Fisheries and Oceans Canada / Pêches et Océans Canada
Science / Sciences

C S A S / **S C C S**

Canadian Science Advisory Secretariat / **Secrétariat canadien de consultation scientifique**

Research Document 2004/125 / **Document de recherche 2004/125**

Not to be cited without
Permission of the authors *

Ne pas citer sans
autorisation des auteurs *

Potential Effect of Seismic Surveys on Fish Eggs, Larvae and Zooplankton

Effets possibles de la prospection sismique sur le zooplancton et les oeufs et les larves de poisson

Jerry F. Payne

Science Branch
Department of Fisheries and Oceans
P. O. Box 5667
St. John's, Newfoundland A1C 5X1

* This series documents the scientific basis for the evaluation of fisheries resources in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

* La présente série documente les bases scientifiques des évaluations des ressources halieutiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Research documents are produced in the official language in which they are provided to the Secretariat.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

This document is available on the Internet at:

Ce document est disponible sur l'Internet à:

http://www.dfo-mpo.gc.ca/csas/

ISSN 1499-3848 (Printed / Imprimé)

ABSTRACT

Data are generally insufficient to provide informed opinion on the size of injury zones for eggs and larvae of fish and shellfish (or on other planktonic organisms) stemming from seismic activities. With respect to fisheries, it follows that this knowledge gap will have to be considered before questions of potential impacts on populations can be addressed with confidence. It would also be premature at this time to adopt specific reference levels. However it is important to point out that the primary concern would be in relation to the potential for impacts at the stock or sub-stock level such as in a confined bay or similar type of risk zone. A few representative studies on distance-effect relationships would greatly aid understanding in this area with the potential for effects stemming from cumulative energy as well as peak energy being considered, including under conditions of 3-D surveys. Such studies are needed if only for assurance. In addition to injurious effects of a more or less physical nature on larvae or other planktonic forms, the question of subtle effects such as those which may be connected with behavioral functions of communication, movement in the water column or larval settlement can also be asked (with the understanding that like behavioural functions could also be influenced by injurious effects of a physical nature). Although not discussed here, it can also be asked whether other sources of sound such as that associated with select ship traffic lanes may often present equal or greater concerns with respect to some effects, such as those which may be implicated in affecting behaviour.

RÉSUMÉ

Les données sont généralement insuffisantes pour formuler une opinion éclairée quant à la superficie d’action nocive des activités de prospection sismique sur les oeufs et les larves des poissons, des mollusques et des crustacés (et sur d’autres organismes planctoniques). En ce qui concerne les pêches, il s’ensuit que cette lacune devra être prise en considération avant de pouvoir répondre avec assurance aux questions sur les impacts possibles sur les populations. Il serait en outre prématuré à ce moment-ci d’adopter des niveaux de référence spécifiques. Il est cependant important de souligner que les impacts possibles au niveau du stock ou du sous-stock, comme dans une baie confinée ou une zone à risque semblable, constituent la préoccupation première. Quelques études représentatives sur les relations entre la distance et les effets, tenant compte de la possibilité d’effets découlant de l’énergie cumulée et de l’énergie de crête, y compris dans des conditions de levés sismiques tridimensionnels, aideraient grandement à comprendre quels pourraient être ces impacts. De telles études sont nécessaires, si ce n’est que pour confirmer l’absence de ceux-ci. En plus des effets néfastes, de nature plus ou moins physique, sur les larves ou d’autres formes planctoniques, la question des effets subtils, comme ceux ayant trait aux comportements sous-tendant la communication, les déplacements dans la colonne d’eau et l’établissement des larves sur le fond, se pose (compte tenu que les effets néfastes de nature physique pourraient aussi avoir un impact sur les comportements semblables). Quoique le sujet ne soit pas abordé ici, la question se pose à savoir si d’autres sources de bruit, comme ceux associés à certains couloirs de navigation, peuvent souvent être tout aussi ou davantage préoccupantes pour ce qui est de certains effets, comme ceux donnant lieu à des modifications des comportements.

Overview of Studies

An overview of various studies carried out with eggs and larvae of finfish and shellfish follows. No studies on zooplankton proper were found.

