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A simple and inexpensive device to measure immersion times in wave exposed shores

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An inexpensive and easy to build and deploy device to measure immersion times is described. The device consists of an LCD timer mounted in a small waterproof PVC housing. Time is recorded and integrated when seawater creates a connection between two stainless steel contacts. The device was tested in the laboratory and under field conditions on a wave swept shore. Under laboratory and field conditions, the device gave precise estimates of immersion times with maximum error of less than 4%. Applicability of this device in ecological and physiological studies is discussed and compared to other methods proposed in the literature.

The existence of steep stress gradients over few metres in the rocky intertidal offers superb opportunities to test general ecological models related to the direct and indirect effects of physical and physiological disturbances, as well as the outcome of species interactions (e.g. Menge & Sutherland, 1976; Underwood, 1989; Hall et al., 1992; Dudgeon et al., 1995). In these systems, perhaps the most important source of stress affecting marine organisms is the periodic exposure to air they undergo during periods of low tide, which primarily causes desiccation and heat stresses (Denny, 1988; Underwood, 1989; Raffaelli & Hawkins, 1996). Despite its overriding importance in the distribution and zonation of intertidal organisms, there is not yet a simple, easy way to precisely quantify air exposure for different microhabitats.

Typically, air exposure is implicitly or explicitly estimated using tidal charts, from which it is possible to calculate the 'expected immersion time' for a given tidal height across extensive regions of the coast. This coarse approach is based on the fact that tides are essentially predictable. A continuous cycle of differing fluctuations is caused at sea level by the gravitational pull of the sun and the moon and the rotation of the earth on the waters of the world's oceans. Yet, observed tides might differ significantly from those predicted by tidal charts due to topography, changes in barometric pressure, wind or wave conditions on a more local scale. In these cases, actual tidal heights can be obtained from a tidal gauge, and these data can then be used to estimate immersion times for some unspecified region of the coast around the tidal gauge. However, none of these methods gives a precise and quantitative estimate of actual times of immersion or air exposure to which organisms are exposed in the places and microhabitats where they occur.

In wave exposed environments, waves and topological features will largely determine the actual times of air exposure, and the use of tidal heights is bound to give misrepresentations of immersion regimes. For instance, the bed of chthamaloid barnacles, so characteristic along most rocky shores of the world, in Chile is several centimetres above the highest high tide mark recorded in the past 20 years (Castilla, 1981; authors' personal observations). In spite of the need to quantify *in situ* immersion in different microhabitats, there are few antecedents concerning methodologies that could be used on a local scale and simultaneously at several sites or places (Druhel & Green, 1970; Denny, 1988). Here we present an instrument to record actual immersion times that is small, inexpensive, easy to construct, and easy to deploy and retrieve in wave exposed habitats.

We define the immersion time as the time that a place or object is completely covered by water. Air exposure is then the inverse of immersion. Immersion time is not constant over small spatial and temporal scales and this is where measurement becomes necessary. We assembled a device we call an 'immersometer' to provide actual quantification of immersion time from seconds up to thousands of hours (Figure 1). The immersometer consists of a digital LCD timer (Trumeter Co. Ltd, Manchester, England, part no. 7510 DIN 8) containing an internal 3V lithium battery with an expected duration of ten years that functions in a temperature range between −10 and 60°C. This timer has dimensions of 3.45×4.80×2.40 cm (depth×width×height) and allows cumulative registration of individual immersion events of one second or longer with a response time of 15 ms. The timer was incorporated inside a waterproof housing made of two non-threaded PVC pipe caps of 5.0 cm internal diameter and 0.4 cm thick walls. A window was made in the end face of one of the PVC pipe caps by drilling a 4.8 cm diameter hole and gluing from the inside a transparent piece of Plexiglass® 5.0 cm in diameter and 0.6 cm thick (Figure 1A). In the other PVC pipe cap, two holes 0.2 cm in diameter were drilled on opposite sides (Figure 1B), through which stainless steel screws (0.635 cm in diameter) connected the back part of the timer to the exterior of the PVC housing (Figures 1B,C).

