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A FIBER OPTIC SENSOR FOR HIGH RESOLUTION MEASUREMENT AND CONTINUOUS MONITORING OF VALVE GAPE IN BIVALVE MOLLUSCS

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ABSTRACT We describe a novel sensor based on fiber optic technology for fine scale (~0.1 mm) laboratory measurements of valve gape in bivalve molluscs. We have illustrated the operation of this sensor by measuring valve gape in conjunction with depletion rate assays in the Eastern oyster (*Crassostrea virginica*, Gmelin 1791). The sensor is capable of accurate and repeatable measurements, with few of the drawbacks of other valve gape sensing methods (e.g., levers, strain gauges, electromagnetic sensors). This sensor technology can be applied to other systems requiring the measurement of axial distances while immersed in seawater or other harsh environments.

KEY WORDS: bivalve suspension feeding, valve gape, fiber optic sensor

INTRODUCTION

Because of their economic and ecological value, researchers have attempted to gain a more complete understanding of bivalve molluscs and the factors that influence their feeding processes for more than a century. Of primary interest has been the determination of filtration and pumping rate. Volume flux through a bivalve is very difficult to measure directly without disturbing the animal (Galtsoff 1926, Davids 1964, Drinnan 1964, Foster-Smith 1976b, Hildreth 1976, Davenport & Woolmington 1982, Famme et al. 1986, Riisgård 2001). Parameters used to approximate pumping rate have included valve gape, pallial cavity pressure, excurrent flow velocity, and clearance rates (Table 1).

There are drawbacks to each of these methods of monitoring. Hildreth (1976) demonstrated that back pressure created in the bivalve pump system by the collection of exhalant flow using physical separation of the inhalant and exhalant apertures had a strong negative affect on pumping rate. The clearance rate method is an indirect determination of volume flux through an animal that is fraught with difficulties that have been a subject of some debate because of the prevalence of differing techniques used in experiments to measure particle depletion rates (Cranford 2001, Riisgård 2001). Many of these methods are labor intensive and produce data that are difficult to analyze. Often, the sampling scale is on the order of minutes to hours, which is often too long to identify changes in physiologically relevant parameters such as changes in valve gape or area of the exhalant aperture. Finally, the relevance of measured parameters to feeding activity is often vague (e.g., pallial cavity pressure or valve gape).

The main purpose of the majority of the aforementioned studies was to ascertain feeding rates in bivalves in the laboratory to comment on the likely behavior of these animals in nature. In contrast, we are interested in identifying the most important measurable components of feeding behaviors to explore, in detail, the physiological mechanisms used by bivalves to control feeding rates. Valve gape alone is only a coarse indicator of feeding activity, but it is one of the most important and easily measurable behavioral mechanisms exhibited by bivalve molluscs (Newell et al. 2001, Riisgård et al. 2003, Kittner & Riisgård 2005). The body of literature dedicated to the study of bivalves is large and diverse, but unanimously acknowledges the often surprising and underestimated complexity of these creatures.

Whereas valve gape has been measured in a number of different ways as listed previously, it is clear that valve gape measurement alone is not a good measure of feeding activity in bivalve molluscs. We designed our system specifically to measure fine scale changes in a laboratory setting, to be used in tandem with other laboratory measurement equipment; specifically, particle image velocimetry (PIV) and video methods.

Our primary objective was to design and test an instrument capable of continuous, high resolution (<0.12 mm) measurements of valve gape in bivalve molluscs of shell height ~3 cm or larger. This device was designed to be portable and inexpensive to construct, with interchangeable parts for easy repair. One important advantage of using fiber optics in designing sensors for use in marine environments is the ability to isolate the sensor from the associated electronics. Separating the sensor from the electronics allows the sensor to be fully immersed in water and eliminates the potential for introduction of electrical noise possible with electromagnetic sensors.

Our secondary objective was to use the valve gape sensor to establish the extent to which changes in valve gape were related to changes in clearance rate in the oyster, *Crassostrea virginica*, during a depletion rate assay. This simple experiment was designed to illustrate the functioning of the instrument and examine the predictive value of valve gape for volume flux in the oyster under the null hypothesis that change in valve gape is unrelated to changes in clearance rate.

