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# INCREASES IN VISCOSITY MAY KILL FISH IN SOME BLOOMS

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## ABSTRACT

In both cultures of some marine flagellates, and in non-bloom seawater, viscosity is composed of a newtonian component, $\eta_W$, plus a non-newtonian component due to dissolved polymers, $\eta_E$. $\eta_W$ is constant but $\eta_E = k.q^P$, where q is shear rate, k is a constant and P is a power value found to vary from 0 to -1.6. *Gyrodinium aureolum* kills fish when in excess of roughly 10,000 $cm^{-3}$. Trapped bubbles were seen in a bloom of 2700 $c\,m^{-3}$. This has allowed calculation of a $\eta$-q coordinate, 5.4 mPa s and 30 $s^{-1}$ for 0.1-mm bubbles, or 140 mPa s and 5.8 $s^{-1}$ for 0.5-mm bubbles. Based on published values for gill dimensions and pumping rate at high activity in bass and tuna of weight 0.33 to 1667 g, and assuming 0.5-mm bubbles, the energy required for gill pumping would be about 14 times normal if P is -0.3, but only 1.001 times normal if P is -1.4. High shear stress involved in pumping more viscous liquid might also tear epithelia. Whether changes in viscosity can kill fish without contributary factors depends on P. This should be investigated in red tides.

## INTRODUCTION

It has been suggested that death of fish in red tides of certain species, particularly *Gyrodinium aureolum* Hulburt (north-west European Shelf population) and algae of the *Chattonella-Olisthodiscus-Hornellia* complex, may be caused by clogging of gills [15, refs in 1]. Yellowtail, *Seriola quinqueradiata*, exposed to a bloom of *Chattonella antiqua* (Hada) Ono [13] (as *Hemieutreptia antiqua* Hada) showed both lowered blood $O_2$ levels and behaviour characteristic of hypoxia [8], while fish exposed to blooms of *G. aureolum* also showed hypoxic-type behaviour [3]. In blooms of both species some fish died when water concentrations of $O_2$ were high. Bubbles occur, as if trapped, in some *G. aureolum* blooms [3,4], and at least some species of the *Chattonella* complex discharge mucus [9].

The viscosity of a *Chattonella antiqua* bloom, in which these yellowtail died, was measured using a Morton viscometer, and found to be up to twice as viscous as normal seawater [8]. From the descriptions of the Morton viscometer [5,6,8], it can be concluded that the shear rate at measurement lies between 100 and 5,000 $s^{-1}$.

So as to form a quantitative framework for further investigation of gill clogging in relation to red tides, published and submitted results are brought together on: bubbles trapped in *G. aureolum* blooms; viscosity variations in both phytoplankton cultures and non-bloom seawater; the relationship between polymer concentration and viscosity; and hydrodynamics of respiration in fish.

## RESULTS

### Phytoplankton cultures [Ref. 1]

Out of eight cultures, the three which showed the highest values of $\eta$ when q was 0.15 $s^{-1}$ were measured over a range of q. For one culture, Fig. 1a shows the variation of excess viscosity,

$$\eta_E = \eta - \eta_W \qquad \text{(Eq. 1)}$$

where $\eta_W$ is the viscosity of pure water.

The cultures investigated showed constant values of P over ranges of q, where

$$\eta_E = k \cdot q^P \qquad \text{(Eq. 2)}$$

where k and P are constants. Such power-law, shear-thinning behaviour is characteristic of many colloidal polymer solutions, and the inflexions found may result from the additive effects of different polymers. P varied from 0 to -1.3.

### Rheometry of non-bloom seawater samples [Ref. 2]

Considerable variation in $\eta_E$ was found between samples. Fig.1b shows the means of $\eta_E$ plotted against q. The mean value of P from each sampling trip varied from -0.9 to -1.6 (Fig. 1b). Variation within and between samples indicated either considerable lumpiness (rheological heterogeneity), or that unavoidable differences in handling of the samples promoted marked changes in their rheological properties.

