Marine Mammal Scientific Support Research Programme MMSS/001/11

USD 2:

Testing the hypothetical link between shipping and unexplained seal deaths

Sea Mammal Research Unit

Report to

Scottish Government

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1 Executive summary

This investigation was driven by the need to determine the cause of spiral lacerations in seals; a cause of death which has been reported with increasing incidence in the UK for the past decade. The purpose of this study was to demonstrate the ability of certain propulsion systems used on vessels to cause these types of injuries. The effect of animal size, propeller speed and propeller type on the occurrence of seal- propeller interactions was investigated. All trials were conducted with scale models of seals comprised of silicon rubber cores and wax outer layers.

A total of 59, 80 and 75 seal models were recorded and analysed for the ducted propeller, open propeller and Voith-Schneider propeller treatment groups respectively. Each propeller type was tested at four different rotation speeds and three model sizes representing different life stages were subjected to each speed. Only scale models which were subjected to a ducted propeller (a propeller fitted with a static housing) displayed characteristic injuries similar to those seen on stranded seals in the UK and Canada. Propeller speed was a significant factor in determining damage attributes, with slower speeds producing more spiral lacerations. Model size appeared to be unimportant in determining damage characteristics. Open propellers and Voith-Schneider propellers did not produce these patterns in any of the trials.

Ducted propulsion systems were the only mechanism which produced spiral lacerations under these test conditions. Consequently observations on candidate vessels are vital to gain a better understanding of the circumstances under which these interactions can occur in coastal regions. Viable mitigation can then be developed to reduce the number of cases and protect seal populations.

2 Introduction

The coastal distribution of seals around the UK inevitably exposes some populations to the possibility of interactions with anthropogenic activity, be it benign or harmful. Often the range of individual populations coincides with a high prevalence of anthropogenic activity ranging from small privately owned vessels to large commercial cargo ships, and offshore energy installations. This overlap increases the probability of potentially harmful interactions such as increased noise exposure (Richardson & Thomson, 1995) and direct collisions (Goldstein *et al*., 1999; O'Shea, Beck, & Bonde, 1985; Stroud & Roffe, 1979). To date analytical methods have been hampered by the unpredictable nature of these interactions and are largely restricted to observations of behavioural changes (Southall & Moretti, 2012) and, ante and post-mortem analysis of stranded individuals (Bexton *et al*., 2012; Goldstein *et al*., 1999).

One tool that has been used to assess such impacts is strandings monitoring, including necropsy to determine the cause of death. Strandings monitoring has been successful in identifying disease outbreaks in seals and can also determine whether animals have been killed through interaction with vessels. Necropsy analysis relies on tide, current and wind to allow carcasses to make landfall or drift into a coastal area where recovery and necropsy is realistic. This results in a high likelihood that the number of reported cases of harmful interactions is a gross underestimate (Laist *et al.*, 2001) and this must be taken into consideration when assessing detrimental effects of anthropogenic activity on marine mammals. Additionally, annual changes in the number of specific stranding reports cannot be directly related to prevalence of causal interactions unless physical mechanisms are identified, numbers of unreported individuals are estimated and reports are adjusted for effort.

This forms part of the reporting on USD2 (Unexplained Seal Deaths) within the Marine Mammal Scientific Support Research Programme MMSS/001/11. The report describes progress made to date in the investigation of potential mechanisms responsible for corkscrew injuries to seals with the aim of identifying the characteristics of the device that produce the wounds. Through a process of elimination ducted propellers appeared to be the most likely cause (Thompson *et al*., 2010, Bexton *et al*., 2012). The basis of this conclusion is described briefly below and the results of a series of trials to test the effects of passing scale models of seals through various scale modelled ship propulsion systems presented.

