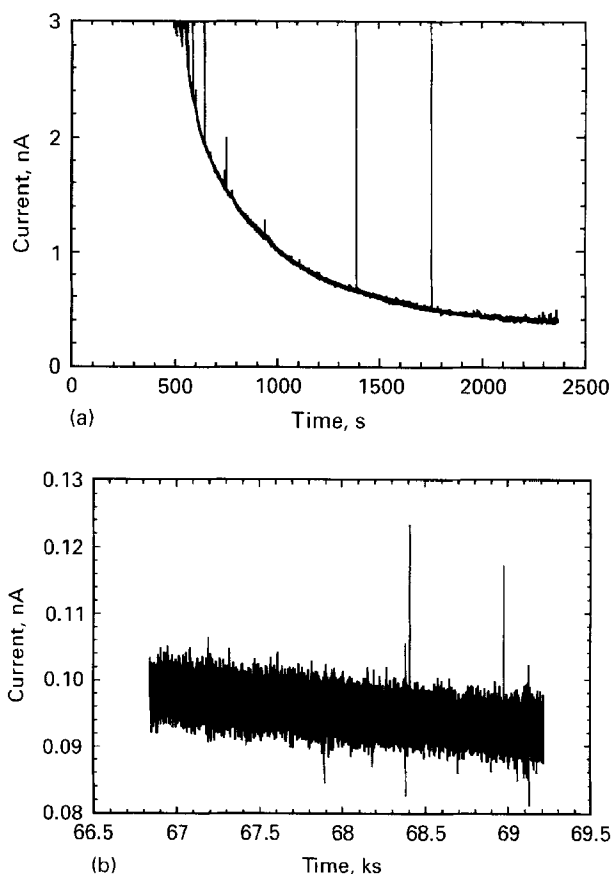


Figure 2 Decay of current due to passivation of Ti-6Al-4V in acidified Ringer's solution, pH 2.5, at 0.50 V(SCE) (a) showing the occurrence of transient breakdown events as the metal passivates. Specimen diameter 250 μm . (b) Trace recorded 18.6 h after the start of polarization and is a continuation of the trace shown in Fig. 2a.

still a significant value. The transient anodic events observed in Fig. 2a are now much smaller in Fig. 2b, and cannot be distinguished unambiguously from the background noise. (The background noise is itself characterized by current spikes equally in the anodic and cathodic directions about the mean.) Clearly the amplitudes of these anodic events decay with time of polarization.

The fact that the anodic current transients are due to the chloride component in the electrolytes is demonstrated in Fig. 3, which shows a similar current/time plot for the alloy in the chloride-free solution. The metal in this solution shows continuous passivation, and no superimposed current transients can be detected at all. The chloride anion is exclusively responsible for the generation of the anodic current transients.

The data shown in Figs. 1-3 describe the behaviour of the alloy Ti-6Al-4V. Fig. 4 shows the behaviour of pure titanium in the acidified Ringer's solution, the most aggressive of the solutions used here. Note that the titanium specimen was of much smaller surface area ($2 \times 10^{-9} \text{ m}^2$), and thus the passivating currents are smaller throughout. The passivating current densities are however, of comparable magnitude for both materials. Note too, that the instrument overload limit was 300 pA for this specimen, since the smaller passivating current allowed greater instrument sensitivity. Titanium shows continuous decay of current, demonstrating continuous passivation, similar to

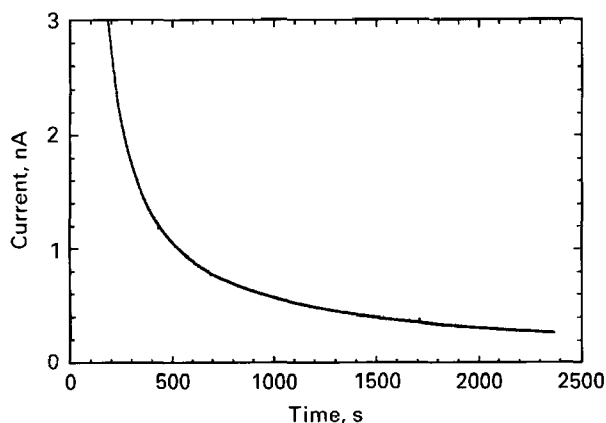


Figure 3 Decay of current due to passivation of Ti-6Al-4V in the chloride-free analogue of Ringer's solution at 0.50 V(SCE). No depassivation events are observed. Specimen diameter 250 μm .