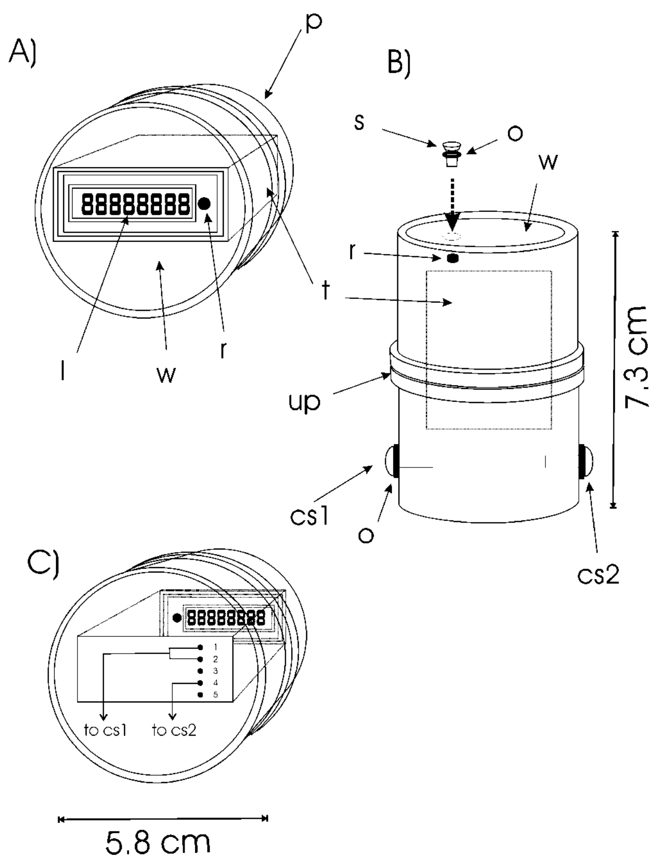

Figure 1. (A) Front view of the immersometer. (B) Side view of immersometer. (C) Rear view of immersometer with rear panel cut away showing electrical connections. p, PVC housing; t, Truemeter® timer; r, reset button; w, viewing window; l, 8 digit LED display; s, screw; o, o-ring; up, union of PVC end caps; cs1 & cs2, stainless steel screws serving as electrical contacts.

Internal connections were made following the Trumeter® specifications so as to leave the circuit open (Figure 1C). The stainless steel screws, which were fitted with o-rings and sealed in silicone sealant, served as contacts to complete the electrical circuit and begin registry when immersed in seawater. A hole was drilled and tapped into the Plexiglass® window above the reset button to fit the thread of a stainless steel M5 machine screw (1 cm in length). Removing the screw permitted access to the reset button (Figure 1B). The two pipe caps were glued together with Vinilit® PVC cement with the Trumeter® timer connected inside. The immersometer was affixed to rocks with either a PVC pipe clamp and two stainless steel screws, or plastic cable ties and two stainless steel eyebolts.

Recording of immersion time begins once a minimum current of 0.7V crosses the stainless steel contacts. Therefore, conductivity of seawater causes registry to begin once both contacts are submerged. Recording ends once at least one of the contacts becomes uncovered. Unlike regular digital clocks, the 7510 DIN 8 Trumeter® timer does not reset upon interruption of the circuit, but integrates the time of immersion until it is manually reset with the resetting button. The total cost of the immersometer, including the Trumeter® timer, PVC pipe caps and other materials and parts is less than 40 US dollars each at time of publication.

Calibration in the laboratory: an immersometer was manually plunged into a seawater tank for event durations between 1 and 9 seconds combined with event frequencies of 3, 4, 5, 6, 10, 12, 15, 20 and 30 events min^{-1}. We used only those combinations of event durations and frequencies that ensured the immersometer was out of the water for at least one second between events. Immersion frequencies of about 6 events min^{-1} correspond to typical wave periodicity levels observed in exposed coasts (Denny, 1988). In each case, we recorded the total immersion time after 1 to 3 minutes and repeated the process 4 to 6 times. The difference between actual (expected) immersion time per minute (event duration times frequency) and the reading of the immersometer was calculated after each trial and expressed as percentage deviation from the expected time. The 95% confidence interval of the mean of the independent repetitions was also calculated. To determine the behaviour of the immersometer for longer event durations, we left the immersometer under water for 1, 2, 4, 8, 16, 32, 60, 120, 140, and 196 minutes and registered the time at the end of the immersion period. A precision chronometer was used to keep time during all these trials.