MATERIALS AND METHODS

The main components of the valve gape system are a cradle, optical fibers, optoelectronics, and a data logger (Fig. 1). The cradle was constructed of three polyvinylchloride (PVC) components; a platform with legs and a guide tube. The PVC platform (10-cm wide, 10-cm long, 0.35-cm thick) formed the base of the valve gape sensor. Short legs, formed of sectioned PVC pipe, positioned the plate about 3 cm off the bottom. The upper surface of the plate was covered with Velcro tape ("loop" side). A hole was drilled through one edge of the platform into

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TABLE 1.

Parameters used to approximate pumping rate, with associated measurement method and representative previous studies.

Measured Parameter	Representative Studies
Measurement Method	
Valve Gape	
Systems of strings, pulleys and levers attached to recording devices	Brown (1954) Galtsoff (1964) His (1982) Markich et al. (2000)
Strain gauges	Higgins (1980) Shumway & Cucci (1987)
Electromagnetic inductance sensors	Kramer et al. (1989) Shaffer et al. (1999) Wilson et al. (2005)
Video analysis	Newell et al. (1998, 2001) Nielsen et al. (1993)
Pallial Cavity Pressure	
Spinal tap needle	Bernard & Noakes (1990)
Fiber optic pressure sensor	Frank (2003)
Excurrent Flow Velocity	
Hot bead thermistors	Foster-Smith (1976a) LaBarbera & Vogel (1976) Meyhöfer (1985)
Particle image velocimetry	Frank et al. in review
Clearance Rates	Coughlan (1969) Hildreth & Crisp (1976) Riisgård (1977, 1988) Rodhouse & (O'Kelly 1981) Shumway et al. (1985) Jørgensen et al. (1990) Widdows et al. (1990) MacDonald & Ward (1994)

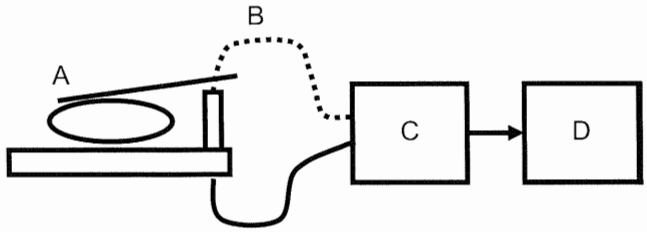

Figure 1. Diagram of the main components of the valve gape system. (A) Bivalve outfitted with valve gape arm (horizontal black bar) positioned over the fiber guide tube (vertical black bar) on PVC cradle. (B) Optical fibers. The light emitting fiber is shown as a solid line and the light receiving fiber is represented as the dotted line. (C) Optoelectronics package including light emitting and light receiving diodes. (D) Data logger.

which a guide tube (6.4mm o.d and 2.5 mm i.d.) was cemented. A light emitting fiber was secured ~5mm into the bottom of the guide tube and ran under the platform to the light emitting diode and electronics package.

The active sensor components were: (1) a fixed, light-emitting fiber, (2) a movable, light-receiving fiber, and (3) the associated optoelectronics. The optical fiber used in this study (Mitsubishi Rayon Co., Ltd., SH4001) had a polymethylmethacrylate (PMMA) core material (980-µm diameter) and a polyethylene (PE) jacket (2.2 ± 0.07 mm diameter). The refractive index of the core and cladding were 1.495 and 1.402, respectively. Optical fibers were cut into lengths of ~1 m each using a straight-edge razor blade. The cut ends of the fully jacketed fibers were polished in a two-step process (2,000 grit sandpaper followed by 3-µm polishing film) under a dissecting microscope. Both ends of each fiber were polished until the PMMA core appeared glassy and transparent. The emitting fiber was cemented into the fiber guide tube on the cradle using a silicone sealant (Fig. 2). The receiving fiber was placed into the guide tube but secured to the uppermost (right) valve of the oyster such that in the closed position, the end face of the receiving fiber was in contact with the end face of the emitting fiber. As the animal opened its valves, the fibers were drawn away from each other. The amount of light received depended on the gap between the fixed (emitting) and movable (receiving) fibers, increasing as the gap was reduced and decreasing as the gap increased. This gap indicates the relative position of the receiving fiber. Thus, the valve gape sensor measures axial displacement of the optical fibers. Data were logged onto a Campbell Scientific CR10X data logger programmed to record high-resolution readings of one datum point every second. The wire output leads of the instrument were connected directly to a single ended analog input channel and an analog ground channel in the wiring panel of the CR10X. Analog to digital conversion was performed on integrated data values using a 13-bit successive approximation technique yielding a resolution of 670 µV.