3 Background

In 2009 and 2010, both harbour (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals were found stranded on the coast of Fife and Tayside with fatal injuries consisting of a single continuous curvilinear skin laceration spiralling down the body. Marine Scotland commissioned the Sea Mammal Research Unit (SMRU) to investigate the causes and consequences of these traumatic deaths. The initial response to the appearance of these unusual mortality events and results of preliminary investigations were reported in Thompson *et al*., (2010). At that stage a number of severely damaged seal carcasses had been found on beaches in eastern Scotland (St Andrews Bay, Tay and Eden Estuaries and Firth of Forth), along the North Norfolk coast in England (centred on the Blakeney Point nature reserve), and within and around Strangford Lough in Northern Ireland.

3.1 Pathology

All of the seals had a characteristic wound consisting of a single smooth edged cut (Figure 1) that started at the head and spiralled around the body (Figure 2). In most cases the resulting spiral strip of skin and blubber was detached from the underlying tissue. The wound was identified as the cause of death in all cases for which a detailed post mortem examination was carried out. Post-mortem examinations of 20 harbour seals revealed they had been alive and healthy when the injuries were sustained, with no evidence of any underlying disease or disability (Bexton *et al*., 2012).

Figure 1. Photograph of the wound on a juvenile harbour seal. The smooth edged cut through the skin and tearing of the blubber by a lateral shearing force was common to all carcasses examined.

Figure 2. Harbour seal juvenile showing typical spiral wound. Collected in the Eden estuary in St Andrews Bay, July 2009.

The wound patterns were the same in necropsied seals found in Norfolk (RSPCA, and Animal Health and Veterinary Laboratories Agency), Scotland (Scotland's Rural College) and Northern Ireland (Agri-Food and Biosciences Institute). Post-mortem findings from all three areas are presented in Bexton *et al.,* (2012) and are summarised below (Table 1). A total of 20 harbour seals from these areas were the subjects of thorough necropsy. The proportion of animals exhibiting each characteristic is shown in Table 1. Eight seals were x-rayed and four subjected to detailed histopathological examination.

Table 1. Summarised necropsy results from 20 seals (12 from Norfolk, 4 from Scotland and 4 from Northern Ireland) (Bexton *et al*., 2012).

1.	Continuous helical skin laceration originating at the head and spiralling down the body terminating between the ribcage and pelvic area (corkscrew wound)	20 (100%)
2.	Skin and blubber sheared from the underlying fascia with connective tissue attachments torn caudo-laterally	20 (100%)
3.	Scapular attachments to the axial skeleton severed and the fore flipper partially de-gloved	18 (90%)
4.	Wound edge smooth and perpendicular or angled slightly caudally to the axis of the body, with hairs immediately adjacent to the wound uncut	20 (100%)
5.	Bruising, notably to the neck, thoracic inlet, and/or sternum consistent with blunt trauma to the chest area	9 (45%)
6.	Animals in good physical condition with adequate blubber reserves	18 (90%)
7.	Food remains in the stomach consistent with recent feeding activity	10 (50%)
8.	X-ray confirmation of the absence of foreign material such as metal fragments, hooks, gunshot, or embedded tooth fragments	8 (100% of those radiographed)
9.	Absence of any additional significant gross pathological changes indicative of underlying disease or injury	20 (100%)
10.	Absence of any significant histopathological changes	4 (100% of those examined)
11.	No significant tissue loss associated with wounds	20 (100%)
12.	Lesions to the head, including slice wounds on the muzzle or skull fractures with lesion orientation consistent with a frontal impact	19 (95%)
13.	Patterned injuries comprising a series of linear or triangular wounds or abrasions 15 mm in length and 12 to 15 mm apart	5 (25%)

Based on the pathological findings it was concluded that mortality was caused by a sudden traumatic event involving a strong rotational shearing force (Bexton et al 2012). The extremely neat edge to the wound strongly suggested the effects of a blade with a smooth edge applied with considerable force, while the spiral shape of the wound was consistent with rotation about the longitudinal axis of the animal. The separation of a large section of the skin and blubber layer from the front of the carcass and avulsion of the shoulder blades in most cases, was evidence of the application of a powerful lateral force pushing the body past a rotating blade.

