Implantation, orientation and validation of a commercially produced heart-rate logger for use in a perciform teleost fish

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Quantifying how the heart rate of ectothermic organisms responds to environmental conditions (e.g. water temperature) is important information to quantify their sensitivity to environmental change. Heart rate studies have typically been conducted in lab environments where fish are confined. However, commercially available implantable heart rate biologgers provide the opportunity to study free-swimming fish. Our study aimed to determine the applicability of an implantable device, typically used on fusiform-shaped fish (e.g. salmonids), for a perciform fish where morphology and anatomy prevent ventral incisions normally used on fusiform-shaped fish. We found that ventrolateral incisions allowed placement near the heart, but efficacy of the loggers was sensitive to their orientation and the positioning of the electrodes. Electrocardiogram detection, signal strength and subsequent heart rate readings were strongly influenced by logger orientation with a significant effect on the quality and quantity of heart rate recordings. We provide details on the surgical procedures and orientation to guide future heart rate biologger studies on perciform-shaped fish.

Key words: Biologging, electrocardiogram, heart rate, Pachymetopon grande, sea bream, Sparidae

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Introduction

Measurement of the heart rate ($f_H$) of fish can provide estimates of metabolic rate and energy expenditure (Lucas et al. 1991; 1993; Cooke et al. 2010) and serve as an indicator of stress in response to different environmental conditions and human-induced disturbances (Schreer et al. 2001; Graham and Cooke 2008; Brijs et al. 2019). As such, quantifying how the $f_H$ of fish responds to environmental stressors like temperature is important to accurately predict how ectothermic organisms will respond to environmental change. Increases in metabolic rates drive a rise in oxygen demand, which relates to an increase in cardiac output (Farrell et al. 2009; Ekström et al. 2018). This measure of increased cardiac activity, which may relate to food acquisition or predator avoidance, is a promising aspect for the refining of bioenergetics models (Cooke et al. 2016). Acquiring remote measurements from wild fish fitted with $f_H$ loggers could provide important
insights into how warming or upwelling events or variability in temperature in general affects foraging success, activity, behaviour and habitat use at an individual level (Cooke et al. 2012; Ekström et al. 2018). Autonomic regulation, for example, modulates \( f_H \) in response to temperature to meet oxygen demands, but at critical thermal maxima, heart rate is shown to plateau and subsequently decrease indicating that the delivery of oxygen is compromised at critical temperatures (Anttila et al. 2014; Skeeles et al. 2020). Individual differences in thermal tolerance as well as the mechanisms involved (e.g. coronary perfusion) may be important selective factors associated with warming (Ekström et al. 2019).

 Weak correlations between \( f_H \) and metabolic rate in some instances have led to criticism in the use of \( f_H \) telemetry (Thorarensen et al. 1996; Butler et al. 2004). This weak relationship is primarily attributed to the varying contribution of stroke volume to total cardiac output, which may be a regulatory mechanism for a number of species (Clark et al. 2005). Nonetheless, as more species are found to predominantly regulate cardiac output through changes in \( f_H \) (Schreer et al. 2001; Cooke et al. 2002; Clark et al. 2005; Cooke et al. 2010) the method is well situated to provide important information on the physiology, ecology and energetics of wild fish (Cooke et al. 2004, 2016). Species-specific investigations into the relationships among cardiac activity and oxygen consumption rates should however be explored prior to field applications (Cooke et al. 2016).

 Modern, fully implantable devices are leadless, lightweight and small; have sufficient battery power and data storage for months to years of observations; and are minimally invasive, with little to no hydrodynamic or behavioural modifications (Butler et al. 2004). These have been used for detecting the heart rate of a range of free-swimming fishes, particularly the salmonids Oncorhynchus nerka (Clark et al. 2009, 2010; Prystay et al. 2017), O. kisutch (Donaldson et al. 2010) and O. mykiss (Brijs et al. 2018; Ekström et al. 2018; Brijs et al. 2019) and gadoids Gadus morhua (Bjarnason et al. 2019; Davidsen et al. 2019). Up to now, there are few published studies on the use of these devices in perciform fishes (but see Prystay 2018; Prystay et al. 2019; Skeeles et al. 2020).

