TECHNICAL NOTE

A Novel Acoustic Dissolved Oxygen Transmitter for Fish Telemetry

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ABSTRACT

The multiple responses of fishes to changes in dissolved oxygen saturations have been studied widely in the laboratory. In contrast, only a few studies have included field observations. The objective of the present study was to evaluate the performance of a novel acoustic dissolved oxygen transmitter for field biotelemetry. The results demonstrated that the output of the transmitter was unaffected by three different temperatures (10 to 30°C) and described the dissolved oxygen saturation with high accuracy ($r^2 > 0.99$) over the entire range of 0 to 191% saturation. The response time (≥ 90% of end value) of the transmitter was 12 s both in terms of decreasing (100 to 0%) and increasing (0 to 100%) oxygen saturations. When externally attached to fishes, the present findings support the use of the transmitter for reliable dissolved oxygen measurements on individuals living in environments that may change both temporally and spatially with regard to ambient temperature and dissolved oxygen saturation.

Introduction

There are several ways of collecting time series information on fish migration (Lucas and Baras, 2000). In recent studies, the use of telemetry on free-ranging fishes has enabled accurate quantification of changes in the use of space over time on an individual level (Lucas and Baras, 2001). Using a variety of sensors attached to free-ranging animals living in marine and freshwater environments, telemetry studies increasingly include remote measurements of the physiology, behaviour and energetic status of the tagged animals and environmental conditions that are relevant to the organismal physiology (Cooke et al., 2004). This methodology has been termed biotelemetry, and Cooke et al. (2004) predicted that some of the most interesting future findings in ecology will be derived from research that incorporates telemetered or logged field measurements.

Owing to its immense influence on aquatic life, the impact of changes in dissolved oxygen (DO) has received substantial attention among researchers working with aquatic animals. Several laboratory studies on marine and freshwater species have shown that changes in DO saturation may cause multiple effects on fish behaviour, physiology, biochemistry, metabolism, swimming performance, growth and mortality (Kutty and Saunders, 1973; Siefert et al., 1973; Tetens and Lykkeboe, 1981; Bushnell et al., 1984; Petersen and Petersen, 1990; Schurmann and Steffensen, 1992; Nilsson et al., 1993; Schurmann and Steffensen, 1997; Dalla Via et al., 1998; Chabot and Dutil, 1999; Brauner et al., 2000). Despite these profound effects, dissolved oxygen measurements are not commonly included in fish biotelemetry field studies (Cooke et al., 2004). Priede et al., (1988a,b) developed and applied a transmitter capable of detecting changes in dissolved oxygen, however to our knowledge no subsequent studies have utilized DO transmitters, presumably reflecting the limitations of conventional oxygen sensor technology and difficulties associated with the method. As indicated by the authors, the polarographic oxygen sensor is vulnerable to drift and thus requires frequent recalibrations, which may be impractical for field work. In addition, polarographic sensors require a stabilized polarising power supply, which may be complicated to obtain in a telemetry transmitter set-up.

The objective of the present study was to conduct a controlled laboratory examination of a novel DO transmitter and critically evaluate its performance in relation to field biotelemetry. When attached to fishes in the wild, the DO transmitter may be exposed to temporally and spatially changing temperatures. This issue is emphasized by laboratory studies on Atlantic cod (*Gadus morhua*) demonstrating how this species may decrease the preferred temperature as a response to hypoxia (Petersen and Steffensen, 2003). Accordingly, the transmitter was tested at different temperatures with oxygen saturations ranging from 0 to 191%. Using a tower tank, Claireaux et al. (1995) demonstrated how Atlantic cod voluntarily may perform short foraging excursions into hypoxic water. In order to evaluate the applicability of the DO transmitter to detect and quantify this type of foraging behaviour, the response time (≥90% of end value) was tested by transferring the transmitter directly from 100% to 0% DO saturation and *vice versa*.

