Water quality requirements for culture of the green sea urchin, *Strongylocentrotus droebachiensis*

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Sea urchin roe is a highly prized seafood in a number of countries and is considered one of the most valuable seafoods in the lucrative Japanese market (Hagen 1996). Demand for high quality sea urchin gonad over the last three decades has led to extensive exploitation of wild sea urchin populations all over the world, with resulting over-fishing and declining fisheries stocks in many countries (Andrew et al. 2002). This, together with the global increase in the popularity of sushi, has led to increased interest in aquaculture of a range of sea urchin species, including the cool-water species *Strongylocentrotus droebachiensis* (Figure 1). This species has a broad arctic-boreal distribution and is found across the whole northern hemisphere from latitudes as high as Greenland in the north and as far south as Cape Cod on the east coast of the USA, southern Scandinavia, northern UK, Oregon on the west coast of the USA, and northern Japan. Because of its wide distribution and excellent taste and market value, there has been extensive research on the biology, ecology and fisheries of the species. More recently it has also been identified as one of the sea urchin species to have the best potential for aquaculture. Consequently much of the research investigating various aspects of sea urchin aquaculture has focused on *S. droebachiensis*.

The aquaculture of any new species presents a range of challenges. In addition to having a suitable feed, either natural or manufactured, and available holding system technology, it is essential to understand the environmental requirements of any cultured species. In this article, we summarize some of the research that has been carried out on water quality requirements of *S. droebachiensis* related to the potential culture of this species.

**Sea Urchins and Aquaculture**

Sea urchins are ancient and primitive organisms that lack many of the organs found in higher animals (Figure 2). They have no specialized respiratory system or circulatory system, no heart, no blood vessels and no oxygen binding molecules in their body fluids, nor do they have any specialized excretory organs. Basically, sea urchins consist of a mouth, a digestive system or gut tube, gonads, also known as the roe, and a primitive nervous system, all surrounded by a hard, calcareous shell, also known as the test. On the outside of the test are spines, podia (tube feet) and some gripping devices called pedicellaries (Figure 2).

The limited number of specialized organs means that sea urchins have a limited capacity to regulate their internal bodies when faced with variations in the external environment. This means they are, to a much greater extent than higher animals, at the mercy of their surroundings. Because the composition of their body fluids, particularly the ceolomic fluid found in the cavity inside the test, mirrors the composition of surrounding seawater, sea urchins are known as conformers and are generally intolerant to changes, rather than living in stable environments where the conditions remain relatively constant. For example, sea urchins have a very limited ability to osmoregulate and consequently are never found in fresh water (Barker and Russell 2008). In fact, sea urchins can be used as indicator organisms for environmental degradation, such as water pollution, in much the same way as canaries were used to detect poisonous gases in coal mines in earlier days (Meriç et al. 2005).

Because of the sensitivity of sea urchins to changes in water quality and the inability to regulate their internal en-
environments, it is crucial to understand the water quality tolerance limits of sea urchins in aquaculture holding systems. This is particularly important for intensive culture of sea urchins, where levels of harmful substances can be elevated well above concentrations that normally occur in natural environments.

The Importance of Oxygen and Water Movement

The single most important water quality parameter in any aquaculture holding system is a continuous and sufficient supply of oxygen, inasmuch as this is a prerequisite for the survival, growth and well-being of all animals. In most species of sea urchins, oxygen is taken up by five pairs of external gills that are thin-walled projections of the body cavity located around the mouth. In other species, including *S. droebachiensis*, oxygen is taken up through the podia and transported internally through radial water canals that connect all podia (Figure 2). The movement of water inside radial water canals is facilitated by cilia. Because of the lack of respiratory pigments, oxygen is transported only as dissolved gas, giving a transport capacity 200 times lower than that of fish blood (Steen 1965). The internal organs of sea urchins are bathed in the coelomic fluid and receive oxygen from this fluid by simple diffusion, although the movement of oxygen may be enhanced by cilia on the inside of the coelomic cavity.