By a process of elimination the initial investigations concluded that the injuries were consistent with the seals being drawn through a ducted propeller such as a Kort nozzle or some types of Azimuth thrusters. No other mechanism with the required characteristics could be identified at any of the locations where these strandings were reported. Such systems are common to a wide range of ships including tugs, self- propelled barges and rigs, various types of offshore support vessels and research boats. All the other explanations of the injuries that have been proposed, including Greenland shark predation (Lucas *et al.*, 2010), are difficult to reconcile with actual observations and, based on the evidence to date, seem very unlikely to have been the cause of these mortalities.

Although persuasive, the identification of ducted propellers as the only plausible mechanism of injury remained speculative and required confirmation either through direct observation of mortality by a device or a clear demonstration that such wounds can be inflicted on seals by ducted propulsion systems such as azimuth pod drives or ducted bow thrusters.

The absence of observations of animals approaching or being drawn through propellers in the field implies that the events are either difficult to observe or occur under conditions where no-one is available to witness them. It was therefore determined that an experimental approach using scale models of propellers and seals was the most appropriate. The specific aims of these trials were to determine:

a) What damage would be sustained to seal models drawn into fast spinning boat propellers; and

b) Whether damage similar to documented spiral laceration cases could be inflicted by any of the test propulsion systems.

4 Methods

4.1.1 Scale models of seals

Under a research agreement with a marine propulsion engineering company (VOITH Turbo, Germany), an initial series of tests using different scale models of seals with different materials and a range of sizes were carried out. In collaboration with VOITH's engineers and fluid dynamics group, a range of prototype seal models using flexible RTV silicone to represent the body core and a low melting point, petroleum based wax to represent the sculp (skin and blubber layer) were developed (Figure 3) . Preliminary versions of these seal models were tested in a simplified test rig comprising an electrically driven outboard engine fitted with a plastic propeller. Initial results suggested that the wax layer behaved in a similar fashion to the sculp of seals with corkscrew injuries. In addition to cutting and peeling in a manner similar to the recorded injuries, the wax layer retained an imprint for all impacts, including those that did not cause cuts or splits in the seal model (Figure 4).

Figure 3. Scale replicates of (a) a juvenile grey seal body core and (b) a juvenile grey seal with a blubber layer. The body core measure 13 cm in length.

Figure 4. An example of a scale model of a swimming juvenile grey seal showing marks of a low impact collision which did not produce characteristic corkscrew lesions. The pointer indicates the position of an indentation in the wax coating caused by a collision with a straight bladed propeller.

Based on these results accurate 3D CAD seal models based on morphometrics from juvenile grey seals photographed in a swimming flume were developed. These CAD seal models were used to produce a series of seal models of similar shape but different scales using a 3D milling machine. Moulds of these CAD seal models were used to produce the silicone cores. Wax layers were added by dipping the cores repeatedly in molten wax. The silicone material used for the core of the seal models was chosen to mimic the flexibility and resilience of a seal carcass, but was relatively easily cut (See Figure 8 for photographic example of sustained cuts into seal model cores). To investigate the observed narrow size range of seals found with spiral lacerations, three seal model sizes were used (small, medium and large), representative of three broad life stages: young, adolescent and adult. Propeller size remained constant throughout. Results could therefore additionally be interpreted from the perspective of small to large propulsion systems.

4.1.2 Preliminary trials

A series of preliminary tests were carried out in a flume tank at VOITH's research facility, Heidenheim, Germany to assess the feasibility of the proposed experiments. Seventy-seven trials were carried out in which seal models representing a range of different sizes were released upstream of an engineering scale model of a ducted propeller (an Azimuth pod drive system). This comprised a straight bladed propeller, within a 20 cm diameter clear Perspex duct.

The initial results were highly variable and a high proportion of seal models, especially large models, jammed against the front of the propeller. Those which went through had single lacerations, in some cases these were curving single lacerations similar to the corkscrew wounds, but the cuts were all relatively short with none longer than half the circumference of the model. The seal models which jammed against the front of the blades were thought to pose a damage risk to the propeller engineering model, so the trials were suspended to allow further investigation in a simplified rig using a much less expensive plastic propeller.