Kostyuchenko (1973) studied survival and injury in fish eggs of various species exposed at 0.5, 5, and 10 meters from a single air gun (5 liter or 200 cu. in). Apparently, the eggs were exposed to one discharge only. Pathological effects were reported to occur in a small percentage of anchovy and blue runner eggs at 5 m , and crucian carp at 0.5 m, No effects were noted in mullet eggs. The pathological effects included embryo curling, membrane perturbation and yolk displacement. The reported percentages for egg survival (combined species) were 75.4, 87.7, 90.2, and 92.3 for the 0.5, 5.0, 10 m and control exposures respectively. Survival seemed to be little affected beyond the 0.5 m exposure, but survival was assessed only one day past exposure. Regarding egg pathology, although the number of eggs examined was small and the frequency of pathology low, it is reasonable to assume a cause effect relationship at 5 m since effects were recorded at this distance for two species but absent at 10 m (and presumably in the controls).

Dalen and Knutsen (1986) exposed eggs, larvae and fry of cod to a small air gun having a source level of 220.0 dB re 1µPa. Exposures were carried out between 1 and 10 m with (a) egg stages 2, 5 and 10 days past fertilization, (b) larval and post-larval stages up to 41 days after hatching, (c) fry up to 110 days after hatching. Other than a transient effect on buoyancy in older fry no other effects were recorded. Supposedly, only immediate (within hours) and not delayed mortality was assessed in the various larval and fry stages studied. Older fry were also exposed to a larger airgun having a source level of 231.0 dB re 1 µPa. Results were similar to the exposures with the small airgun. Also, as for the exposures with the small airgun, presumably only immediate mortality was assessed. It is noted that the various studies were carried out with one discharge only.

Holliday *et al*. 1987 investigated effects on the eggs and larvae of northern anchovy exposed to energy from up to four 4.9 liter (300 cu. in) air guns. The organisms were exposed 1.5 m below the center of the guns and discharges were varied to stimulate the passage of a survey vessel. Studies were carried out over a two year period. In the first year, they found a significant but small difference in long-term survival between eggs under control conditions and eggs exposed at a peak pressure of 221.8 dB (1.23 bars) and cumulative energy density of 0.60 bar^2 sec. However in year 2 when they conducted tests at a peak pressure of 5.69 bar (235.1 dB) and cumulative energy of 2.17 bar^2 sec., significant differences were not found in either short-term or long-term survival between exposed and control eggs. In other words, exposure at a lower peak level and lower cumulative energy appeared to have a greater effect. Also, it is noted that the percentage difference between the control and the exposed groups in the first year of the study was small ~9%.

In the case of two-day yolk-sac larvae, they noted a significant reduction in short term survival at two exposures: peak pressure of 1.53 bar (223.7 dB) with an energy density of 1.87 bar^2 sec. and peak pressure at 2.50 bar (228.0 dB) with an energy density of 4.07 bar^2 sec. However, exposure at a peak pressure at 2.88 bar (233.7 dB) with energy density of 1.58 bar^2 sec. did not show a significant reduction in survival of yolk-sac larvae. Thus, their results indicate that energy density was more important than peak pressure in producing damage bringing up the question of their relative importance. In the case of fish, it has been shown with the use of explosives that peak pressures having rapid rise times may be important in producing damage (e.g. Yelverton et al, 1975) but airguns do not have such rapid rise times as explosives.

This study brings us to the question of the relative importance of peak pressure and cumulative energy for producing various types and degrees of injury.

Matishov (1992) exposed 5 day old cod larvae to a “series of airpulses” from “grouped bolt airguns” (model 190 CT) at 1, 2, 3 and 4 meters. Sound exposure was not measured but has been estimated to be ~ 214-220 dB re 1 µPa (Turn penny and Nedwell, 1994) Histological studies were carried out on gills, liver, kidney, intestinal, brain and retinal tissues. It is not known if all the tissues were examined with electron and light microscopy but studies carried out with electron microscopy on retinal tissues revealed rupturing of nerve and epithelial layers in larvae exposed at 1m.

Pearson *et al*. (1994) assessed immediate and long term survival and time to molt in stage II zoeae of Dungeness crab exposed to single discharges of a 13.0 liter array of seven airguns of mixed sizes. The exposure regime was based on typical patterns followed by seismic survey vessels. Through analysis of model simulations it was assumed that in the near field (<10m) the proposed seven-air-gun array would simulate the peak pressure, cumulative energy, density, and pressure signature of a 32-gun array. They reported no effects in zoeae in exposures 1 m from the array with sound pressures as high as 231 dB re 1 µPa and cumulative energy density up to 251 J/m^2. However, one statistical test (linear contrast) which compared the time to moult between the average of the three control levels and three treatment levels indicated a slight but significant difference for time to moult to stage III. But, interestingly the same test did not reveal a significant difference for time to molt to stage IV. Overall, any cause effect relationship on survival or time to moult seems tenuous and appears at best to be quite small. However the zoeae were exposed to only one discharge in the near field of the test array and this leads again to the question of the importance of peak pressure or total energy, (or both) for producing effects.