 One of the reasons for this may be the difficulty of implanting these loggers to effectively detect heart rate. This may partly be attributed to the morphology of these fishes, which have anteriorly positioned pectoral and pelvic girdles, making placement near the pericardium difficult, a narrow ventral cavity, have anteriorly positioned pectoral and pelvic girdles, making placement near the pericardium difficult, a narrow ventral cavity, which encourages movement of the body cavity of perciforms is necessary. Using an archetypal perciform fish, the aim of this study was to describe an optimal procedure for the implantation and attachment of a commercially available \( f_H \) logger and to compare its efficacy when placed at different orientations in both anaesthetized and captive free swimming fish.

**Methods**

**Study species, surgery and instrumentation**

Bronze bream (Pachymetopon grande; Günther, 1859; Sparidae) are endemic to southern Africa occurring in shallow, rocky coastal areas. Their oblong, slightly compressed body is typical of other sparids, an important Perciformes family of both commercial and recreational importance that is represented by approximately 29 genera and over 100 species worldwide (Heemstra and Heemstra 2004). For this study, *P. grande* were collected near Port Alfred (Eastern Cape, South Africa) with rod and line (permit number RES2019/76) and transported to the nearby NRF-SAIAB Aquatic Ecology Research Platform (AERP) at Rhodes University, Makhanda (formerly Grahamstown). Prior to experiments, fish were held for a minimum of 1 month in 5900-L tanks operating on a saltwater recirculation system. Water temperature and light periodicity were controlled and reflected natural conditions at the time of capture; temperature was maintained at ~18°C and light:dark cycle 10:14. An anaesthetized baseline study was initially carried out on 10 restrained fish (length range 278–360 mm Fork Length), followed by an active, free-swimming treatment (\( N = 18, 260–368 \) mm FL). The aim of the baseline study was to determine whether logger position and orientation would be maintained with a double suture wrap (see Skeeles et al. 2020) while fish had limited mobility. Position and orientation of the logger were confirmed upon retrieval of the device at the completion of each trial. Following the baseline study, fish were used in a free-swimming treatment where logger orientation was randomly assigned at the time of surgery. Three logger orientations were investigated: down—electrodes faced 180◦ away from the ventrolateral incision and were in contact with the intestine; side—electrodes positioned at a 45◦ angle ventrally and in direct contact with musculature; and up—electrodes positioned towards the incision and were in contact with musculature (Fig. 1).

Biologgers used in the study were DST micro-HRT (\( L = 25.4 \) mm, \( W = 8.3 \) mm, Mass = 3.3 g, Star-Oddi, Iceland) heart rate and temperature loggers. The compact, lightweight devices monitor heart rate via a single-channel electrocardiogram (ECG) amplifier that uses two electrodes incorporated into the ceramic, leadless casing. Heart rate values are derived from mean R–R intervals, the positive peak in the QRS complex associated with ventricular depolarization (Fig. 2a), which is captured by burst measurements of ECG at set time intervals (Cooke et al. 2016; Bjarnason et al. 2019). Bursts are graded with a quality index (QI) which is rated from 0 to 3, ranging from great to poor (see: DST Micro-HRT User Manual). A temperature sensor is also located within the casing with an accuracy of 0.2°C as well as a real-time clock with an accuracy of 1 min. Captured measurements of \( f_H \) in
Figure 1: Proximity of biologger and incision (stippled line) relative to the pericardium (red), pelvic and pectoral girdles (grey) and within the abdominal cavity for *Pachymetopon grande*, a typical sparid. Three logger orientations tested: down—electrodes faced 180° away from incision; side—electrodes positioned ventrally at 45°; and up—electrodes positioned towards incision.

Figure 2: Conceptual electrocardiogram (ECG) at top (a) indicating elements associated with electrical conductivity where P wave indicates atrial contraction, QRS complex ventricular contraction and T wave ventricular relaxation. Poor electrode positioning may result in elevated T waves (stippled red line) which are falsely detected as R waves. Raw ECG waves from the three logger positions are shown below (b), note elevated T wave of down position.