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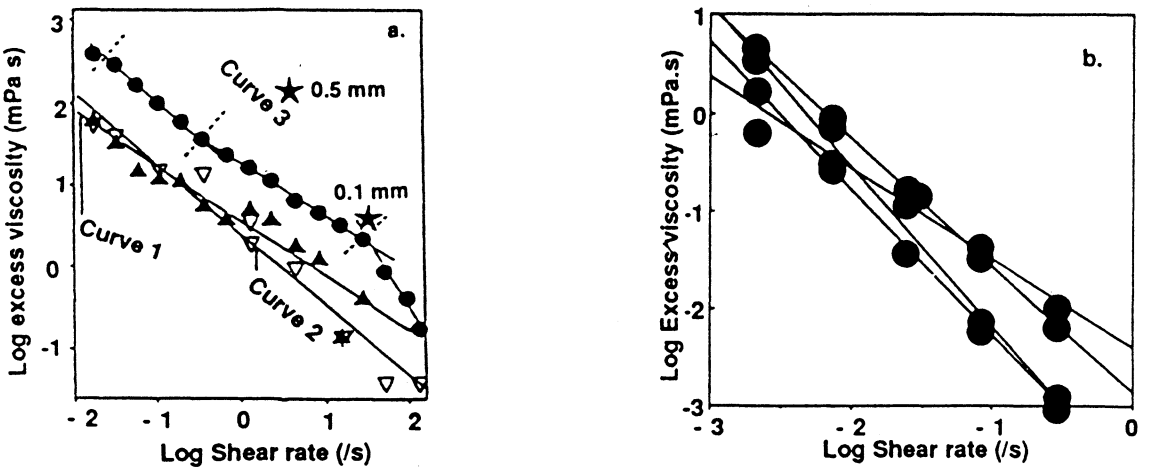


Fig. 1. *Log-log plots of excess viscosity, $\eta_E$, against shear rate, q. a. Culture of* Dunaliella marina, *84 cells mm$^{-3}$. Curves 1 and 2, less concentrated sample. Curve 3, with more settled material. Asterisks denote $\eta$-q intersect for bubbles [Ref. 1]. b. Non-bloom sea (pooled depths 0 to 100 m) from the Rade de Villefranche, France on four different occasions. Each point represents the mean of 4 to 16 readings. Regression line shown for each occasion [Ref. 2].*

**Observations on a bloom of *Gyrodinium aureolum* [Ref. 3]**

Water coloured brown due to *G. aureolum* extended to a depth of 30 to 50 cm. A sample from the coloured water contained 2.7 x $10^3$ cells cm$^{-3}$ of *G. aureolum*. Where the brown water washed over rocks, barnacles and periwinkles were active. Many small bubbles were suspended in the brown layer, as if trapped. While the bubbles were not measured, I eastimate from memory that the diameter of the largest was about 0.5 mm. At a rising speed of more than 1 mm they would have cleared the brown layer in < 9 minutes, and their motion would have been noticeable.

**Calculation of viscosity/shear rate intersect for the bloom**

For a small, spherical particle at equilibrium in a liquid, from Stoke's law, the viscosity of the liquid,

$$\eta = \frac{2 \cdot g \cdot \rho_E \cdot r^2}{9 \cdot w} \qquad [\cancel{m s^{-1}}]\ [kg.\ m.\ s^{-1}] \qquad \text{(Eq. 3)}$$

where $\rho_E$ is the excess density of the particle, w its vertical velocity, r its radius and g is the acceleration due gravity.

The tendency of the particle to accelerate under gravity is opposed by an equal drag acting on its surface,

$$F = 4/3 \cdot \pi \cdot r^3 \cdot \rho_E \cdot g \qquad [kg\ m\ s^{-2}] \qquad \text{(Eq. 4)}$$

and the surface area of this spherical particle,

$$A = 4 \cdot \pi \cdot r^2 \qquad [m^2] \qquad \text{(Eq. 5)}$$

Combining Eqs 4 and 5, the mean shear stress over the surface of the particle,

$$\tau = \frac{F}{A} = \frac{g \cdot \rho_E \cdot r}{3} \qquad [kg\ m^{-1}\ s^{-2}\ \text{or Pa}] \qquad \text{(Eq. 6)}$$

and the corresponding shear rate in the water touching the particle,

$$q = \frac{\tau}{\eta} \qquad [s^{-1}] \qquad \text{(Eq 7)}$$

The corresponding $\eta$-q intersects for 0.5-mm bubbles (r = 2.5 x $10^{-4}$ m), as well as for 0.1-mm bubbles is shown in Fig. 1. The 2.6 million cell/dm$^3$ bloom of *G. aureolum* was thus thicker at q = 6 to 30 s$^{-1}$ than the thickest cultures reported [1].

**Flow dynamics in fish gills (ref. 7]**

As fish subject to sublethal concentrations of *G. aureolum* show hyperactivity [1,8], similar to that shown in hypoxic conditions, only data for "maximum" respiratory activity will be considered here. In a shear-thinning medium, the best policy for the fish would be to maintain high inspiration pressure and thence q, as this would minimise $\eta$. Observations mentioned above suggest that the fish do this.