Booman *et al*. (1996) investigated effects on eggs and larvae of a number of fish species found in Norwegian waters. Exposures simulated conditions of a seismic survey and the distances from the air gun or the center of the air gun clusters were in the 0.75 to 6.0 m range, corresponding to sound pressure levels of 242 to 220 dB re 1µPa. Effects varied, with highest mortality rates and pathology in the 1.4 m range and low or no mortality rates and infrequent pathology in the 5 m range. Pathological effects in turbot larvae included "strong" vacuolation of the brain, nerve tissues and eyes at 0.75 m. Sensory cilia of free neuromasts which are organs involved in mechanosensory function were also ablated to some extent in turbot and cod larvae. Interestingly, both cod and turbot larvae were also reported to have buoyancy problems. Overall, this study like that of Kostyuchenko (1973), provides evidence for effects in the 5 m range.

There is only one study **(Christian *et al*. 2004)** which has investigated the potential effects of seismic on egg development in crustaceans, namely commercial important snow crab. The study was opportunistic in nature. Fertilized eggs containing developing embryos were stripped from females and incubated at 4ºC for a period of approximately two months. Although 4ºC is slightly higher than that associated with crab habitat, it was chosen in order to enhance development (Mallet et al, 1993) and to reduce the potential for onset of disease, which can be a problem in rearing crustacean eggs and larvae under laboratory conditions (e.g. Aiken and Waddy, 1985). Eggs were not disinfected in order to avoid increased potential for sub-lethal effects. Approximately 4,000 eggs showing essentially the same level of eye development were divided in to two masses and placed into two small nylon mesh bags. Both the treatment and control egg samples were taken to the experimental field site. One sample was exposed to the energy from a 40-in^3 sleeve gun at two metres and a total of 200 shots were fired, one every 10 seconds. The exposed and control eggs were returned to the laboratory, held in aquaria at 4ºC and analyzed twelve weeks after exposure.

Eggs were initially divided into two categories based on color criteria: (1) "beige" eggs and, (2) orange-brown eggs. The orange-brown eggs were further divided into three categories based on eye size criteria: (1) no eyes, (2) small eyes, and, (3) big eyes according to a categorization system described by Moriyasu and Lanteigne (1998). Small-eyed eggs had lengths ranging from 140 to 240 µm and widths from 60 to 100 µm, Big-eyed eggs had lengths ranging from 240 to 400 µm. The percentage of eggs in each category was calculated relative to the total of 2,095 control eggs and 2,091 treatment eggs that were analyzed. Significant differences were found between the control and treatment eggs in all categories. The most significant differences between controls and treatments were in respect to the proportions of big-eyed eggs and small-eyed eggs. More than 70% of the untreated eggs were big-eyed while less than 45% of the treated eggs had big eyes. This indicates that exposure to the seismic energy resulted in delayed embryonic development.

Discussion

Overview of Studies

A few studies (Table 1) have been carried out on the effects of seismic energy on finfish eggs and larvae (Kostyuchenko, 1973; Dalen and Knutsen, 1986; Holliday et al, 1987; Matishou, 1992). Where observed, larval mortality has been in the range of 0.5-3.0 m and associated with relatively high peak energy levels. Observations have generally been made in relation to short term survival only and sometimes with one discharge event. A distance of 5m has also been indicated as the range for producing various pathological effects in eggs and larvae. One study has also investigated effects on the larvae of Dungeness crab (Pearson et al 1994) while Christian et al (2003) have provided some preliminary observations on developing eggs of snow crab (Table 1). There was indication of a slight effect on one moulting stage in Dungeness crab larvae at 1 m with a particular statistical test, but a cause-effect relationship was tenuous. Overall it is important to note that any effect on either larval survival or time to moult was very small. However a distinct difference was noted in the development of snow crab eggs three months post exposure to relatively high peak energy levels at a distance of 2 m. This observation was of an opportunistic nature and only involved one exposure distance.