The uptake of oxygen and amount of dissolved oxygen (DO) in the coelomic fluid of sea urchins is closely related to ambient DO concentration in the surrounding seawater. Thus, sea urchins are oxygen conformers and oxygen uptake may be restricted by insufficient oxygen supply (Giese et al. 1966, Johansen and Vadas 1967, Webster and Giese 1975, Spicer 1995). Accordingly, Siikavuopio et al. (2007b) found that gonad growth of *S. droebachiensis* was strongly affected by oxygen saturation in the surrounding water. When oxygen saturation was reduced from 100 percent to 63 and 42 percent, gonad growth was reduced by 39 and 48 percent, respectively. Although not conclusive, these data suggest a linear relationship between growth performance and oxygen saturation. This effect has also been described in another echinoderm, the sand dollar *Mellita quinquiesperforata* (Lane and Lawrence, 1979).

A linear correlation between growth performance and oxygen saturation is not surprising for animals that lack oxygen binding compounds in their body fluids. With most teleosts, on the other hand, growth is not affected until oxygen saturation falls below a certain threshold level, often around 70 percent (Jobling 1994), as a result of the oxygen binding characteristics of fish hemoglobin. Above the threshold level the oxygen carrying capacity of hemoglobin is fully exploited and oxygen uptake and growth are independent of oxygen saturation.

The relationship between growth and oxygen saturation in sea urchins is also influenced by water movement. In the wild, sea urchins are often larger and have greater roe content in areas of high water movement (current) compared to those found in areas of lower water movement (James et al. 2007). Water movement increases the gonad growth of captive adult *Evechinus chloroticus* (James 2006) and somatic growth of juvenile *S. droebachiensis*. Increased growth is thought to be a result of improved oxygen availability. However, whether this is caused by an increase in oxygen present in seawater (greater DO concentration) or a greater flow of water across the surface of the animal (where most oxygen uptake occurs) is unclear. When exposed to very low flow rates, the oxygen consumption of *S. droebachiensis* increases dramatically compared to the oxygen consumption of urchins held in very high flow rates. This indicates that urchins actively extract oxygen, as much as is possible for a sea urchin, from the surrounding seawater when flows are low and the metabolic cost reduces their growth. Further research is required to fully understand the complex interaction between oxygen consumption and water movement in sea urchins but it is clear that any sea urchin aquaculture holding system should provide high dissolved oxygen levels and a means of ensuring sufficient water movement across the surface of animals held within the system to allow optimal access to dissolved oxygen available in the seawater supply.
Effects of Metabolic Waste Products - CO$_2$, NH$_3$, and NO$_2$

**Carbon dioxide**

In intensive aquaculture, particularly those relying on partial or full recycling of seawater within the production system, the waste compounds that cause most negative effects on growth and development are normally CO$_2$ and NH$_3$ (in that order). During aerobic metabolism CO$_2$ is produced at a rate of 0.7 to 1.0 gram per gram O$_2$ consumed. The effect of CO$_2$ on sea urchins and other marine organisms has recently attracted attention due to ocean acidification caused by anthropogenic CO$_2$ release. It is predicted that the surface pH of the sea will drop by 0.4 units to 7.6 - 7.8 by 2100. Several studies have demonstrated that reducing pH to such values will have negative effects on fertilization and development of sea urchin larva. Down-regulation of genes (reduced activity of enzymes) involved in calcification and metabolism has also been demonstrated (Moulin et al. 2011).

In contrast, the effect of CO$_2$ on sea urchin culture has not been adequately studied. Test growth of Paracentrotus lividus is completely inhibited when the partial pressure of CO$_2$ is elevated five to nine times above the normal level in seawater (Grosjean et al. 1998). An increase in CO$_2$ concentration from 1.1 to 18.1 mgL$^{-1}$ leads to a 67 percent decrease in gonad growth of adult S. droebachiensis (Siikavuopio et al. 2007a), a decrease attributed to reduced feed intake and less efficient feed conversion. The explanation for the negative effect of increased CO$_2$ on test growth is probably that CO$_2$, through its pH effect, impairs the precipitation of bicarbonates into calcium carbonate, which is the main constituent of the sea urchin test. Fortunately carbon dioxide is easily stripped from water in recirculating aquaculture systems using trickle towers or other methods to degas the CO$_2$. In flow-through or sea-based systems, CO$_2$ is unlikely to be an issue in the immediate future.