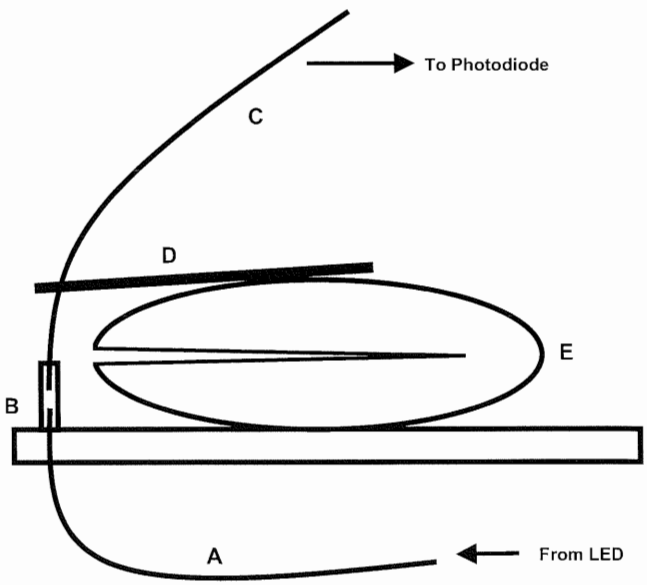

Figure 2. Illustration of working valve gape sensor with the guide tube shown in cross section. The fixed, light emitting fiber (A) is attached at one end to a red LED. It runs under the cradle platform (shown as black bar) and into the guide tube (B) shown here in cross section, where it is cemented. The free end of the movable, light receiving fiber (C) is held in place in the guide tube by a PVC valve gape arm (D) attached to the oyster (E). The terminal end of the receiving fiber is coupled to a photodiode. The oyster (E) is shown here gaping slightly with a corresponding separation between the light emitting and light receiving fibers.

Light Source

A red light emitting diode (LED; Industrial Fiber Optics part number IF-E96) was used as a source of light into the fixed (emitting) fiber. Because the light output was found to vary with LED temperature, a feedback system (Fig. 3) was used to maintain a constant light output level. Two identical LEDs were driven with the same current source, implemented by transistor Q1. One LED functioned as the light source for the valve gape sensor; the second LED was connected to a photodiode (Industrial Fiber Optics part number IF-D91). The output of the photodiode was connected to the inverting input of an operational amplifier (op-amp, U1), whose output controlled the LED drive transistor Q1. Resistor R1, Zener diode D1, and trimmer potentiometer R2 set the nominal op-amp output voltage. Photodiode D2 and resistors R3 and R4 provided the feedback signal to the op-amp. Resistor R5 set the gain of the feedback loop, resistor R6 prevented parasitic oscillation of Q1, and resistor R7 determined the ratio between the op-amp output voltage and the LED drive current. The potentiometer was set to produce a nominal 12 mA current in the LED. Power for the light source was obtained from a 12 Volt battery.

Light Detector

The light signal from the movable, receiving fiber was coupled into a photo-detector consisting of a photodiode and amplifier (Fig. 4). The amplifier was set to produce a maximum voltage (approximately 2 volts in the sensor described here) when the light signal was at its maximum. As the light signal was reduced (by an increasing valve gape), the voltage was reduced.