Peak Pressure and Cumulative Energy in Relation to Effects

Although effects have been observed out to 5 m with relatively high peak energy levels, it is not known if this approximates the true range for injury, since the relative importance of peak pressure and total cumulative energy is unknown, especially in relation to subtle but potentially injurious sub-lethal effects which have not been investigated to any extent. Some effects could be linked to peak pressure while others could be linked to total cumulative energy. For instance mortality of an immediate or very short term nature as seen in the few studies to date could be more or less linked to peak pressure while more subtle effects of which we are unaware such as chronic overstimulation of neuroendocrine systems or for instance mechanosensory systems, such as sensitive cilia in ears and lateral lines (of fish, but analogs also exist across a wide range of species), could also be occurring and linked to cumulative energy. Of course it would be difficult to separate one from the other with both having a role even in the case of one particular type of injury. For instance acute and immediate injury to mechanosensory systems might be primarily due to high peak pressures, while additional injury might stem from more chronic exposure to much lower peak pressures and thus at greater distances in the water column.

Overall, it is premature to suggest that peak pressure alone is important for producing larval injury with a 5 m distance representing the injury zone. More subtle effects resulting in delayed development and mortality through injury or overstimulation of neuroendocrine systems or for instance loss of normal behavioral or communication responses through damage to mechanosensory systems could be a reasonable possibility and extend to greater distances in the water column (Also see discussions by Hastings et al (1996) and Popper (2004) about potential effects of noise on fish hearing). Taking an example from adult fish, McCauley et al (2003), in a trial simulating a seismic survey, produced evidence for a level of damage to sensory hair cells in the ears of snapper exposed to around 212 dB re 1 µPa. However, Enger (1981) earlier observed in more fundamental studies on auditory systems in fish, that chronic exposure of cod to much lower levels of peak energy (180 dB re 1 µPa) in the 50-400 Hz frequency range also resulted in similar ear injury. It is noted that “most” of the frequency range used in the latter study with cod is generally beyond that associated with seismic surveys, but the potential for producing effects under conditions of chronic exposure to sound at lower levels of peak energy is an open question. The example given is in relation to mechanosensory systems in fish but the potential for damage to other systems and in other species would also be of interest. Of particular importance may be 3-D surveys which can concentrate activity in a few hundred km^2 for upwards of a month with tracklines in the tens of meters range.

Larval Loss and Fish Recruitment

It has been speculated that loss of larval populations in the 5% range such as might be associated with a 5 m injury zone, would likely have little impact on recruitment into a fishery or on most fish populations in general. However, a 5% larval loss at earlier periods of development may not be nearly as important as a 5% loss at more critical and later stages of development and metamorphosis. Seemingly each species would have to be assessed on a case by case basis in relation to life history characteristics such as patchiness in distribution and time. Also, as noted above, in the absence of information on the potential for serious sub-lethal effects, an injury zone of 5 m can not be stated with any degree of assurance.

However, in perspective it is important to point out that the extensive seismic surveys which have been carried out in such areas as the North Sea have not resulted in measurable impacts on commercial fish populations. Thus the primary concern would be in relation to the potential for producing impacts at the stock or sub-stock level such as in a particular bay or similar situation. For instance it is reasonable to question if a seismic survey throughout Placentia Bay might affect lobster populations in the area. This question cannot presently be answered with any level of scientific confidence either in relation to potential impacts on larvae per se or delayed mortality or morbidity in “adult” animals, especially during sensitive life history stages such as molting.

Effects on Behaviour

Little is known about the effects of sound on behaviour in larval forms or zooplankton but is sketchily introduced since there may be instances where seismic might be considered to be of special importance. Effects on behaviour are being considered here somewhat outside the aspect of cellular injury noted above, realizing there is no strict demarcation. Suffice to say, adult and larval forms of marine organisms in general are influenced by hydroacoustic disturbances and particle motion and a wide variety of invertebrate as well as fish are sensitive to low frequency (10-150 Hz) which overlaps the frequency range of seismic energy. However the extent to which mechanosensory or other systems in pelagic and planktonic organisms may be influenced or "injured" by sound with respect to orientation in the water column, communication, feeding behaviour, predator avoidance, or settlement is unknown. This would seem to be the case for animals as diverse as fish and crabs. In the case of settlement, it has been suggested that larval lobster and reef fish may use underwater sounds for orientation (e.g. Jeffs et al, 2003 and references therein).