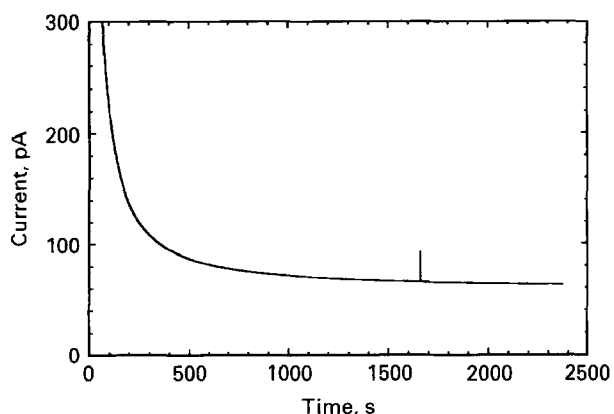


Figure 4 Decay of current due to passivation of pure titanium in acidified Ringer's solution, pH 2.5. No depassivation events are observed. Specimen diameter 50 μm .

Figs. 1-3, but there is only one low amplitude anodic current transient. In neutral Ringer's solution, also at 0.5 V(SCE), titanium showed no evidence whatever of any anodic current transients. Pure titanium is thus less susceptible to the breakdown phenomenon than the alloy.

Three types of anodic current transient from Ti-6Al-4V were observed unambiguously above the background noise, and these are shown in detail in Fig. 5. The first (Fig. 5a) involves a sharp current spike which decays rapidly to the background, both the rise and fall being equally sharp. They were generally the smaller transients and could be resolved basically to one data point at the peak maximum. Clearly the data acquisition rate of 13.5 Hz was insufficient to resolve them. The second type of current transient, shown in Fig. 5b, also involves a sharp current rise but this time the decay of the transient current towards the background appears somewhat slower, and roughly exponential in form. These transients tended to be bigger than the ones of Fig. 5a. The approximately exponential decay of the transient current can be resolved for a few seconds as shown in Fig. 5b. The one transient observed from Ti (Fig. 4) was of this second type and of small amplitude (27 pA). The third type of transient is shown in Fig. 5c. This type takes many seconds to decay fully, and indeed, over the 4 s displayed in

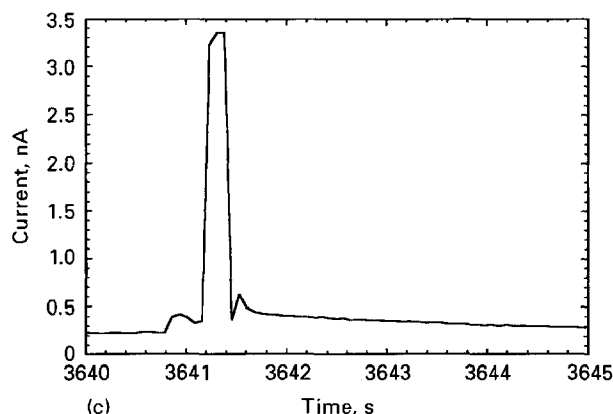
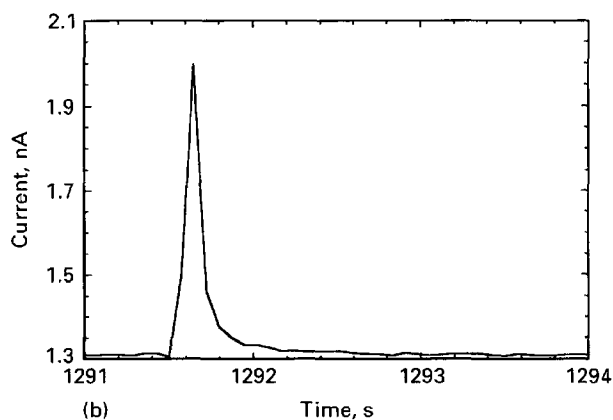
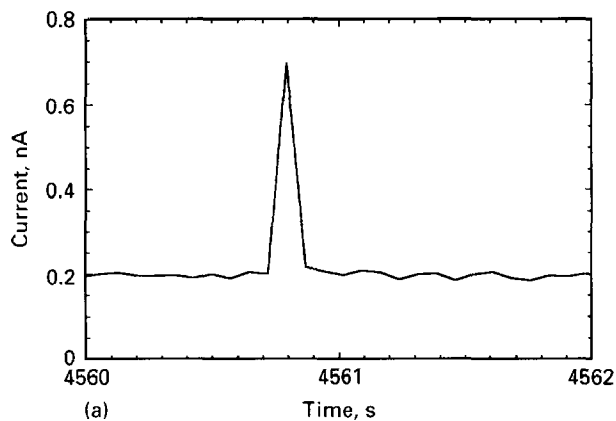