The propeller used in the initial trials was a new design, with straight leading edges. Further trials with similar seal models were carried out using simpler propellers with both straight and convex curved leading edges. The result with straight edge blades was similar to the trials with the engineering scale model propeller, with a large proportion of the seal models becoming "stuck" on the leading edge and no evidence of spiral lacerations on the few examples that passed through. During trials with the simplified curved blade, all seal models passed through and sustained spiral lacerations. This resulted in an adaptation to the experimental design with engineering model propellers to incorporate a convex curved edged blade.

4.1.3 Trial protocols

Twelve treatment groups comprised two hundred and fourteen trials, carried out using three different propeller types: a curved leading edge 3-blade propeller within a clear Perspex duct (ducted propeller), a curved leading edge 3-blade propeller without a duct (open propeller) and a Voith-Schneider propeller (VSP). Each propeller type was run at four different speeds. Speeds were set ensuring thrust changes were standardised across the three propeller types i.e. each propeller type was tested using the same four thrust values. The RPM required to achieve the same thrust was reduced for the VSP compared to the ducted and open propellers. These three propeller types were chosen to represent those in use across the breadth of the shipping industry.

The ducted and open propellers both had diameters of 210 mm. With constant blade length, the different sized seal models allowed evaluation of the effect of animal size on inflicted damage. Model length and axial girths are given in Table 2. Scaling the propeller up to full size of 1700 mm diameter, gives a ratio of approximately 1:8, and this was used to scale up the seal model sizes (Table 2).

Table 2. Model sizes and associated scaled up measurement assuming a propeller diameter of 1700 mm.

Seal model Size	Length (mm)	Axial Girth (mm)	Scaled length (mm)	Scaled Axial Girth (mm)
Small	90	80	728.57	647.61
Medium	130	110	1092.85	890.48
Large	160	130	1295.23	1052.38

All trials with engineering scale model propellers were carried out in the test tank at VOITH. The propeller under test was suspended under a fixed model boat hull and held rigidly in place (Figure 5). All trials were recorded using two video cameras. A high speed camera (400 frames per second) was positioned at 90^o to the water flow to provide slow motion close up images of the seal model as it passed through the propeller and a standard speed (30 frames per second) underwater video was positioned to provide an image along the direction of flow, giving a view of front of the propeller. All seal models were numbered and photographed to record all marks on the wax layer.

Prior to the trials the seal models were kept in a warm water bath at approximately 30^{0}C which ensured that the wax was soft and flexible on each trial run. In each trial the propeller was set to rotate at a pre-determined speed and allowed to run for more than 20 seconds to ensure that flows were relatively stable in the tank. Seal models were then released in front of the propeller via a launch tube comprising a large bore 2 m long clear Perspex pipe (Figure 6). A water reservoir 1 m above the surface of the flow tank provided a pressure head which, when released propelled the seal model along the tube. By controlling the rate at which water was released, the speed of the seal model could be controlled. In practice the resulting speed was variable between approximately 0.5 and 2 body lengths per second which equates to the range of swimming speeds exhibited by harbour seals during transit swimming and in foraging dives (Davis *et al*., 1985; Thompson *et al*., 1993; Gallon *et al*., 2007).