The power from two 12-volt batteries was regulated down to plus and minus 9 volts by components R1, D1, and C1 (for the positive side) and R2, D2, and C2 (for the negative side). A photodiode (Industrial Fiber Optics part number IF-D91) was used as the detector, with series resistor R3 providing over-current protection. The current from the photodiode was sent to operational amplifier (op-amp) U1. Resistor R4 and trimmer potentiometer R5 together set the gain of the op-amp, whose output was a positive voltage that increased as the amount of received light increased (Fig. 4). The amplified signals from the sensor was digitized and recorded in nonvolatile memory as high resolution data points by the Campbell Scientific CR10X measurement and control module.

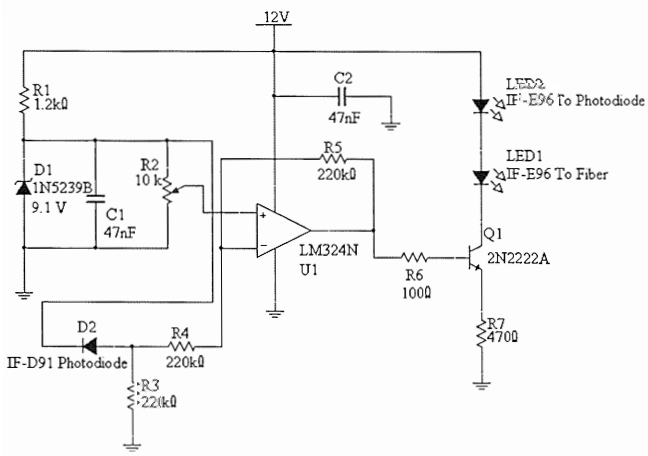

Figure 3. The feedback system used to maintain a constant light output to the fiber optic valve gape sensor.

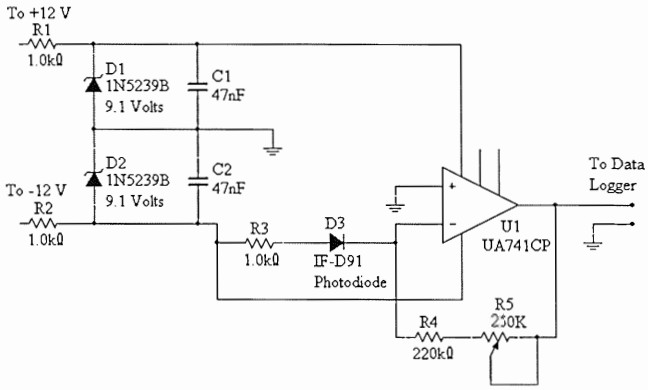

Figure 4. The light detector used in the fiber optic valve gape sensor.

External Modifications of Animals

To prepare animals for examination with the valve gape sensor, a 5-cm diameter PVC disk was cemented to the lower (left) valve of the animal using a two-part, marine epoxy (Marine Tex). The bottom of the disk was covered in Velcro ("hook" side). The Velcro on the underside of the disk was complimentary to the Velcro covering the platform of the cradle such that the disk securely held the animal in position under experimental conditions. A PVC arm (8 cm × 5 cm) was secured to the uppermost (right) shell of the oyster using the same two-part, marine epoxy. The arm extended over the inhalant margin and was positioned such that the center of the tip of the arm was situated directly over the cradle's fiber guide-tube. The free end of this arm had a notch through which the movable fiber was threaded into the guide tube and secured in place by a setscrew. The movable fiber was placed in contact with the fixed fiber when the bivalve was closed (the valve gape was zero). Movement of the shell valve pulled the movable fiber away from contact with the fixed fiber as the valve gape increased, reducing the amount of light arriving at the detector.

Calibration

The valve gape sensor was calibrated while fully submerged in seawater. Care was taken to ensure that the guide tube was completely filled with water and all air removed. A micromanipulator was used to control the position of the movable fiber within the guide tube. In the zero position, the movable fiber was set in contact with the fixed fiber, mimicking the closed position of a bivalve. The gain of the light detector was set to provide a voltage output of approximately 2 volts. The micromanipulator was moved in 1-mm increments to a maximum setting of 6 mm; at each 1-mm step the voltage reading was recorded. This process was repeated for a total of 5 calibration data sets.