Under event frequencies below 6 events per minute and all event durations, the immersometer recorded the expected immersion time with <4% error and did not deviate significantly from zero (Figure 2). In most cases, error was bound to within 1% of expected immersion time and variability among trials was low (Figure 2). Under high frequency conditions, between 10 and 30 events min^{-1}, there was higher variability among the different trials at a given event duration, but maximum mean error was still below 4% and did not differ significantly from zero (Figure 3).

Under all the long duration immersion events, from one to 196 minutes, the immersometer recorded expected immersion time to within one second, with a maximum error of 1.7%.

Calibration in the field: to determine the precision of the immersometer under field conditions, we installed the device, using stainless steel screws, in the low and mid tidal levels (~20 and 100 cm above mean low lower water (MLLW), respectively) of the wave exposed rocky intertidal zone at the Estación Costera de Investigaciones Marinas (ECIM) at Las Cruces, central Chile. The immersometer was left at each tidal height for periods of 1.5 hours, during which two people recorded the immersion time with a precision chronometer. One person observed when water covered and uncovered the contacts of the immersometer from four metres away, while the other manipulated the chronometer. These observations were done during a period of spring tides, with the ocean having relatively large swells.

Furthermore, in order to compare daily fluctuations in immersion times at the same tidal levels, daily measurements of immersion time were made simultaneously at 10, 90, 145 and 225 cm above MLLW (Low, Mid, High and Spray, respectively), over three consecutive days. For comparison, expected immersion times were obtained from tidal height predictions using the computational program Tides and Currents v 2.4 for Windows (Nautical Software, Beaverton, OR).

A total of 256 different immersion events (waves) were recorded in the field at the mid and low intertidal zones

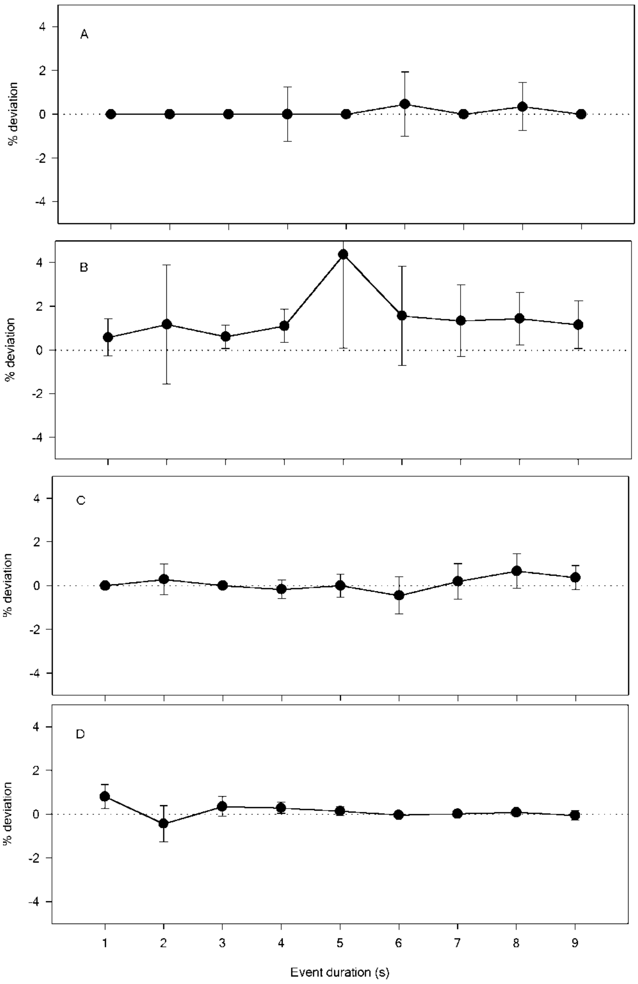

Figure 2. Calibration of the immersometer in the laboratory under conditions resembling the natural environment in duration (one to nine seconds) and frequency. (A) Three events min^{-1}; (B) four events min^{-1}; (C) five events min^{-1}; and (D) six events min^{-1}. Data are the mean per cent deviation and 95% confidence intervals of separate trials.