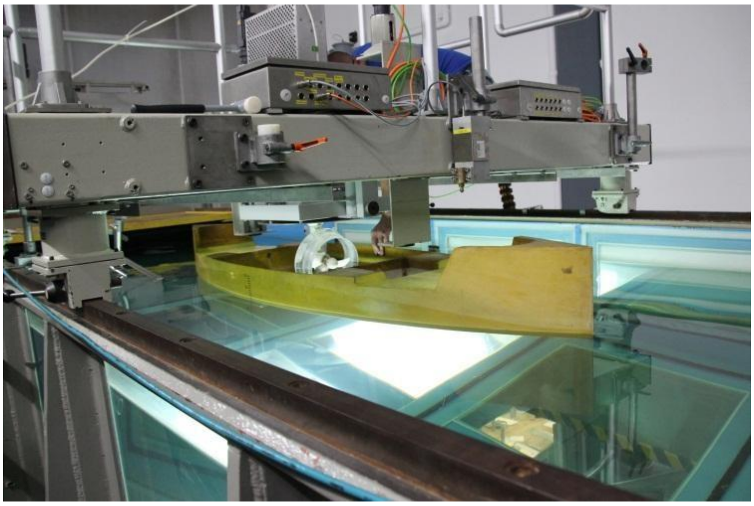

Figure 5. Propeller test rig at VOITH engineering laboratory, Germany. The model boat hull is shown before being lowered into the tank with a Kort Nozzle propeller being lowered through the hull.

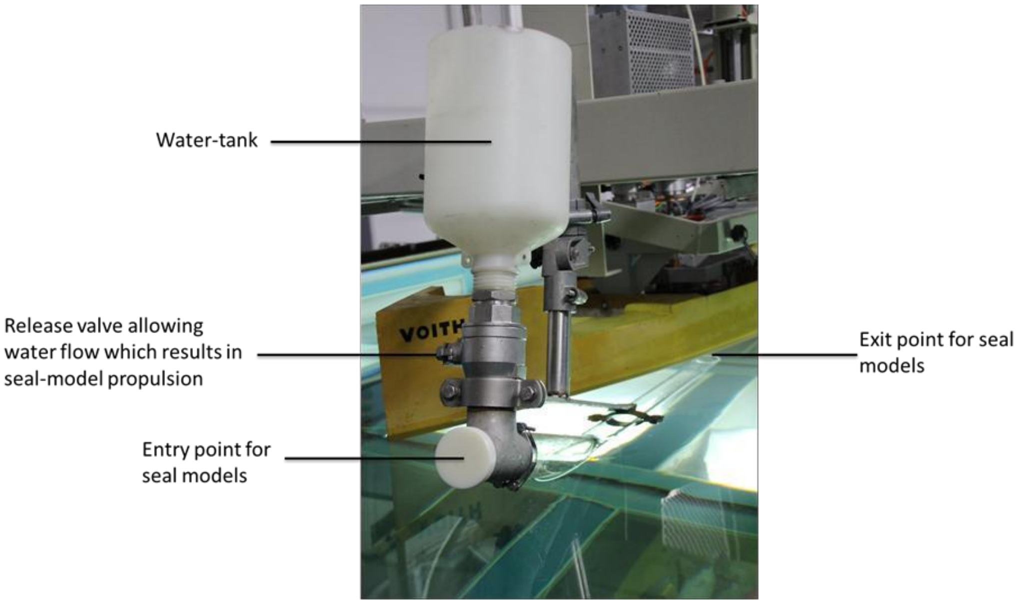

Figure 6. Seal propulsion pipe

Although the tests were carried out in a flume tank the pump was not used so there was no background flow in the system; all flows observed during the trials were the result of the propellers under test. Thus all trials were equivalent to tests of either stationary or slow moving vessels with seal models approaching the propellers at speeds approximately equivalent to typical seal swim speeds of between 1 and 2 m.s^{-1}. Water flow was removed from the system as the vessels which typically have ducted propulsion systems often operate in coastal regions at slow speeds. Furthermore ducted propellers are indicative of dynamic positioning systems and water flow during these periods would be very low. Finally fast moving vessels would be would be less likely to result in interactions as the maximum speed for a grey seal is under 3 m.s.$^{-1}$ (5.83 knots, Gallon *et al*., 2007).

Propeller speed was controlled through a central computer, to allow adjustments between individual trials. Acceleration phases for the motor were short, and the propellers were rotating at the pre-set speed before the seal models were released.