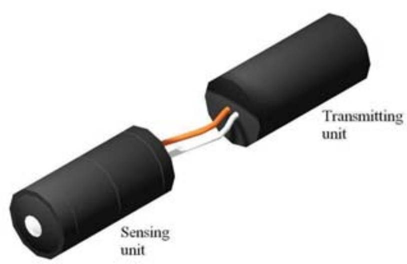
Methods

Transmitter Specifications

The DO transmitter is based on an oxygen sensor attached to an acoustic transmitter (e.g. 69 kHz) (Figure 1). Simplified circuits are shown in Figure 2. When the two units are connected (Figure 1), and the transmitter is activated using a reed switch, the DO saturation in the water is determined and transmitted to a hydrophone connected to a receiver. Multiple transmitters may apply different frequencies, which would allow simultaneous reception of signals from several transmitters. In response to changing DO saturations, the transmitter modulates the inter pulse period. Dissolved oxygen saturations ranging from 0% to 200% corresponds to inter pulse periods ranging from 1000 ms to 3000 ms. Thus, the DO saturation is transmitted with a frequency of 1 – 0.33 Hz. The pulse length is 10 ms. The output power level is 148 – 150 dB re 1 µPa @ 1m, and it is similar to other acoustic telemetry transmitters (e.g. the V13 transmitter available from Vemco Ltd., Halifax, Nova Scotia, Canada). The signal transmission distance depends on numerous factors including the occurrence of waves, bubbles, thermoclines, haloclines, boat traffic etc.

FIGURE 1

The acoustic DO transmitter. The sensing and transmitting units are connected by two wires. The battery is included in the transmitting unit, and the sensing surface is indicated by the white circle.

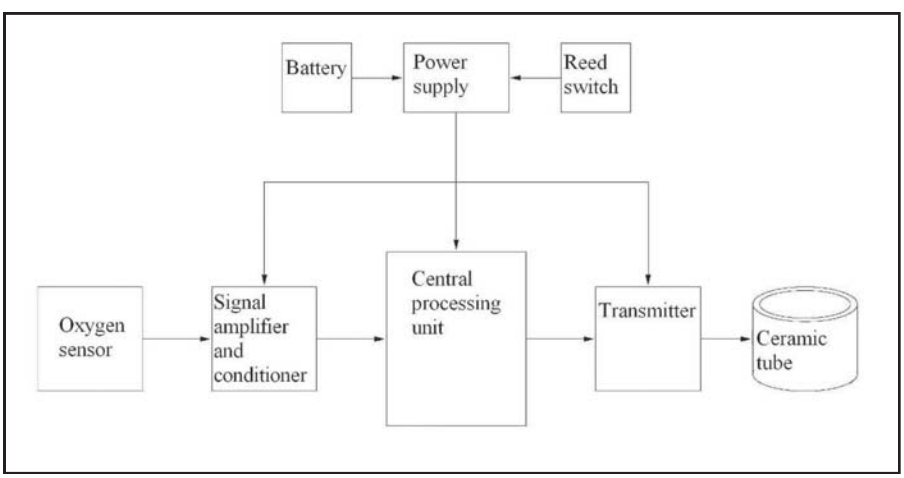


The DO transmitter applies a galvanic oxygen sensor type, which measures the oxygen saturation of the water. The sensor produces a voltage of 0 and 20 mV in response to 0% and 100% saturation, respectively. Effectively, this enhances battery life as power is only used for the transmitting unit. The accuracy of the transmitting unit itself is ±1% when the output (mV) from the oxygen sensing unit corresponds to DO saturations ≥ 25%. Below 25%, the accuracy is ±2%. The accuracy of the sensing unit is ±1%. Both the sensing and the transmitting units are unaffected by different salinities and by pressure equivalent to a water depth of 2000 m.