Figure 5 Detail of three forms of current transient observed for breakdown processes on Ti-6Al-4V. The data acquisition rate was 13.5 Hz. (a) Sharp rise and fall of current (first type). (b) Sharp rise of current followed by a relatively slow rate of current decay (second type). (c) Double activation transient, possibly showing sign of brief pit propagation (third type).

Fig. 5c, still has not decayed fully to the background level. These transients have a curious form. The large current rise (which overloads the recording instruments for the transient in Fig. 5c) is preceded by a small transient, which decays, but only partially.

4. Discussion

We regard the anodic current transients described above as transient depassivation events, that is to say, the passivating oxide is lost locally from some part of the surface. The locally depassivated surface reacts rapidly giving the observed anodic transient. These breakdown events would not be detectable by conventional corrosion testing using larger specimens, since

the small amplitudes of the breakdown events would then be masked by the correspondingly larger passive current.

Under the experimental conditions described above, the metals are passive and show no sign of *permanent* pit propagation: the observed breakdown events are transient. The breakdown process giving rise to the anodic current transient is essentially the nucleation of a corrosion pit, which, because it occurs below the pitting potential of the metal, does not develop into a permanently propagating pit, but repassivates instead. The evidence for this is that none of the events show a permanent rise of current with time: each event is accompanied by a fall in current back to the base current, indicative of repassivation. The observation of these transients from Ti-6Al-4V in Ringer's solution shows that passivity is nevertheless not fully stable; such breakdown as occurs, despite being succeeded by repassivation, shows an inherent instability of the passive surface. This instability is caused by the chloride anion in solution. It is also noteworthy that both metals show passivation in these electrolytes and the passive current densities are quite low, but passivity takes a long time to achieve; the passive current density is still decaying after 19 h polarization. Nevertheless, despite the continued passivity of the metal, some breakdown still occurs. Interestingly, for these electrolyte solutions, only Ti-6Al-4V shows significant depassivation; pure titanium shows only one event in the acidic solution (of low amplitude) and none at all in neutral solution. We have shown elsewhere [37] that titanium does show detectable breakdown events in more concentrated hydrochloric acid solutions (higher chloride concentration and lower pH), also conditions where conventional corrosion testing would show the metal to be passive. The measurements in neutral Ringer's solution do not imply that breakdown on titanium does not occur, only that we have been unable to detect any breakdown events. Any breakdown events on titanium that do occur must be too small in amplitude or too fast to be detected by the present method. Nevertheless, this observation implies that titanium is much less susceptible to transient breakdown of passivity than Ti-6Al-4V. The occurrence of the events is basically a property of titanium, but is enhanced by the presence of the alloying elements. The effect may have some bearing on the reported differences in the degrees of tissue acceptance of implants made from the two metals [27, 42].

The depassivation (or pit nucleation) events are not fully resolved using the present experimental technique. Details of the transients plotted in Fig. 5 show that the rise time is faster than the 74 ms period of data acquisition for all transients. What causes depassivation is not entirely clear; nevertheless, we believe that the passivating oxide film covering the metal surface is lost in some way, an action caused by the presence of chloride. Depassivation could arise chemically through localized dissolution of the passivating oxide film, or it could arise physically, by mechanical rupture of the oxide film. No events are seen in the absence of chloride, and the events are bigger and

