Estimating Metabolism of Fish in Aquacultural Production Systems

W. H. Neill[1]*, E. L. Oborny Jr. [2], S. R. Craig[3], M. D. Matlock[4], D. M. Gatlin III[1]

[1]* Department of Wildlife & Fisheries Sciences
Texas A&M University
College Station, TX 77843-2258 USA

[2] PBS&J
206 Wild Basin Road
Austin, TX 78746 USA

[3] VA-MD Regional College of Veterinary Medicine
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0442 USA

[4] Department of Agricultural Engineering
Texas A&M University
College Station, TX 77843-2121 USA

* Corresponding Author

ABSTRACT

Open-system respirometry offers a practical approach for measuring metabolic rates of fish cultured at high densities in uncovered raceways. Central to this methodology is analysis of a dynamic mass-balance on oxygen supply and demand. Here, we present a validated mass-balance equation, describe minimally disruptive procedures for estimating its parameters, and illustrate its use in estimating the oxygen-uptake rate of fish as a group, in real time and under actual production conditions.

INTRODUCTION

Oxygen respirometry is the dominant technique for estimating aerobic metabolism of fish and other water-breathing animals. In effect, the rate of oxygen-uptake by a fish in a closed or semi-closed chamber is presumed to be equivalent to the rate of oxygen disappearance from the water contained in or flowing through the chamber. The equivalency may or may not be adjusted for disappearance or appearance of oxygen in a "blank" control chamber, attributable to microbial activity. Static respirometers have only the water movement necessary to assure mixing

and adequate irrigation of the oxygen electrode; active respirometers are intended for measuring oxygen-uptake rate in fish forced to swim at constant speed against a water current. Cech (1990) has provided a thorough review of conventional respirometry. Springer and Neill (1988) have described the development of computer-automated respirometry.

Respirometry as described above, is more suited to the research laboratory than the fish farm. The object of study generally is metabolism of a fasted, isolated fish, confined in a small glass or plastic chamber under controlled conditions of lighting (typically dim or dark) and temperature. If the fish is forced to swim at maximum sustainable speed, "active" metabolism is estimated; otherwise, "standard" or "routine" metabolism is observed. Some who have made such measurements (e.g., Neill and Bryan 1991) have expressed concern about their applicability to more normal situations. Such concern motivated us to consider a more direct approach to respirometry in one "real-world" situation—intensive aquaculture in raceways — a situation in which the strong metabolic signal from a very concentrated fish biomass overwhelms the noise that otherwise might defeat the approach.

METHODS AND MATERIALS

Open-system respirometry

Oxygen uptake rates of fish in aquacultural production systems can be estimated from continuously (or intermittently) recorded oxygen concentration data, by solving for M in the equation

1) $(dOc/dt)*C = (Oi-Oc)*Q + (Os-Oc)*K + M + BCOD$

where:

Oc = O_2 concentration in raceway (or the system compartment containing the fish) and effluent from raceway, mg/L;

Oi = O_2 concentration in influent to raceway, mg/L;

Os = O_2 concentration in raceway at gas saturation, mg/L, where the gas is air or oxygen-enriched air;

C = raceway volume, L;

Q = water exchange rate, L/t (t = time);

K = reaeration rate, L (water aerated)/t;

M = rate of oxygen removal attributable to metabolism of fish, mg O_2/t;

BCOD = rate of oxygen removal (rarely, resupply) attributable to other biological and chemical oxygen "demand" processes, mg O_2/t.

In effect, this equation states that the time-rate of change in dissolved-oxygen concentration of a well-mixed production tank with volume C is the resultant of oxygen supply and use. The first two terms on the right side of the equation normally are positive; they represent net rates of oxygen-concentration change attributable to water exchange and reaeration, respectively. The demand terms, BCOD and M, normally are negative (although, rarely, photosynthesis can cause BCOD to be positive).

All variables and parameters in this mass-balance equation can be measured easily and directly except for K and BCOD (Figure 1). The reaeration rate K is a measure of how effectively the raceway is resupplied with oxygen via aeration or injection of oxygen (in closed-system respirometry, K is zero). Estimation of K requires that the system be perturbed, in that Oc must be displaced from its steady-state value, Oc' (or vice versa); then, K can be computed from the rate at which Oc approaches the new Oc'. The perturbation must be accomplished without changing the system dynamics. Two methods have been utilized to displace Oc from its steady-state value: 1) temporarily infusing oxygen or nitrogen, to displace Oc from Oc'; or 2) zeroing M, by