The total mass of the DO transmitter is 15 g in air and it houses a silver oxide battery with an expected life-time of 30 days in severe hypoxia (i.e. short inter pulse periods). The lengths of the sensing and the transmitting units are 27 and 30 mm, respectively. The diameter is 12.5 mm. Owing to a low oxygen consumption of the galvanic oxygen sensor type, a minimum flow of less than 1 cm s^{-1} is required. The transmitting unit was developed in cooperation with Thelma, Trondheim, Norway but the DO transmitter is available from LoligoSystems, Hobro, Denmark. The DO transmitter may be supplied with the transmitting unit and the sensing unit disconnected or connected and sealed with epoxy. In the latter case, the length of the sensing unit is reduced to 23 mm. The acoustically transmitting unit could potentially be substituted by a unit transmitting VHF radio signals (Lucas and Baras, 2000). Such an arrangement may be appropriate for studies on fishes living in freshwater. Alternatively, the oxygen sensor could be attached to a data storage tag (Lucas and Baras, 2000).

FIGURE 2

The simplified circuits of the acoustic DO transmitter.



Experimental Procedures

In order to evaluate the DO transmitter in terms of water temperature, the two connected units were submerged in a 0.5 l conical bottle with demineralised water and stirred on a magnetic stirrer. Constant water temperature was maintained using a digital temperature controlling unit, a 100 W aquarium heater and a cooling bath. A DIGAMIX gas mixing pump from H. Wösthoff, Germany (type M 300/a) was used to obtain appropriate mixtures of gaseous oxygen and nitrogen. Gas mixtures were bubbled through a ceramic diffuser immersed in the conical bottle to maintain accurate oxygen saturations in the water. A Vemco VR60 acoustic receiver picked up the signals from the transmitting unit and provided the inter pulse periods (to nearest ms). These procedures were followed at 10, 20 and 30° C (± 0.1° C) using oxygen contents adjusted to 0, 48, 96, 143 and 191% saturation. The temperatures 20 and 30 ° C (± 0.1° C) were examined using 100% saturation. At each temperature, three inter pulse periods were logged per oxygen level. A similar approach was applied to examine the response time of the DO transmitter. Using gaseous nitrogen and air bubbled through ceramic diffusers, 100% and 0% DO saturations were established in two 1 l buckets with identical flows, created by two 400 l h^{-1} water pumps. Water temperature was kept at 18° C (± 0.2° C). The DO transmitter was held in the 100% saturation bucket, allowed to stabilize and then transferred directly to the 0% saturation bucket. The Vemco VR60 receiver recorded the inter pulse periods. As the inter pulse periods stabilized at values equivalent to 0% saturation, the DO transmitter was transferred back to the 100% saturation. Simultaneously, the receiver recorded the corresponding inter pulse periods until they stabilized at values equivalent to 100% saturation.

Results

The inter pulse periods, recorded from the transmitting unit, varied with the DO saturation in the water (Figure 3). There were no indications of any temperature effects on the transmitter output. Data were consequently pooled and described by the following linear equation: $y = 0.10\ (\pm\ 0.00)\ x - 100.55\ (\pm\ 0.93)$ ($P < 0.0001$) where y is the oxygen content (% saturation), x is the inter pulse period (ms), and ± 1 S.E. are given in parentheses. Both estimated parameters were significant ($P < 0.0001$). The equation gave a highly accurate estimate of oxygen content in the water ($r^2 > 0.99$). The transmitter responded rapidly to the decreasing and increasing oxygen saturations (Figure 4). In both cases, ≥ 90% of the end value was reached in 12 s.

FIGURE 3

Linear relationship between the transmitted inter pulse period (ms) and the dissolved oxygen saturation (%) of the water (n = 51).