Summary

Limited data indicate that some fish eggs and/or larvae may be damaged at a distance of approximately 5 m from a seismic discharge(s). In the absence of studies on a wider variety of species and lack of attention to long-term survival and sub-lethal effects, it is premature to suggest that 5 m is the approximate injury zone for effects on the eggs and larvae of finfish and shellfish, zooplankton, or planktonic life stages in general. The question of peak energy levels and cumulative energy is of interest in this regards and especially in relation to effects which might principally be due to loud sounds of short duration versus those due to weaker sounds of longer duration. Sound energy connected with 3-D surveys seems of special note in this regard. Given myriad species, speculation about potential effects could admittedly be rather limitless. However a few representative studies on keystone species such as those of commercial importance would be helpful in shedding light on whether a distance of 5 m is a reasonable approximation as the zone of injury for eggs and larvae of finfish and shellfish and other planktonic organisms. These studies are needed if only for assurance. In the case of commercial species, it follows that until the issue of the size of injury zones is clarified, speculation about potential effects on fish recruitment or population loss can not be addressed with confidence. It would also be premature at this time to adopt specific reference levels. However most concern is in relation to potential effects at the stock or sub-stock level not broadside population level effects over large geographical areas. In addition to injurious effects of a more or less physical nature, questions can be asked about more subtle effects such as those connected with behavioural functions of communication, predator avoidance and larval settlement. Any deliberation in this area would be highly speculative but there may be special concerns which warrant attention. Finally it should be noted that although this overview deals with sound from seismic surveys connected with oil and gas exploration, questions can also be asked about other sound exposures such as those associated with ship traffic lanes where the potential for chronic exposures may exist to a great degree. Such sources might also be more important in relation to sound exposures which are not so physically injurious as such but interfere with normal communication and behavioural functions.

References

Aiken, D.E. and Waddy, S.L. 1985. Production of seed stock for lobster culture. Aquaculture 44:103-114.

Booman, C., Dalen, J., Leivestad, H., Levsen, A., van der Meeren,T., and Toklum, K. 1996. Effecter av luftkanonskyting på egg, larver og yngel. Fisken og Havet 3:1-83. (Norwegian with English Summary).

Christian, J.R., Mathieu, A., Thomson, D.H., White, D., and Buchanan, R. A. 2003. Effect of Seismic Energy on Snow Crab (*Chionoecetes* opilio). Environmental Research Funds Report No. 144. Calgary. 106p. ISBN 0-921652-56-9.

Dalen, J. and Knutsen, G.M. 1986. Scaring effects in fish and harmful effects on eggs, larvae and fry by offshore seismic explorations. *In* Progress in Underwater Acoustics. Edited by H.M. Merklinger. Plenum, New York. pp. 93-102.

Hastings, M.C., Popper, A.N., Finnerman, J.J., and Lanford, P.J. 1996. Effects of low-frequency underwater sound on hair cells of the inner ear and lateral line of the teleost fish *Astronotus ocellatus.* Journal of the Acoustical Society of America 99: 1759-1766.

Holliday, D.V., Pieper, R.E., Clarke, M.E., and Greenlaw, C.F. 1987. The effects of airgun energy releases on the eggs, larvae and adults of the northern anchovy (Engraulis mordax). API Publication 4453. Report by Tracor Applied Sciences for American Petroleum Institute, Washington D.C. 115p.

Jeffs, A., Tolimieri, N., and Montgomery, J.C. 2003. Crabs on cue for the coast: the use of underwater sound for orientation by pelagic crab stages. Marine and Freshwater Research 54: 841-845.

Kostyuchenko, L.P. 1973. Effect of elastic waves generated in marine seismic prospecting on fish eggs on the Black Sea. Hydrobiol. J. 9:45-48.

Mallet, P., Conan, G.Y., and Moriyasu, M. 1993. Periodicity of spawning and duration of incubation time for *Chionoectes opilio* in the Gulf of St. Lawrence. ICES CM, K26,19 p.

Matishov, G.G. 1992. The reaction of bottom fish larvae to airgun pulses in the context of the vulnerable Barent Sea ecosystem. Fisheries and Offshore Petroleum Exploitation. 2nd International Conference, Bergen, Norway, 6-8 April.

McCauley, R.D. Fewtrell, J., and Popper A.N. 2003. High Intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America 113: 638-642.

Moriyasu M., and C. Lanteigne. 1998. Embryo development and reproductive cycle in the snow crab *Chionoectes opilio*, in the southern Gulf of St Lawrence, Canada. Can. J. Zool. 76: 2040-2048.

Pearson, W.H., Skalski, J.R., Sulkin,S.D., and Malme C.I. 1994. Effects of seismic energy releases on the survival and development of zoeal larvae of Dungeness crab (*Cancer magister*). Mar. Environ. Res. 38: 93-113.