Depletion Rate Assay

At the beginning of each experimental trial, the animal was stimulated to close its shells by gentle prodding with a blunt implement to establish a zero gape (shells closed) reference

value for the valve gape sensor. We then adjusted the output voltage of the valve gape sensor for a reading of 2 volts when in the closed position. At the end of each experimental trial, we again stimulated the animal to close its shells, to ensure that the sensor returned to the 2-volt value. The voltage was then converted to mm output using the calibration equation (Eq. 1).

Each oyster was placed into an individual 2 L polycarbonate chamber filled with 0.45 µm filtered seawater. After a brief acclimation period during which the chamber was spiked with a small volume of *Tetraselmis chuii* (PLY 429) to induce a feeding response, more *T. chuii* was added to bring the total volume in the containers to 1.5 L, resulting in a final concentration of $\sim 2.5 \times 10^4$ cells per ml. To determine clearance rate, water samples (10 mL) were taken every 5 minutes for 30 minutes. Samples were analyzed on a Coulter Counter Multisizer (electronic particle counter) in the range of 5–20 µm. Clearance rates (CR) were calculated after the equation from Coughlan (1969) and are defined here as the volume of water cleared of particles under the assumption that the animal is clearing 100% of the particles within the size range measured. As particle concentrations decrease, more water must be filtered to obtain the same number of food particles. Thus, CR is an approximation of volume flux through the animal, calculated in relation to measured changes in particle concentration over time.

Data Analyses

The change in valve gape with decreasing food concentrations in seven oysters ranging in size from 69–83.8 mm (mean 76.9 mm ± 5.3 mm standard deviation, Table 2) was measured. We calculated the clearance rates of each oyster over the six five-minute time spans. As valve gape was measured at each of seven time points from time zero minutes (T0) to time 30 min (T30), we calculated a running average (T0-T5, T5-T10…) resulting in an equal data set of six points each for clearance rate and valve gape (Table 2).

In a static chamber design such as this one, depletion rate (decrease in particle concentration over time) increases in a decreasing manner in the presence of an actively feeding bivalve. The first and second 15-min time blocks approximately correspond to the linear and non linear sections of the particle depletion rate. We also calculated R and R^2 for the relationship between CR and VG for each oyster over the first and second 15 min of the experiment.

RESULTS

Calibration

The recorded data were plotted with distance as a function of voltage, and a third order polynomial was fitted to the data points (Fig. 5). The R^2 value from the regression was 0.999. There was no discernable pattern to the residuals. A 95% confidence interval for the fitted line had a deviation from the curve of at most 0.12 mm. The regression equation, with D as the distance in millimeters and V the sensor output in volts was:

$$D = 9.768 - (13.358 \times V) + (8.838 \times V^2) - (2.295 \times V^3) \quad (1)$$

This equation assumes that the output voltage has been adjusted to 2.00 Volts when the distance is zero.

Depletion Rate Assay

The diameters of the algal cells were normally distributed around a mean of approximately 8–9 µm. Relationships between clearance rate (CR) and valve gape (VG) for each oyster, over the 30 min experimental period were examined (Fig. 6). Correlation coefficients (R) ranged from –0.91–0.62 and coefficients of determination (R^2) ranged from 0.02–0.82 with an average value of 0.25 ± 0.28 SD (Table 2). In this case, only one of the seven animals had an R^2 higher than 0.5.

Examination of R^2 for the relationship between VG and CR in relation to linear (first 15 min) and nonlinear (second 15 min) decrease in particle concentration yielded values of $R^2 > 0.5$ for four animals out of the seven (Table 2).