**Ammonia**

Ammonia excretion by sea urchins has been the subject of several ecology-oriented articles, but there is a paucity of studies looking at the effects of elevated ammonia concentration on sea urchin growth. Sea urchins excrete several nitrogenous compounds, but the main excretory product is ammonia (NH$_3$). The release of NH$_3$ varies according to the substrate used for energy metabolism. Brockington and Peck (2001) found an O:N ratio of 7 in Sterechinus neumayeri during the onset of the austral summer when sea urchins use protein as their main source of energy. A ratio of the same magnitude may be expected for cultured sea urchins, which are fed diets with higher protein content than normal natural-food diets. As is the case with CO$_2$, accumulation of NH$_3$ is generally not a problem in flow-through culture systems but may be a problem in recirculating systems, depending on the degree of water reuse and the ammonia tolerance of the specific urchin species. Siikavuopio et al. (2004a) tested the effects of different ammonia concentrations on gonad growth of S. droebachiensis, and found that gonad growth was significantly reduced at an un-ionized ammonia (UIA) concentration of 16 µg/L during a 43-day experiment. At UIA levels of 32 and 68 µg/L, mortalities of 45 and 76 percent were recorded. A surprising result in this experiment was that feed intake was not significantly affected by increasing concentrations of UIA, meaning that reduced gonad growth was mainly the result of reduced feed conversion efficiency. S. droebachiensis has a low tolerance for UIA compared to many cultured marine fish species and invertebrates.

**Nitrite and Nitrate**

In recirculating systems, ammonia is oxidized to nitrite (NO$_2$) and then nitrate (NO$_3$) by autotrophic bacteria in biofilters. While nitrate is a relatively non-toxic compound, nitrite may cause problems if it accumulates. Gonad growth of S. droebachiensis is significantly impaired at a NO$_2$-N concentration of 0.55 mg/L, which is relatively low compared to many species of fish and invertebrates (Siikavuopio et al. 2004b). As occurs with ammonia, increasing levels of nitrite does not affect feed intake, and there was no mortality during the 42-day experiment, where the highest concentration of NO$_2$-N tested was 10 mg/L.

**Phosphate**

Phosphorus is normally found in minute quantities in aquatic environments. In natural seawater, dissolved phosphorus, which exists predominantly as inorganic phosphate, is usually found at very low (< 1 um) concentrations (Barr et al. 2008). Concentrations of phosphate may be greatly elevated in intensive aquaculture systems, particularly those where there is very little water replacement and where phosphate-rich manufactured feeds are used. However, there is limited research on the specific effects of elevated phosphate on any aquaculture species. A phosphate concentration of 1.25 µM has an inhibitory effect on the rate of in vitro calcium carbonate crystallization in both the marine bivalve Rangia cuneata and the freshwater gastropod Helisoma duryi over a 24-hr period (Bernhardt et al. 1985). Exposure to elevated phosphate concentration for one month has an inhibitory effect on shell growth and causes increases in mortality in both species. Exposure of the sea urchin Lytechinus variegates to phosphate concentrations greater than 1.6 mg/L (17 µM) has a negative effect on urchin growth and righting behavior and inhibits feeding, fecal production and nutrient absorption (Böttger et al. 2001). There is a significant negative impact on growth (both shell length and wet weight) when small abalone Haliotis iris are exposed to phosphate concentrations greater than 10.7 µM and for larger abalone when exposed to phosphate concentrations greater than 60.9 µM. However, elevated phosphate concentrations do not significantly impact abalone survival (James and Barr 2010). Inorganic phosphate should be maintained below 10.7 µM to optimize growth of abalone in intensive aquaculture systems and this recommendation likely applies to other benthic invertebrates such as sea urchins.
Summary