BPM, as well as QI, are stored independently (ECG discarded) to reduce memory requirements and extend battery life. Loggers were programmed to record $f_H$ at 15-s intervals at a frequency of 200 Hz, while ECG was recorded at 1-min intervals for a selected number of individuals for later validation of $f_H$ readings, using the application software Mercury v 4.84 and the associated Communication Box (STAR-ODDI, Gardabaer, Iceland).

Fish were anaesthetized prior to surgery with 2-phenoxyethanol at a dose of 0.2 mL L$^{-1}$ (Priborsky and Velisek 2018) until the loss of equilibrium, upon which they were placed in an operating sling lateral side up. A soft wet microfibre cloth covered the eyes while anaesthetic water was poured over the gills and cloth to maintain anaesthesia and keep external organs moist. Surgery involved a single ventrolateral incision immediately posterior of the pectoral girdle of ~25 mm. The logger was placed within the body cavity, posterior to but in contact with the pericardial membrane, while care was taken to not pierce the membrane. Two sutures (Clinisut® silk suture; 3–0) were attached to the logger which was inserted with the transparent-epoxied part, where the temperature sensor is located, pointing posteriorly. The afferent suture was placed through the designated suture hole, while the other was secured to the posterior end via a suture wrap.

For the anaesthetized baseline treatment, fish were placed in an upright foam sling in 250-L glass tanks connected to an 800-L recirculation sump. The tanks had two inflows, one to regulate water temperature and the other inserted into the mouth to create flow over the gills to maintain fish respiration. Water temperature was maintained at the same temperature as that from the holding system and dosed with 0.2 mL L$^{-1}$ of 2-phenoxyethanol to ensure anaesthesia for the duration of the 1-h-long treatment. For the free-swimming treatment, following surgery fish were released back into the 5900-L holding tanks with conspecifics. Recovery time was monitored, and fish were released once they had regained equilibrium and showed signs of vigour. They were recap-
tured 1 h after recovery and sacrificed with a lethal dose (0.5 mL L\(^{-1}\)) of 2-phenoxethanol prior to recovery of the logger whereupon orientation of the device was confirmed for all individuals.

**Data processing and analysis**

Data processing involved removing measurements recorded prior to recovery (once core temperature matched water temperature and erratic heart rates had subsided) and before collection (indicated by erratic heart rates associated with capture or handling). Data analysis was performed by calculating the proportion of good (\(QI \leq 1\)) \(f_{11}\) readings per trial by dividing the count of 0 and 1 \(QI\) values by the total number of values. To determine if logger orientation influenced \(f_{11}\) accuracy, we implemented a beta regression with the proportion of good \(QI\) values as the dependent variable and logger orientation as the independent variable within the `betareg` package (Cribari-Neto and Zeileis 2010) for free-swimming fish only. We used Tukey’s post hoc tests to determine which logger orientation positions were significantly different. The small sample size for anaesthetized fish prevented any statistical testing. Median \(f_{11}\) are presented throughout due to the distribution of the data with a number of extreme outliers skewing means. All analyses were conducted in R version 3.5.1 (R Core Team 2018).

Captured ECG data traces were used to manually validate heart rate calculations using the software Pattern Finder (v. 1.14.0, Star-Oddi, Iceland). Intervals between the QRS waveform were measured using a double cursor that outputs the interval in beats per minute. Manually derived \(f_{11}\) were then compared with those calculated by the biologger.

**Results**

A total of 28 fish were operated on ranging from 260 to 368 mm FL, corresponding to 500–1400 g, with no significant difference in length among treatments. Post-surgery recovery ranged from 1 to 9 min with an average of 4.5 min before equilibrium was regained and either active swimming took place or opercular beats became rhythmic. Time to recovery was positively related to size (Spearman’s rank correlation: \(r_S = 0.62, P < 0.01, N = 18\)), with larger individuals typically taking longer to recover from the effects of anaesthesia.