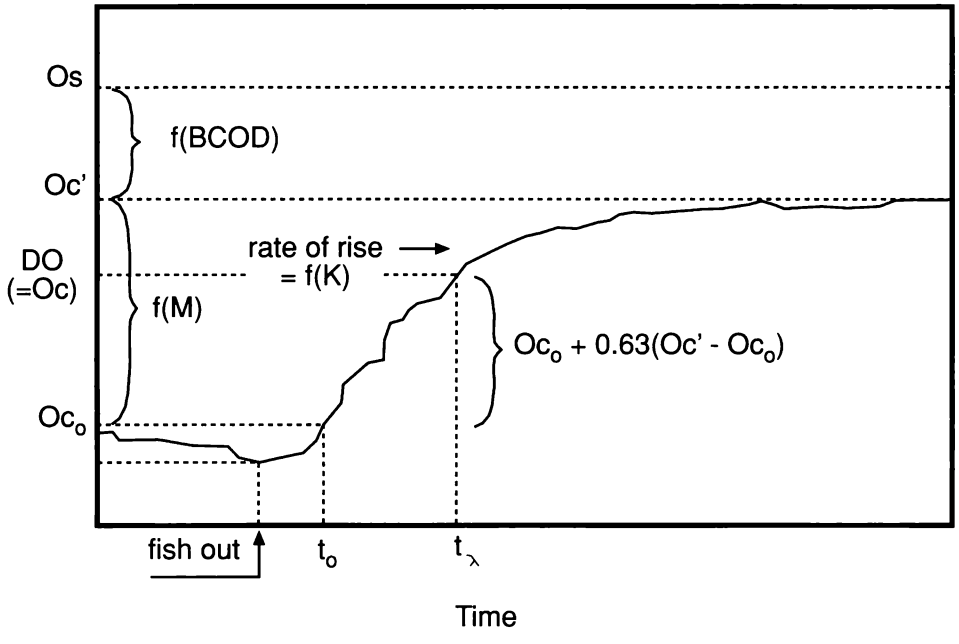

Figure 1. Pattern of change in dissolved oxygen concentration (DO) in an uncovered raceway, before and after removal of fish. See text and Appendix for interpretation.

removing the fish from the system, to displace Oc' from Oc. The first method avoids the work and disruption of moving the fish; in addition, any stirring of the water by the swimming activity of the fish, which may be an important component of K, remains in effect. However, the second method allows what normally should be better estimation of BCOD (see below). It also affords the opportunity to measure fish sizes and total biomass. Under production conditions, the removal of fish from the raceway would be impractical, except when the respirometry trial coincides with a planned fish transfer or harvest.

In any case (whether or not M = 0), at steady state

2) $M + BCOD = - (Oi - Oc')*Q - (Os - Oc')*K.$

Then, for the transient state,

3) $(dOc/dt)*C$
$= (Oi - Oc)*Q + (Os - Oc)*K - (Oi - Oc')*Q - (Os -Oc')*K$
$= (Oc'- Oc)*(K + Q).$

Thus, Oc approaches Oc' as an exponential decay process, with the rate coefficient equal (K + Q)/C; so, K can be estimated by finding the 63% time constant for the response in Oc (see Appendix), taking its inverse, multiplying the result by C, and finally subtracting Q.

Only the BCOD in the production tank itself is relevant since other BCOD, such as that in an external biofilter or other plumbing, will manifest itself as an effect on Oi. If most of the relevant BCOD is that associated with dissolved or suspended materials, BCOD can be estimated by measuring rate of oxygen-concentration change (normally, a decrease), dObcod/dt, in $mgO_2/(L*t)$, in a water sample contained in a "light" bottle incubated at mid-depth in the production tank:

4) $BCOD = dObcod/dt*C.$

In many production systems, however, a large fraction of relevant BCOD may be associated with surfaces. In that case, a better estimate of BCOD will be obtained by solving equation 2 with M set to zero—i.e., with the fish removed from the tank:

5) $BCOD = - (Oi - Oc')*Q - (Os - Oc')*K.$

Now, with numeric estimates both for K and BCOD in hand, the parent equation (1) can be solved for M:

6) $M = (dOc/dt)*C - (Oi - Oc)*Q - (Os - Oc)*K - BCOD.$

The aquacultural production systems envisioned in developing this analytical approach, were well-mixed, uncovered tanks or raceways with either once through flow or recirculation of water from an external biofilter. In the case of a tank with internal biofilter or a system with negligible differences between Oi and Oc, one simply deletes the water exchange term (but, in the latter case, not Q in the computation of K!) and, for recirculating systems, excludes from C the volume of water in any external biofilter and other plumbing. In principle, there is no reason our methodology could not be applied to earthen ponds, provided they are sufficiently well-mixed to be without marked oxygen gradients. Any photosynthetic production of oxygen or plant respiration would show up in the BCOD term and could be expected to impart a diel cycle on Oc, independent of M.

RESULTS

A rectangular fiberglass raceway at Texas A&M University System's Aquacultural Research and Teaching Facility (Burleson Co., TX, USA) contained approximately 350 500-g red drum (*Sciaenops ocellatus*) in 7,000 L of 3 ppt artificial seawater. These fish were removed from the raceway and weighed, for a total biomass of 175.05 kg. Just before the fish were disturbed, DO was 3.4 mg O_2/L = Oc and declining at 0.05 mg O_2/L per minute [dOc/dt = -0.05 mg O_2/(L*min) = -3.0 mg O_2/(L*h)]; after the fish were removed, DO rose from 3.0 mg O_2/L to a new steady state of 5.3 mg O_2/L = Oc'. Time for 63% of the change (from 3.0 to 4.5 mg O_2/L) was 42 minutes, or 0.70 hours; thus, K = (1/0.7)*7,000 = 10,000 Lh^{-1}. (In this case, the internal biofilter's volume is included in C for the system, and Q is taken as zero.) Water temperature was approximately 27°C; so, Os was taken to be 7.7 mg O_2/L.