more frequent in the acidic solution. Once the metal surface has been denuded, the reaction is the reformation and growth of the oxide: the metal repassivates. We are unable to establish clearly whether the metal undergoes dissolution during repassivation or not. The form of the first two types of transient (Figs. 5a and 5b) is that of repassivation, with the current decaying continuously with time. The first type (Fig. 5a) is probably a low amplitude version of the second type (Fig. 5b). Apart from the third type of transient (Fig. 5c), these transients show continuous decay, perhaps implying a negligible dissolution rate. The generation of metastable pits as observed on stainless steel [31-36] and on titanium in more concentrated hydrochloric acid solutions [37] was not observed in the present work. Metastable pitting is typified by a transient where, after nucleation, the current rises slowly with time as the pit expands, before the metastably growing pit itself repassivates [31-35]. The third type of transient (Fig. 5c) however, was not observed on titanium itself, and may well involve a dissolution component, since it shows not only an initial nucleation event, but further activation prior to repassivation. Repassivation for this type of event was of rather long duration, probably implying some dissolution, despite the fact that these transients do not resemble metastable pitting transients as observed on stainless steel [31-36]. Because these were observed only from Ti-6Al-4V, and not from pure titanium, the ability to propagate as a pit, even transiently, depends on the presence of the alloying elements. These features may well have a bearing on the behaviour of implant materials *in vivo* since dissolved ions from a highly localized depassivation event would involve transient local ejection of metal ions into the adjacent tissue.

To gain an idea of the numbers of events which occur, it is necessary to separate the anodic current transients from the background noise involved in the current trace. It is already apparent from Figs. 2a and 2b above that the frequency or amplitude (or both) of the depassivation events decays with time of polarization. A computer program was devised to count peaks whose amplitude was greater than a predefined current threshold. Analysis of the results from Ti-6Al-4V in neutral Ringer's solution and the acidified Ringer's solution is shown in Figs. 6 and 7. The graphs show on double logarithmic axes the mean frequency, λ , of events (measured by counting events over a 39.5 min period and dividing by the time) above the threshold as a function of the threshold, I_t . The initial steep fall in $\log \lambda$ with increase in $\log I_t$ is characteristic of the background noise, which in the absence of depassivation, would decay asymptotically towards $\lambda = 0$. The succeeding much slower decay in $\log \lambda$ as the logarithmic threshold current is increased further describes the anodic current transients. Thus for example, in Fig. 6, the first graph (for the period starting at $t = 0$) shows a transition threshold of 16 pA, above which λ describes the frequency of breakdown events, and below which the frequency is that of background noise. The second graph, for the period starting at $t = 43$ min, shows no unambiguous anodic

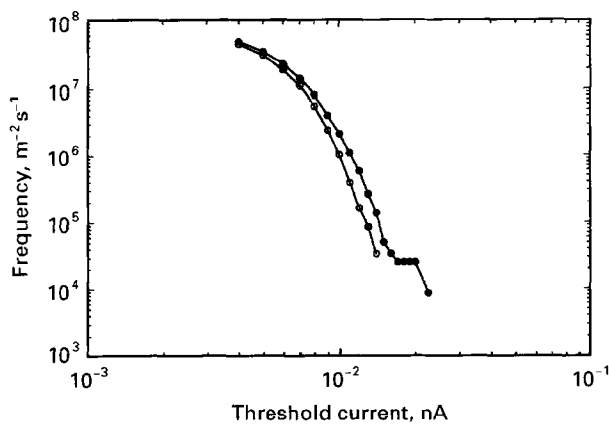


Figure 6 Frequency of current spike generation on Ti-6Al-4V in Ringer's solution, pH 6.7, at 0.50 V(SCE), measured as a function of the threshold amplitude. Each frequency was measured as the mean over a 39.5 min period starting at: ● 0 min, ○ 43 min. The transition thresholds, above which the current transients are predominantly anodic depassivation events are: 16 pA (0 min) and > 14 pA (43 min). Below the transition threshold the transients are predominantly background noise.