ECG traces showed consistent differences among orientations, with side and up typically being very similar while those from the down position were not sensible. R-wave amplitude, the positive inflection of the QRS complex associated with ventricular contraction, was greatest for the up orientation although this position also exhibited greater noise (Fig. 2b). ECGs from the side orientation exhibited lower R-wave amplitude although reduced signal noise resulted in a greater proportion of good results (low \(QI\)). ECGs from the down position consistently displayed elevated T waves, signal associated with ventricular relaxation, which likely resulted in the elevated \(f_{11}\) values as T-waves were falsely identified as R-waves. Manually derived \(f_{11}\), by measuring R–R interval distance, consistently agreed with beat per minute values automatically calculated by the logger.

Quality index scores differed greatly among logger orientations, as did the distribution of heart rate values (BPM) with side orientation consistently producing a higher proportion of good results when compared to other orientations (Fig. 3). Results for baseline treatments showed a higher proportion of 0 and 1 \(QI\) values associated with the side orientation while proportions were lower for up and dominated by poor values for the down position (Fig. 3a). Likewise, associated heart rate values varied among orientations with both side and up producing relatively low variance around a similar median of 59 and 57 BPM, respectively (Fig. 3c). The downward orientation produced unusable results with a high proportion of extreme values.

For the free-swimming treatment, there was a significant difference (\(X^2 (2, N = 18) = 809.63, P < 0.001\)) among the proportion of good values recorded per logger orientation (Fig. 4). Side orientation again produced the highest proportion of good results (\(QI = 0\) and 1) at 66% of total recordings while down and up orientations progressively tended toward poorer \(QIs\) of 58 and 50%, respectively (Fig. 3b). Side and up orientations also captured better heart rate values, although medians differed moderately with 99 and 79 BPM, respectively. This moderate variation between orientations is most likely attributed to individual \(f_{11}\) variation, which differed greatly among individuals, rather than to ECG detection of individual loggers among orientations. Median values for side ranged from 67 to 182 BPM, with up similarly ranging from 56 to 165 BPM. Assessment of individual \(f_{11}\) typically displayed little variation around median values, although means were skewed due to few unrealistic elevated values. Median \(f_{11}\) values recorded from the down position were unrealistic, ranging from 120 to 215 BPM and further showing great variation around a median value.

**Discussion**

Studies using and detailing biologger attachment or positioning have typically focussed on salmonids (Clark et al. 2009; Norling 2017; Brijs et al. 2018) and gadoids (Neat et al. 2006; Righton et al. 2006; Bjarnason et al. 2019; Davidsen et al. 2019) where, due to the specific anatomy of these fishes, incisions have been made along the ventral midline to access the peritoneal cavity. The skeletal system, specifically the pelvic girdle, of many perciform species prevents ventral access to the heart for biologger placement, therefore requiring a different approach. We found that for a typical sparid, *Pachymetopon grande*, the ventrolateral surgical implantation of the biologger immediately posterior to the scapulocoracoid of the pelvic girdle ensured a high consistency of successful implantations and enabled placing the logger near the peri-
Proper placement of R-wave detectors is critical in order to maximize the clarity and size of the ECG signal (Ponganis 2007; Cooke et al. 2016). Double recordings may be attributed to the detection of elevated peaks associated with atrial contraction or ventricular relaxation, P or T waves, respectively, which are both positive inflections of the ECG signal, and are noted as a possible source of error in R-wave detectors (Ponganis 2007). Analysis of the ECG signal from the down position indeed verified elevated T waves in the current study, indicating poor electrode positioning. Cooke et al. (2002) recommended that the placement of the electrodes should be near the pericardial cavity but perforation may result in altered cardiac performance. Based on recorded ECG signals, both side and up orientations had satisfactory electrode placement indicated by defined peaks associated with the QRS complex. Side orientation had the greatest number of successful readings, with 66% of data classified as good (QI of 0 and 1), compared to up and down, with 50 and 58% respectively. Movement of the device within the body cavity may also produce poor recordings. This is of particular concern when considering the deep body cavity of perciform fishes and therefore the double suture technique employed was considered necessary to ensure that the electrodes maintain position throughout deployment which was confirmed upon their retrieval. This
appears unnecessary with fusiform-shaped fishes where measurements are typically more successful with ratios of good readings of 84% (Bjarnason et al. 2019) and 89% (Davidsen et al. 2019) for gadoids using a similar device (Star-Oddi, DST Milli-HRT). The median \( f_{\text{H}} \) of anaesthetized fish for both side and up orientations was very similar at 59 and 57 BPM, respectively. These values are higher than those of resting sockeye salmon Oncorhynchus nerka averaging 43 BPM at 19°C (Prystay et al. 2017) or routine rates of \( \sim 40 \) BPM at 18°C for smallmouth bass Micropterus dolomieu (Prystay et al. 2019). Our values did, however, more closely approximate those recorded for resting centrarchid species, pumpkinseed Lepomis gibbosus and bluegill L. macrochirus averaging \( \sim 60 \) BPM at 18°C (Cooke et al. 2002, 2010). Free-swimming rates were notably higher than those of anaesthetized fish. Although there was considerable difference between median values of side and up orientations this was most likely due to individual variation rather than differences between orientation and R–R signal strength, as was confirmed by ECG traces. Bjarnason et al. (2019) similarly found notable individual variation in \( f_{\text{H}} \) for Gadus morhua during a 5-week-long experimental period, with means ranging from 29.9 to 48.3 BPM at 10°C. Free-swimming rates were also comparable to those attained for centrarchids, L. gibbosus and L. macrochirus after exhaustive exercise (\( \sim 100 \) BPM at 18°C (Cooke et al. 2010)) and active swimming yellowtail kingfish Seriola lalandi (95 BPM at 20°C (Clark et al. 2006)). While peak \( f_{\text{H}} \) of stressed O. nerka averaged 105 BPM at 19°C following simulated fisheries catch and release (Prystay et al. 2017). It should be noted, however, that our recorded \( f_{\text{H}} \) are likely elevated for stressed animals may not have the same capacity to control their \( f_{\text{H}} \) as an unstressed animal (Brijs et al. 2018) and insufficient recovery times following anaesthesia and surgery has been suggested to mask \( f_{\text{H}} \) modulation of fishes (Clark et al. 2005). Heart rate of G. morhua, for example, remained elevated for 8–10 days following surgery (Webber et al. 1998), while rainbow trout O. mykiss required \( \sim 4 \) days to regain normal activity (Brijs et al. 2018).