Published data on the dimensions of gill pores and on flow through gills have been reviewed [7] for the largemouth bass, *Micropterus salmonoides*, of sizes from 0.33 to 837g, as well as for tuna of 1667 g. The pressure across the gills is about 1 cm of water (≈$10^2$ kg m s$^{-2}$) in most fishes, but about 2 cm of water in tuna. As water flows through fish gills at only about one tenth the rate calculated from pressure and gill slit dimensions [7], instead of calculating q in gill slits from the Poiseille equation for rectangular tubes, root mean square shear rate $q_{RMS}$, will be estimated from energy dissipation. Energy dissipation per unit mass of water, in the gill slits,

$$\varepsilon = \frac{D \cdot V_W}{V_o} \qquad [m^2\ s^{-3}] = [W\ kg^{-1}] \qquad \text{(Eq. 8)}$$

where D is the pressure difference across the gills, $V_W$ is the mean water velocity through the gill slits and $V_o$ is the measured volume (length x breadth x depth) of the slits. $\varepsilon$ varies little, from 1000 $m^2\ s^{-3}$ for bass of 0.33 g to 620 for those of 837 g (mean for ten size classes 730 $m^2\ s^{-3}$), and 480 $m^2\ s^{-3}$ in tuna gills.

$$q^2 = \frac{2 \cdot \varepsilon}{7.5 \cdot \eta} \qquad \text{[Ref. 12]} \qquad \text{(Eq. 9)}$$

Assuming that the reviewed studies on gill hydrodynamics were carreid out at a typical value of $\eta$ of $10^{-3}$ Pa s [kg $m^{-1}\ s^{-1}$], the corresponding value of q is 14,000 (≈2000) $s^{-1}$ for gill slits of bass of mass 0.33 to 837 g, and 11,000 $s^{-1}$ for tuna gill slits.

**Effects of a bubble-trapping bloom on energy of flow through fish gills**

Table 1 shows the minimum possible values of k for corresponding values of P, assuming bubble diameter of either 0.1 or 0.5 mm. Also shown are the minimum values of energy dissipation in gills (for a given throughput) relative to that in newtonian, non-bloom water.

**Table 1.** *Minimum possible values of* **k**, *and (relative to that in non-bloom water) for "maximum" ventilation in bass ($q_{RMS}$ in gill slits 14,000 $s^{-1}$) and tuna ($q_{RMS}$ 11,000 $s^{-1}$), according to the maximum size of bubbles trapped in the bloom (rising rate ≤ 1 mm $s^{-1}$) and the value of* P

| | P | | | | | | |
|---|---|---|---|---|---|---|---|
| | -0.2 | -0.3 | -0.4 | -0.6 | -0.8 | -1.0 | -1.4 |
| **a. If max. bubble diameter 0.1 mm** | | | | | | | |
| Value of k (x $10^2$) | 0.87 | 1.22 | 1.72 | 3.39 | 6.60 | 13.2 | 51.5 |
| ε in gills - bass | 2.29 | 1.70 | 1.38 | 1.11 | 1.031 | 1.009 | 1.0008 |
| - tuna | 2.35 | 1.75 | 1.42 | 1.13 | 1.039 | 1.012 | 1.0011 |
| **b. If max. bubble diameter 0.5 mm** | | | | | | | |
| Value of k (x $10^2$) | 19.8 | 23.6 | 28.1 | 39.9 | 56.7 | 80.6 | 163 |
| ε in gills - bass | 30.3 | 14.4 | 7.17 | 2.23 | 1.27 | 1.058 | 1.0016 |
| - tuna | 31.8 | 15.5 | 7.79 | 2.50 | 1.33 | 1.073 | 1.0030 |

## DISCUSSION

The percentage of the oxygen in inspired water extracted during passage through the gills is typically about 50% for non-tuna and 70% for tuna [7]. This does not give much margin to allow for any reduction in water throughput. Further, if throughput diminishes, so will diffusion of waste products, such as $NH_4^+$ and $CO_2$, leading to increased concentration in fish tissues.