Popper, A.N. 2003. Effects of anthropogenic sounds on fishes. Fisheries 28: 24-31.

Turnpenny, A.W.H., and Nedwell, J.R. 1994. Consultancy report. The effects on marine fish, diving mammals and birds of underwater sound generated by seismic surveys. Fawley Aquatic Research Laboratories Ltd. 50 p.

Yelverton, J.T., Richmond, D.R., Hicks, W., Saunders, K., and Fletcher, E.R. 1975. The relationship between fish size and their response to underwater blast. Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico.

Table 1. Observations on Eggs and Larvae Exposed to Seismic Energy.

Organism	Life Stage	Exposure distance from airgun (m)	Observed response	Source	Sound Level	Reference
Anchovy	Eggs	0.5	7.8 % injury	5 liter airgun with working pressure of 140 atm		Kostyuchenko (1973)
		5	3.63 % injury			
		10	0 % injury			
Blue Runner	Eggs	0.5	3.7 % injury			
		5	2.9 % injury			
		10	0 % injury			
Crucian carp	Eggs	0.5	1.0 % injury			
		5	0 % injury			
		10	0 % injury			
Red Mullet	Eggs	0.5	0 % injury			
		5	0 % injury			
		10	0 % injury			
Commercial Fish	Eggs	0.5	75.4 % survival			
		5	87.7 % survival			
		10	90.2 % survival			
		Control	92.3 % survival			
Cod (*Gadus morhua)*	Eggs	1-10	No sublethal effects No survival differences	Airgun (Bolt 600B)	222.0 dB//1 µPa re 1m (source level)	Dale and Knutsen (1986)
	Larvae		No sublethal effects. No survival differences			
	Fry		Fry at 110 days had balance problems after exposure but recovered after few minutes			

Organism	Life Stage	Exposure distance from airgun (m)	Observed response	Source	Sound Level	Reference
Cod (*Gadus morhua)*	Fry 110 days old	1-10	Fry at 110 days had balance problems after exposure but recovered after few minutes. None killed.	Airgun (Bolt 1500C)	231.0 dB//1 µPa re 1m	Dale and Knutsen (1986)
Northern anchovy (Engraulis mordax)	Eggs	2 to 3	Yolk sac larvae most sensitive - reduced conditon. -35% reduction in survival for 4 day old larvae. -swimbladder larvae least impacted. -adults swimbladder damage	10 –40 cu in and 120-300 cu in (2000 psi)	235.1 to 233.8 dB re 1 µPa	Holliday (1987)
	Larvae					
	Adults					
Atlantic Cod	Larvae 5 days old	1 2 3 4	Retina delamination at 1 m	Airgun (Bolt model 190 CT)	Estimated 214-220 dB re 1 µPa	Matishov (1992)
Dungeness crab (*Cancer magister*)	Zoeal larvae	1	No significant effects	840 cu. in array	Up to 231 dB//1 µPa	Pearson (1994)
Cod	Eggs	0.75-6	No effect on mortality and hatching	Airgun	242 to 220 dB//1 µPa	Booman *et al.* (1996)
	Yolk Sac Larvae		No effect. No delamination in eyes			
	Larvae	5	Mortality rate higher than controls		223 dB//1 µPa	
	Post Larval Stage	0.75	Mortality rate higher than controls		235 dB//1 µPa	
	Fry	0.9	20% mortality Injuries to internal organs			

Organism	Life Stage	Exposure distance from airgun (m)	Observed response	Source	Sound Level	Reference
Saithe	Eggs	0.75	Increased mortality at early gastrulation.	Airgun	242 dB//1 µPa	Booman *et al.* (1996)
	Larvae		Large handling mortality make effects undetectable.			
Turbot	Larvae	3	Increased mortality.	Airgun	224 dB//1 µPa	
		0.75 -1.6	Brain injury. Free neuromast injury (lateral line effect).			
Herring	Larvae	0.75-6	No effect (high mortality in both exposed and control groups)	Airgun	242 to 220 dB//1 µPa	
Snow crab *(Chionoecetes opilio*)	Eggs	2	Seismic exposure retarded development of eggs. More dead eggs were found in the treatment group.	Airgun 40 cu. in.	216dB re 1 µPa	Christian *et al.* (2003)
	Adults		Increase in post seismic catches unrelated to seismic exposure. No difference in health variables related to seismic exposure.		201-227 dB re1 µPa1	