during the calibration. The mean ($\pm$SE) duration of immersion events was 7.25 ± 1.59 s, which occurred at a mean frequency of 6.0 ± 2.0 events min^{-1}. Comparison of immersion times estimated by direct measures with the precision chronometer and those registered by the immersometer were closely similar (pooled data from both mid and low intertidal: immersometer=0.995 chronometer -0.26, R^2=0.99, $P<0.0001$).

Field measurements made with the immersometer at different tidal heights and for periods of roughly 24 h showed that the total immersion times at any given height changed depending on the state of the ocean. Over the three consecutive days of observations, the general state of the ocean, quantified by wave height measured on the international Beaufort scale, changed from calm to intermediate, to rough. On the calm day, actual immersion time was slightly less than that predicted from the tidal charts (Figure 4A). On the intermediate day, immersion times were substantially higher at low and mid tidal levels than those predicted from the tidal charts, while higher tidal levels experienced similar immersion times to those predicted (Figure 4B). On a rough day, actual immersion times recorded by the immersometer were considerably higher than those predicted by tidal charts (Figure 4C).

Desiccation and thermal stresses during periods of exposure to air have been widely, and sometimes too readily, accepted to be key factors determining upper limits of species distributions in intertidal communities (Underwood & Denley, 1984). Rigorous evaluation of their effect requires the demonstration of a close correlation between upper distribution limits and exposure to air, for which precise quantification of exposure/immersion times is necessary. Over shorter time scales, many physiological, behavioural or ecological variables will be affected by the actual time of immersion to which the organisms are exposed over periods of hours, days or weeks or in different microhabitats. These immersion times will vary considerably over different trials or different locations of the experiments, making it necessary to register actual immersion times. Similarly, larval settlement rates are likely to be affected by the amount of time a suitable patch of substrate is covered by water for larvae to settle. Despite its importance, to date no adequate system of measuring the immersion (or emersion) has been developed for rocky intertidal shores. Most previous systems entail the use of a tide gauge, a chart recorder, or