The excess viscosity of polymer solutions depends generally on a power of the polymer concentration. For non-ionic, random-coil polymer solutions, $\eta_E$ is proportional to $c^{1.4}$ to $c^{3.3}$, depending on c, where c is the polymer concentration [11]. For blooms of *Gyrodinium aureolum*, the threshold concentration for mortality to fish is 6 to 21 x $10^3$ $cm^{-3}$ [14], say, about $10^4$ $cm^{-3}$. If the concentration of extracellular polymer present in *G. aureolum* is proportional to the concentration of the cells, and if $\eta_E$ is proportional to $c^2$, the viscosity of blooms just lethal to most fish should be greater than that at which trapped bubbles were observed (2.7 x $10^3$ cells $cm^{-3}$) by a factor of about $[10^4/(2.7 \times 10^3)]^2$ or ≈14. The energetic cost of irrigating gills varies from 2% to 43%, typically ≈15%, of the total metabolism in most fishes, but is only ≈1% in tuna, which ram ventilate [7]. Taking a value of 15% and assuming that the percentage of oxygen extracted does not change, the energy expended in irrigation would use all oxygen extracted when ε is increased to a factor of ≈7 times that in non-bloom water (an increase of ≈600%). The corresponding increase in ε in tuna would be 9,900%.

As shown in Table 1, considering a bloom trapping 0.5-mm bubbles with P equal to -0.8, ε in bass gill slits is 1.27 times that in non-bloom conditions (an increase of 27%). Multiplying this by 14 for an estimated "just lethal" bloom, with q in the gill slits of 14,000 $s^{-1}$, this gives an increase of 380%, probably not enough to kill the fish. For P equal to -0.6, the corresponding increase is 1,720%, so the fish would probably die of $O_2$ lack. Hence it can be predicted that if the trapped bubbles seen were 0.5 mm in diameter, and if the fish killed used ≈15% of their metabolic energy for gill irrigation, then the mean power of P over the range of q from 6 to 14,000 $s^{-1}$, is around -0.6 to -0.8. This value of P is typical of three phytoplankton cultures whose viscosity approached that of the bubble-trapping red tide, but higher than values found in the non-bloom conditions [2]. If the bubbles were only 0.1 mm in diameter, the

corresponding value for P, over a range of q from 30 to 14,000, would be about -0.3, considerably higher than P typical of the phytoplankton cultures. To kill tuna by the same means, the bloom would have to be about 14 times more viscous, or roughly 3 to 4 times more concentrated in terms of polymer, than one able to kill other typical fish.

If P were sufficiently near zero, fish could be killed by rheological effects without the rising rate of bubbles being noticeably reduced.

The cross-gill pressure, D, is proportional to the square root of $\varepsilon$, and D may be limited by tissue strength, so under significantly increased viscosity the fish would have to let throughput decline, as reported for fish in *Chattonella* culture [8], with corresponding decrease in q and increase in $\eta$. Values of shear *stress*, $\tau$, higher than normal in the gill slits may slough away protective mucus and damage underlying epithelia. The large amounts of mucus secreted from fish gills in association with sublethal blooms of *G. aureolum* and *Chattonella* [8,16] may represent efforts by the fish to replace that sloughed away. Additionally, it could be a response to damage or irritation. Sloughing of gill epithelia in trout kept in high concentrations of *G. aureolum* may indicate mechanical damage. That sloughing of epithelia occurred also in the gut, however, suggests that toxic effects may have been involved, and this has been interpreted [16] as indicating chemotoxins in *G. aureolum*. As increased viscosity, by reducing throughput, may result in increased tissue concentrations of potentially toxic waste products, evidence of a toxic pathology in association with a phytoplankton bloom should *not*, by itself, be interpreted as evidence that a chemotoxin originates from the plankton and enters the fish.

Further, some suspected gill cloggers such as *Chattonella subsalsa* Biecheler possess mucocysts [9], and the shock of being inspired with greatly increased shear stress may cause them to discharge mucus in the gill slits.

In organisms in which a much lower value of q exists at their respiratory surfaces, such as those with external gills, red tides may reduce gas and ion exchange by the following method. An increase in the thickness of the non-turbulent boundary layer may occur, associated with an increase in the size of the smallest turbulent eddies [1]. This would reduce turbulent diffusion, and increase the distance across which molecular diffusion would have to occur.

Plankton patchiness, turbulence and mucus aggregation in a bloom are all likely to result in lumpiness (rheological heterogeneity). The more viscous liquid (lumps) will pass through gill slits more slowly than the less viscous liquid (leads). One corollary to this is that the effective mean viscosity of a lumpy liquid depends on the hydrodynamics of the containing system (gill slits or a rheometer, for instance). Another is that if a chemotoxin were more concentrated in lumps than in the leads, its time in contact with the gills would be greater than if it were prefectly dispersed.

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