7) BCOD = - (Os - Oc')*K
= - (7.7 - 5.3)*10,000
= -24,000 mg O_2/h.

For Oc at 3.4 mg O_2/L and declining at 0.05 mg O_2/(L*min) = 3.0 mg O_2/(L*h),

8) M = (dOc/dt)*C - (Os - Oc)*K - BCOD
= (-3.0)*7,000 - (7.7 - 3.4)*10,000 - (-24,000)
= - 21,000 - 43,000 + 24,000
= - 40,000 mg O_2/h.

Thus, at the moment of interest, metabolic rate of the fish per gram body weight was 40,000/175,050 = 0.23 mg O_2/(g*h). Is this value right or wrong? It can only be stated that this number is consistent with results from closed-system respirometry (Forsberg and Neill 1998). Also, validation work by Oborny (1993) gives us further confidence in the methodology.

DISCUSSION

Oborny (1993) has validated the physics, the biology, and the practicality of open-system respirometry as described here. In addition, he showed that the approach can be extended to accommodate oxygen-enriched systems, simply by setting Os to its supersaturated value. Following is a synopsis the validation studies conducted by Oborny (1993).

Open-system respirometry was physically validated by simulating fish metabolism via constant inflow of oxygen-deficient water into a well-stirred aquarium open to the atmosphere. These trials involved oxygenation of the aquarium both with air and pure oxygen. Calculated metabolism compared very favorably with known rates of oxygen dilution, for both regimes of oxygenation: $r^2 = 0.98$ for air and 0.92 for pure oxygen.

To validate open-system respirometry in a biological sense, Oborny (1993) compared whole-body energy changes in unfed juvenile red drum, measured via proximate analysis and bomb calorimetry, with those estimated from apparent oxygen uptake via open-system respirometry. For three independent trials, the energy loss measured by respirometry was 95.8, 97.7, and 102.1% of that measured by direct calorimetry.

Finally, Oborny (1993) put open-system respirometry to a practical test in large-scale, intensive raceways at a commercial red drum production facility. The experiment compared the proportion of apparent oxygen consumption to the proportion of fish biomass remaining, as fish were harvested from each of two 113,550 L systems. In one system, 80% of the fish consumed 71% of the oxygen consumed by all the fish (on the previous day). The second system yielded 25% oxygen consumption for 33% of the fish biomass. The metabolic rates of the 170-200 g fish in these large systems, at biomass densities up to 0.075 kg/L, ranged from 0.45 to 0.66 mg O_2/ (g*h).

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APPENDIX

More on estimating K and Oc'

- K can be estimated by measuring time for raceway Oc to change from any particular value to a value 63% of the way toward the steady-state value (Figure 1). This time interval, $t_{lambda} - t_0$, is *lambda*, the time constant for the system. For negative exponential processes, *lambda* = 1/k, where k is the exponential rate constant and has units of $(time)^{-1}$.

$$k = (K + Q)/C; \quad \text{(A1)}$$

so,

$$K = k*C - Q = (1/lambda)*C - Q. \quad \text{(A2)}$$

- Alternatively, k can be estimated as -1*slope of the linear regression of $\ln[(Oc - Oc')/(Oc_0 - Oc')]$ on t (which is the more conservative method for estimating negative-exponential rate constants). Then, K can be found, as before, by solving equation A2.

- Of course, both approaches assume that Oc' (and, thus, BCOD and Os), C, Q, and K are representative and constant , at least during the interval (t_0, t_{lambda}). Experience indicates that for most recirculating aquaculture systems, *lambda* will be on the order of 0.5 hour. So, measurement of Oc at intervals of 10 minutes for one hour beginning at to should be sufficient for estimating k via either method.

- Oc', in practice, typically would be estimated after the Oc observations that are collected to estimate K. If the reaeration process is a negative exponential (and it almost certainly is), then Oc should have advanced 95% of the way from Oc_0 to Oc' in 3 *lambda* or in about 1.5 hours, for most systems. To be safe, one should wait 2.5 hours to measure Oc as an estimate of Oc', but not longer than 4 hours, because BCOD may have begun to change after the nutrient sources have been absent from the system for this long.

- Summary of data needs for estimation of K and Oc': 1) Value of Oc soon after animals removed from the system (but after the system is otherwise restored to normal operating conditions, water level, air lifts, etc.); this fixes Oc_0. 2) Values of Oc every 5 to 15 minutes thereafter for at least 1 hour. 3) Value of Oc 2.5 to 4 hours after, to estimate Oc'.