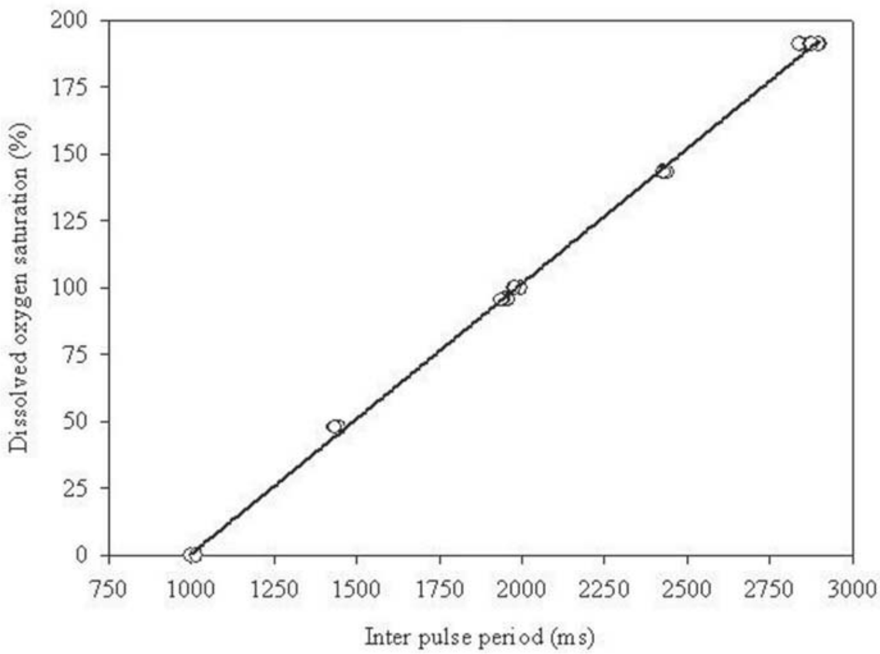
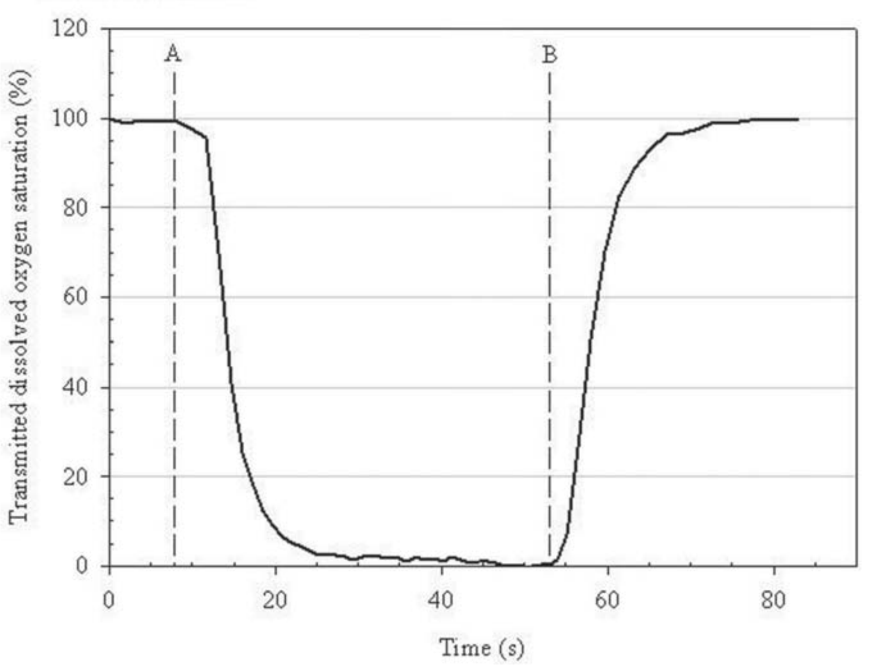


FIGURE 4

Transmitter output at 18°C describing the measured oxygen saturation (%) of the water when the transmitter was transferred directly from 100% to 0% saturation (beginning at dashed line A) and *vice versa* (beginning at dashed line B) (n = 64).