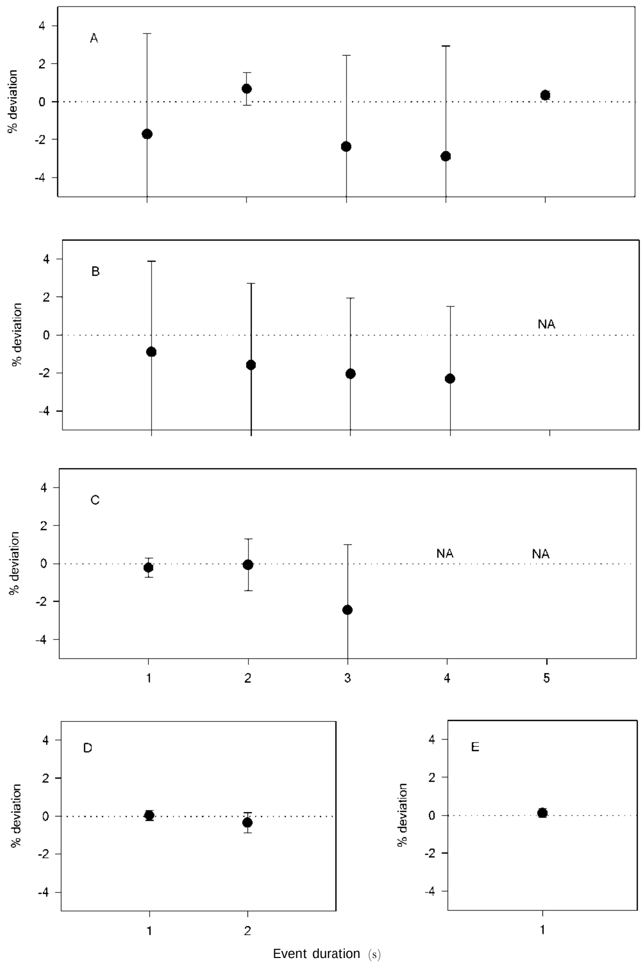

Figure 3. Calibration of the immersometer in the laboratory under high frequency events. (A) 10 events min^{-1}; (B) 12 events min^{-1}; (C) 15 events min^{-1}; (D) 20 events min^{-1}; and (E) 30 events min^{-1}. Data are the mean per cent deviation and 95% confidence intervals of separate trials.

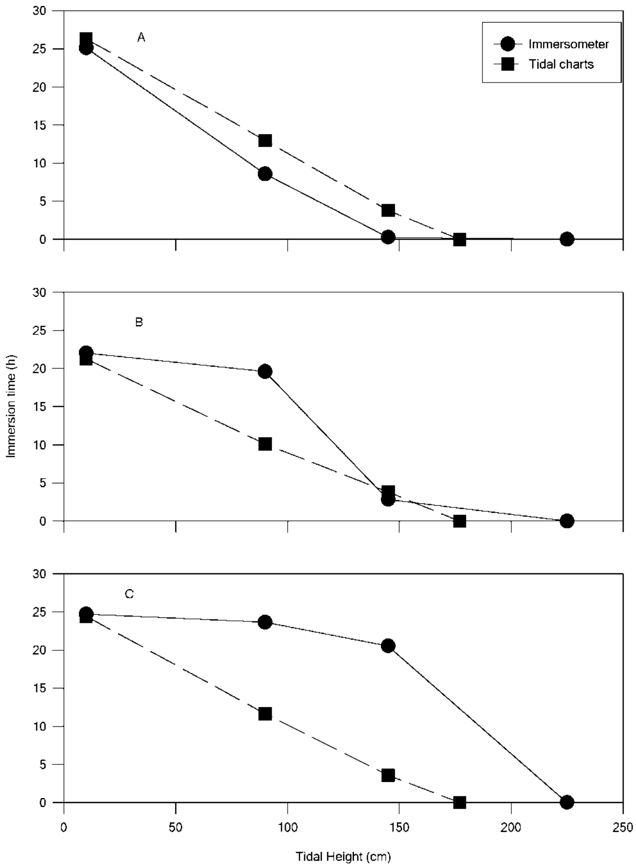

Figure 4. Comparison between immersion times recorded by the immersometer and those predicted from tidal charts over three consecutive days of different wave exposure. The immersometers were deployed at Low (10 cm above MLLW), Mid (90 cm), High (145 cm) and Spray (225 cm) tidal levels. (A) Calm day with daily mean wave height equal to 0.3 m. (B) Intermediate day, with daily mean wave height equal to 0.6 m. (C) Rough day with daily mean wave height equal to 1.0 m. Daily mean wave heights are based on the international Beaufort scale.

estimations calculated from tide tables. Although these may be adequate for larger spatial and temporal comparisons, their use within sites and at wave-exposed sites is limited.

The immersometer we developed provides precise field estimates of actual immersion times for areas of just a few centimetres and for time lapses from a few seconds to three years. The PVC housing offers impermeability to water and resistance to wave shock. The timer can be used at temperatures ranging from −10 to 60°C, deployed for up to just over three years of continuous immersion and has a lithium battery with an expected lifespan of ten years. The low voltage requirement for the initialization of the registry implies that the immersometer can also be used under more estuarine conditions or near river outputs where salinity may be substantially lower. However its accuracy should be evaluated under freshwater conditions. The 7500 DIN 8 timer has an eight-digit display permitting the reading of up to 99999999 seconds (3.17 years) of immersion before automatically resetting. Therefore, the reset button screw is not necessary if data are retrieved within three years of deployment. The specifications of the immersometer can be varied, including the total volume and anchorage system (e.g. cable ties), depending on the necessities and limitations presented by individual studies.

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