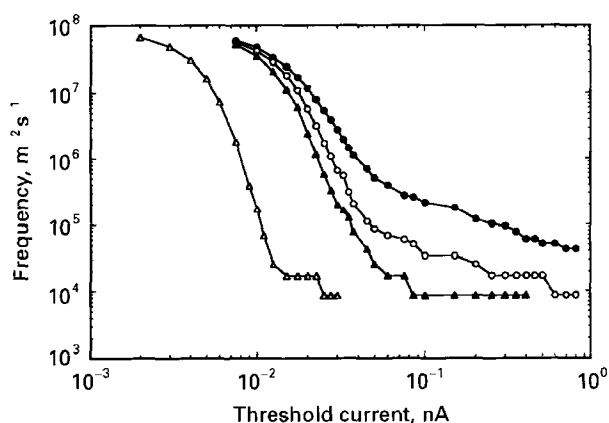


Figure 7 Frequency of current transient generation on Ti-6Al-4V in acidified Ringer's solution (pH 2.5) at 0.50 V(SCE), measured as a function of the threshold amplitude. Each frequency was measured as the mean over a 39.5 min period starting at: ● 0 min, ○ 58 min, ▲ 109 min, △ 1114 min. The transition thresholds, above which the current transients are predominantly anodic depassivation events are, respectively: 60 pA, 60 pA, 60 pA and 14 pA. Below the transition thresholds, the transients are predominantly background noise.

breakdown events at all. The transition thresholds for Figs. 6 and 7 are indicated in the respective captions.

There are a number of conclusions that can be drawn from these figures, as follows. The anodic depassivation events are smaller in amplitude in solutions of neutral pH than in those of acidic pH. The background noise level is also smaller in the neutral solution than in the acidic solution. This result is unexpected. It was originally thought that the background noise was purely electronic in origin; apparently it does have some component which reflects the state of the metal surface. Note too, from Figs. 6 and 7 that the background noise level decays with time, a feature necessarily associated with the electrochemical interface. Finally, the frequency of anodic transient events above a specific threshold decays with time of polarization. This observation can have two possible

origins. Either the frequency of film breakdown really does decay with time, or the amplitudes of the breakdown events may decay with time, with no reduction in frequency; this would give the appearance of a reduction in frequency with time as the smaller peaks became buried in the background noise. The importance of the surface area of the specimen is emphasized here. Were the Ti-6Al-4V specimens smaller, the background passivating current would have been proportionally smaller, allowing a smaller threshold to be used, thus permitting observation of smaller depassivation current transients. Nevertheless, in the first 39.5 min of polarization in the acidic Ringer's solution (Fig. 7), the frequency of depassivation events above the transition threshold of 60 pA is $4 \times 10^5 \text{ m}^{-2} \text{ s}^{-1}$. After 58 min, this figure is reduced to $7 \times 10^4 \text{ m}^{-2} \text{ s}^{-1}$; after 109 min the frequency is $1.8 \times 10^4 \text{ m}^{-2} \text{ s}^{-1}$, and after 1114 min the frequency is zero, all for the same transition threshold of 60 pA. There is thus a clear reduction in the frequency of depassivation events with time, but only when considered at constant threshold. As the background noise level decays with time, so smaller amplitude events are revealed which lie at lower threshold. Thus either of the above explanations of the reduction in frequency is at this stage tenable.

The observations described above are thought to be of some significance in the behaviour of the implanted metals *in vivo*. While much more research needs to be carried out to characterize more fully the state of passivity of the prosthesis metals, some instabilities in the passive state clearly do exist, and that condition could not be determined by conventional corrosion analysis. The consequence of rupturing the passivating oxide film is likely to be the ejection of trace quantities of metal, either as dissolved ions or as ruptured solid oxide (or both) into the adjacent tissue. The results above show that breakdown is more pronounced for Ti-6Al-4V than for titanium. The two metals are often regarded as behaving very similarly, although different degrees of tissue acceptance have been noted [27, 42]. One possible reason for the differences in tissue acceptance could be differences in the microscopic breakdown. Finally, it should be noted that our experiments were conducted at ambient temperature (*ca.* 18 °C), using as-drawn wire, and a mechanically ground (to 4000 grit) surface finish. At the higher temperatures of 37 °C encountered *in vivo*, breakdown in this manner is likely to be more severe; this remains to be investigated. The roles of microstructure and surface finish are under examination.

5. Conclusion

Transient microscopic breakdown of the passive surfaces of titanium-based materials occurs in Ringer's physiological solution, particularly if the solution is acidified. The process, which occurs well below the pitting potential, does not necessarily lead to propagation of structurally damaging pits in the metal; nevertheless transient dissolution of metal from some nucleated sites is expected to occur before the site repassivates. Such breakdown involves depassivation followed by repassivation. No breakdown has been

observed for pure titanium in these solutions at ambient temperature. These observations cannot be made by conventional corrosion analysis methods, which would show simply the overall passivity of the metals. The results may well have implications for the degree of tissue acceptance by the metals in implants.

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