While the measurement of cardiac output and its relationship with metabolism is not a new field of study, the availability of a commercially available device which is fully implantable does present a new set of opportunities. Longer-term studies are indicating that cardiac output is less affected by changes in stroke volume than previously suspected, which may be due to insufficient recovery periods, indicating that \( f_{\text{H}} \) is a reliable indicator of energy expenditure (Clark et al. 2005; Cooke et al. 2016). Contemporary studies using modern \( f_{\text{H}} \) loggers are shedding light on the physiology of fish in response to temperature (Ekström et al. 2018, 2019; Skeele et al. 2020), fisheries catch and release (Prystay et al. 2017), aquaculture stress (Brijs et al. 2018, 2019) and parental care investment (Prystay et al. 2019). They have the potential to contribute notably to bioenergetics modelling (Cooke et al. 2016) as well as provide insights into physiological responses to environmental change and stressors while also illuminating the mechanisms involved in adapting to these changes (Norin and Metcalfe 2019).

Our intention was to describe an optimal implantation method and evaluate the effect of orientation or electrode placement on data quality of a commercially available \( f_{\text{H}} \) logger for a typical perciform fish. We found that the ventrolateral incision enabled placement of the device near the heart, was minimally invasive, offered quick surgery time and did not require extensive surgical training. Orientation of the electrodes was critical for data quality and the three orientations tested produced exceptionally poor to good results. In contrast with our findings, orientation of electrodes was found to have no impact on data quality for rainbow trout as long as the logger was placed as close to the heart as possible (Norling 2017). We advise that for studies on perciform fish using similar devices as that of the current study, loggers should be placed or moved as close to the heart as possible, electrodes should be in contact with musculature and double sutures should be used to prevent risk of movement or displacement. Prior to any investigation using biologgers, researchers should conduct pilot experiments to determine optimal placement of the devices. Trial experiments using both resting/anaesthetized and active fish will also assist with data analysis by determining \( f_{\text{H}} \) threshold limits, values falling outside of these limits can therefore be excluded from further analysis.

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