Discussion

This is the first study to provide a controlled laboratory examination of a biotelemetry transmitter capable of measuring oxygen content in the water. When attached to a fish, the transmitter will rapidly determine the oxygen saturation of water in the immediate vicinity of the fish within the tested temperature range. Commonly, the exposures of individual free-ranging fishes to physiochemical variables in the field have been quantified by equipping the animal with a conventional telemetry transmitter and subsequently measuring the physiochemical variables in the vicinity of the individual (Knights et al., 1995). Particularly in the marine environment, this methodology may infer some disadvantages including difficulties in terms of securing that the variables are measured appropriately close to the fish; disturbances of the fish and a relatively low temporal resolution of the measurements as it may be unsuitable to conduct the measurements at a high frequency. The oxygen transmitter described here offers some advantages as it is not subject to these constraints.

The sensor unit of the transmitter must remain in contact with the water. Thus, the sensor unit or the entire transmitter must be attached externally (Mellas & Haynes, 1985; Økland et al., 2003; Crook, 2004) to the fish. Unlike intraperitoneal attachment, which is currently the preferred method for most other transmitters, external attachment is vulnerable to bio-fouling (Thorstad et al., 2001). The impact of bio-fouling will, however, depend on season, temperature, eutrophication level, study duration, etc. In addition, external attachment may lead to other problems such as the loss of postural equilibrium, increased drag, and physical entanglement and snagging (Lucas & Baras, 2001; Rikardsen & Thorstad, 2006). Hence, it is crucial that negative impacts of the externally attached oxygen transmitter are considered whenever it is included in a study.

When attached to a fish, it is important that the oxygen sensing unit is exposed to an adequate water velocity. This may be accomplished if species living in lotic habitats are investigated. For example, during summer time brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*) show the highest preference for water velocities ranging from approximately 10 to 25 cm s^{-1} (Heggenes and Dokk, 2001). An alternative approach involves fishes that induce the needed water velocity because of their sustained swimming activity. Presumably, this applies to certain pelagic marine fishes such as the elasmobranchs, scombrids and thunnids as they normally maintain a forward swimming speed to generate appropriate lift to prevent sinking (Jobling, 1995).

Acoustically tagged fishes are commonly positioned manually using a directional hydrophone (Lyons and Lucas, 2002) and fish telemetered in the field may be physiologically sampled prior to release (Aarestrup et al., 2000), during the experiment (Nielsen et al., 2004) and recaptured *post* experimentally (Koed and Thorstad, 2001). Using the latter approach, Koed et al. (in press) related differences in growth of northern pike (*Esox lucius)* to their annual movements. In parallel, the oxygen transmitter may permit the quantification of the long term oxygen history of individuals and the associated behavioural and possibly physiological responses. Few studies have applied biotelemetry tools to document the responses of fishes to changing environmental conditions *in situ* and in real time (Cooke and Schreer, 2003). In combination with other biotelemetry tools (Cooke et al., 2004), the oxygen transmitter may allow quantification of the physiological costs resulting from chronic or repetitive exposures to oxygen stress (i.e. allostatic load [McEven and Wingfield, 2003]) of free-living fishes.

Conclusion

The majority of previous fish telemetry studies have been conducted in freshwater resulting in a substantial advance in our knowledge in recent years (Lucas and Baras, 2001). Acoustic telemetry on marine species is however, increasingly included in studies (Clements et al., 2005) regarding aquaculture (Cubitt et al., 2005), marine protected areas, home range and habitat use (Humston et al., 2005; Lindholm et al., 2005; Meyer and Holland, 2005; Picciulin et al., 2005; Popple and Hunte, 2005; Specicato et al., 2005; Starr et al., 2005; Szedlmayer and Schroepfer, 2005; Topping et al., 2005) and swimming (Løkkeborg et al., 2002; Lacroix et al., 2005), food search (Løkkeborg, 1998; Løkkeborg & Fernö, 1999; Løkkeborg et al., 2000) and homing (Mitamura et al., 2005) behaviours. As the signal of the oxygen transmitter evaluated in the present study is acoustic, it may be applied in the marine environment. Such studies are likely to result in new insights and may provide field support for previous laboratory results.

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