Sea urchins require high-quality seawater to develop and grow optimally in culture, as indeed do many aquaculture species. The tolerance limits of *S. droebachiensis* for the water quality parameters described above appear to be as narrow as those for salmonid fishes, which are known to have stringent water quality requirements. Poor water quality in production systems may have negative effects on sea urchin culture performance: reduced growth rate, reduced feed conversion efficiency, increased mortality and down-regulation of different genes involved in test formation and metabolism. However, the lack of response to any of the water quality variables described here on feed intake of sea urchins is remarkable. It indicates that sea urchins have poorly developed appetite regulation when fed to excess and are able to ingest feed far in excess of nutritional and energetic requirements. Sea urchin farmers should be aware that *ad libitum* feeding of sea urchins under sub-optimal culture conditions can result in overfeeding. In turn, this will have a detrimental effect on water quality and easily lead to a negative spiralling effect with increased overfeeding and a progressive decline in water quality. Ironically it appears that sea urchins are well adapted to being fed at very low feed levels. Recent research suggests that restricted feed rates interspersed with periods of no feeding may provide the optimal feeding regime for cultured sea urchins.

Recommendations

Although studies that have been conducted on the effects of reduced water quality on sea urchin growth and mortality are not sufficient to set out exact tolerance limits for various water quality parameters, some recommendations for sea urchin farmers can be made. These mostly apply to *S. droebachiensis*, which is the most studied species with reference to aquaculture. They are also most relevant for holding systems where water supply is limited (e.g., recirculating systems), particularly those systems with limited water renewal.

Oxygen

A sufficient supply of oxygen is most important to sustain optimal growth of sea urchins in culture. Growth is proportionally reduced with decreasing oxygen saturation. Therefore, water should be fully saturated with oxygen to avoid reduced growth. This can be achieved by supplying sea urchins with large amounts of fully saturated water, aerating tank water, or supersaturating inlet water with oxygen. Moderate oxygen supersaturation does not harm sea urchins, so this represents a feasible way of ensuring optimal oxygen conditions without using too much water. Water movement increases oxygen availability for sea urchins. Holding systems that create water movement across the surface of all urchins held in culture tanks would be advantageous. This may be possible by using gravity, aeration, or by creating water waves in culture tanks, as used in abalone culture systems in several countries.

Carbon dioxide

In cases where water flow is reduced, it is possible that CO₂ accumulates to undesirable levels. CO₂ accumulation may be controlled by CO₂-stripping through aeration. Simultaneously this will enrich water with oxygen in the case of undersaturation.

Ammonia and nitrite

Accumulation of ammonia and nitrite to toxic levels may occur in recirculating systems when biofilters do not function properly. Good design and management of biofilters is essential. Bacteria in biofilters also produce acid and contribute to reduced pH, together with CO₂. Adding calcium carbonate to the water can increase pH and buffering capacity. Adding calcium may also prevent calcium depletion from slowing down the calcification of sea urchin tests. However, no experiments have been done to evaluate if the addition of calcium has any positive effect on sea urchins under intensive culture conditions.

Phosphate

In the absence of more specific data for sea urchins, and based on data available for other benthic invertebrates, the level of inorganic phosphate should be maintained below 10 µM. This is relatively easy to achieve in flow-through land-based systems but recirculating systems with limited water exchange should regularly monitor phosphate levels. Moni-
toring should be done at different times of the day because phosphate levels within the system can change dramatically following events such as feeding.

**General**

In general, hygienic conditions should be maintained in holding facilities for sea urchins and this should be a priority in system design. Animals should be physically separated from feed waste and feces on the tank floor using perforated false bottoms in tanks. This configuration also facilitates cleaning tank bottoms and avoids negative water quality effects from organic sediments. Water quality can become an issue in sea urchin farming when the supply of water is restricted, particularly in recirculating systems with minimal replacement of seawater.

Most of the potential problems outlined in this article can be avoided by keeping sea urchins in well-designed sea-based facilities, where natural water currents provide animals with sufficient water to prevent the occurrence of poor water quality. The information presented in this article provides guidelines for understanding some of the water quality parameters that should be considered in the management of land-based aquaculture holding systems and also provides some recommendations for designing such systems.

**Notes**

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