DISCUSSION

Results presented in Table 2 show a trend of increasing valve gape with time and decreasing particle concentration, insinuating that knowledge of recent feeding history is required to approximate feeding rate from valve gape measurements (Kittner & Riisgård 2005, Riisgård et al. 2006). There are behavioral mechanisms underlying these rate changes and the data suggest

TABLE 2.

Valve gape (VG, cm) and clearance rate (CR, $cm^3\ s^{-1}$) data for each oyster over each of the six five-minute time spans of the experimental trial. Coefficients of determination (R^2) are given for the first (T0–T15) and second (T15–T30) halves of the trial followed by the R^2 for the whole trial (T0–T30) for each animal.

	Oyster 22		Oyster 23		Oyster 24		Oyster 25		Oyster 26		Oyster 27		Oyster 28	
Time	VG	CR	VG	CR	VG	CR	VG	CR	VG	CR	VG	CR	VG	CR
5	0.50	5.24	0.36	0.00	0.52	6.66	0.27	1.98	0.50	1.04	0.26	1.21	0.54	2.12
10	0.52	0.00	0.41	2.35	0.58	3.60	0.28	1.42	0.59	1.47	0.28	0.23	0.54	2.23
15	0.55	4.39	0.47	2.60	0.59	0.77	0.28	1.15	0.61	0.94	0.33	0.44	0.60	2.43
20	0.57	1.47	0.44	0.00	0.60	0.65	0.30	0.23	0.61	1.64	0.36	0.69	0.70	2.62
25	0.57	1.49	0.42	0.66	0.62	0.43	0.34	1.57	0.64	1.27	0.37	1.68	0.71	2.10
30	0.57	0.14	0.46	0.64	0.63	1.18	0.35	1.97	0.67	3.66	0.34	0.00	0.72	1.39
R^2 T0–T15	0.001		0.780		0.870		0.898		0.030		0.319		0.878	
R^2 T15–T30	0.001		0.001		0.289		0.999		0.616		0.917		0.992	
R^2 T0–T30	0.227		0.156		0.819		0.043		0.383		0.021		0.086	

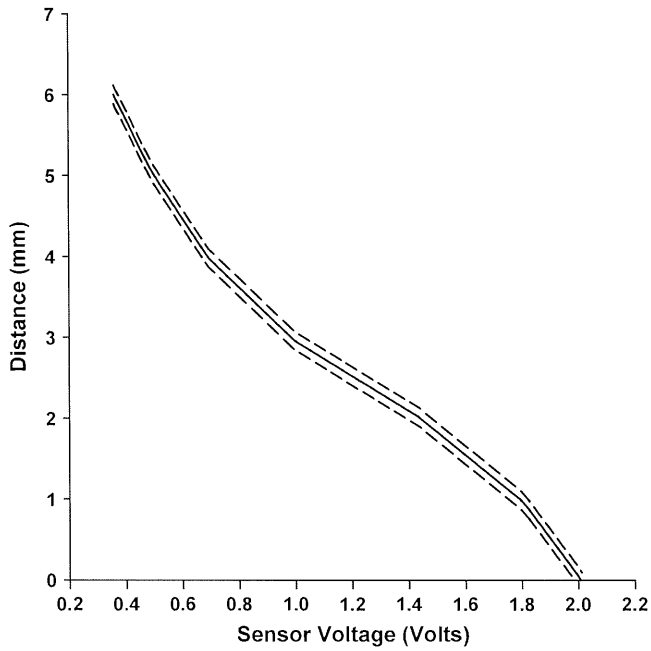

Figure 5. Calibration data for the fiber optic valve gape sensor. The solid line is the fitted third order polynomial. The dashed lines indicate the 95% confidence interval.

that the behavioral repertoire of animals can differ. These results illustrate the problem inherent in using valve gape measurements alone as estimators for feeding activity.

Results from our study are similar to the findings of other researchers where it was shown that valve gape alone was only a coarse indicator of feeding rates in bivalve molluscs and that more information, such as knowledge of prior feeding history, or concurrent measurements of other parameters such as cross sectional area of the exhalant aperture and particle concentrations over time were needed to interpret the valve gape data (Newell et al. 2001, Riisgård et al. 2003, Kittner & Riisgård 2005). Here, variations in valve gape (VG) accounted for between 2% and 82% (25% average) of the variation in clearance rate (CR) in oysters when examined over the 30-min trial.

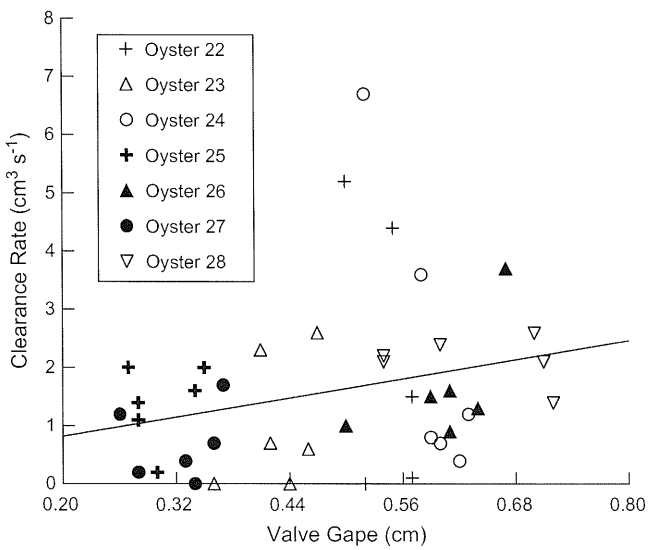

Figure 6. Clearance rate (cm^3 s^{-1}) plotted against valve gape (cm) for each animal. The black line is the regression for all data points taken together. The formula is y = ×2.7021 + 0.2897. The coefficient of determination is R^2 = 0.0671.

These results should not be interpreted to undervalue the utility of a valve gape sensor when set to an appropriate task. In fact, our results illustrate that valve gape does influence clearance rate to varying degrees and that the relationship between the two differs between oysters and even between different periods of time for the same oyster. It is the approximately 20% to 80% of the variation in feeding rates unaccounted for by valve gape that are of the most interest to us. What different physiological mechanisms make up the difference? And what changes when the relationships between VG and CR change for a single animal within a single trial? This system was designed to be used in tandem with instruments measuring other parameters with influence over feeding activity, such as size of the exhalant opening and velocity of the water exiting the animal to facilitate answering the questions posed above.

CONCLUSION

The instrument described here is capable of high resolution (<0.12 mm) measurement of changes in valve gape in the bivalve molluscs. It is portable and inexpensive to construct, with interchangeable parts for easy repair. A fiber optic valve gape sensor has several advantages over other types of sensors. Unlike electronic components, the active components of this sensor (the fixed and movable fibers) are unaffected by complete immersion in seawater, and have no requirement for watertight seals. There is no electrical connection between the submerged animal and the data processing electronics. And, importantly, optical fibers are unaffected by electromagnetic fields and will not act as antennas to pick up stray signals. Furthermore, unlike electromagnetic sensors, which must be calibrated for use with each animal, each fiber optic sensor requires only one individual calibration after construction. Once calibrated, the sensor has proven to be quite stable with time. During our experiments we examined only one animal at a time, however, arrays of animals can be examined simultaneously with the maximum number restricted only by the number of single ended channels available on the data logger.

One disadvantage is the possibility for small amounts of silt and algae to be drawn into the guide tube as the fibers move away from each other with opening of the valves. This may interfere with the optical path, reducing the amount of light coupled from one fiber to the other. In practice, infiltration of particulate material is reduced by minimizing the difference between the outer diameter of the movable fiber and the inner diameter of the hollow tube. There must be at least a small difference in diameter to minimize friction, and to allow water to enter and leave the gap between the two fibers as the valve gape changes. The experiments described here were conducted under laboratory conditions with monocultured algae in filtered seawater, so interference with the optical path was minimized. Furthermore, as this system is designed for use in tandem with other instruments, diminution of light caused by introduction

of particulate matter into the guide tube can be recognized by comparison with output from other measures.

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