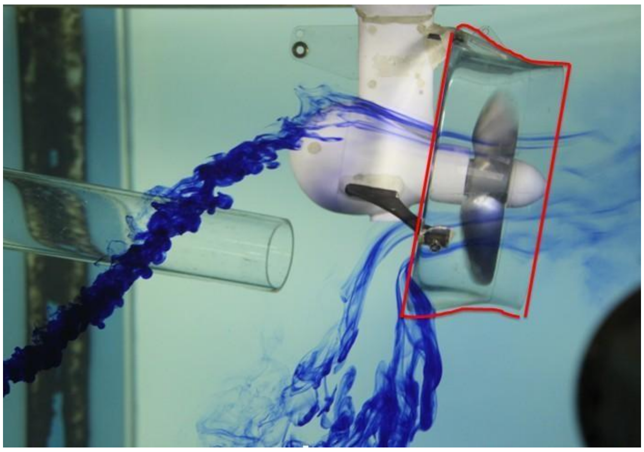

Figure 7. The scale model propeller in a clear Perspex Kort nozzle (outlined in red). The ink traces show the general flow patterns through the nozzle.

Figure 7 shows the propeller in the transparent Perspex duct. Blue ink introduced in front of and below the nozzle shows the general flow pattern. It is interesting to note that although the ink is clearly drawn towards the entrance to the propeller duct, there is no sign of rapid acceleration of flow until the ink stream is within a range approximately equivalent to one propeller diameter. This clearly demonstrates that objects are not drawn rapidly into the propeller from long ranges.

4.1.4 Statistical analysis

Two hundred and fourteen individual seal models were used in the three different experimental set-ups using a range of propeller types. Each seal model was examined by two observers before and after each trial to identify any signs of impact damage. Those with any visual signs were photographed and the damage was assessed against the criteria in Table 1. The scores were given a weighting which produced a hierarchical system whereby injury patterns considered more typical of the injuries observed in the wild received a higher score. Due to the structural limitations of the seal models, attributes involving skeletal trauma and appendage damage were not included. Examples from this experiment are presented in Section 5.

For each characteristic in Table 2, a score of one was allocated if this was present and a score of zero was allocated if it was absent. This produced a binary score for each characteristic, for every trial. A weighted score was then calculated based on how commonly the characteristic was seen on stranded seals determined to have died as a result of blunt force shearing trauma. Binary scores were multiplied by the weighting index and the three resulting scores were summed to produce a weighted score. The weighting system is detailed in Table 3.

Table 3. The scored characteristics and associated weighting index multiples

Characteristic	Weighting Index
A single linear lesion comprising one or more rotations	5
Smooth edge wound	3
Blubber layer peeled away from the core	2
Lesion beginning at the mouth	1

The first analysis used a binomial generalised linear model (GLM), to assess whether propeller type, speed or seal model size affected the production of any of the spiral laceration characteristics. The response variable was the binary index indicating positive confirmation of any of the characteristic attributes. Large seal models were not included for this analysis as none were used in the ducted propeller treatment group and therefore interaction terms could not be assessed. This was because large seal models consistently became jammed between the nozzle and propeller during trials so testing on them was abandoned. Propeller type was ultimately removed from the model due to the fact that both open propeller and Voith-Schneider propeller treatment groups were comprised solely of zeros and consequently there was an inability of the model to calculate the variance. A non-parametric Chi-squared test between the propeller type treatment groups was used to assess whether the binary index scores were taken from statistically different samples. This is because it was noted that positive scores were apparent in the binary index of the open propeller treatment group before large seal models were removed and the data were distributed binomially so a non-parametric test was required.

The second analysis, of the effects of propeller speed and model size within the ducted propeller trials used a negative binomial GLM. This propeller type was investigated in more detail since it was the only type to consistently produce any characteristic lacerations. A negative binomial family was used to account for over dispersion caused by many zeros in the data. Other models trialled (gamma family and zero inflated Poisson) fitted the data less well.

5 Results

During a total of 214 formal trials and a large number of ad hoc trials during preliminary testing, all the seal models either passed through or in some cases became stuck to the front of the propeller. The only examples of seal models being cut through to the core were instances where the seal model was rolled against the main support strut for the duct (Figure 7 and Figure 8).

Figure 8. Examples of cuts to the silicone core of seal models resulting from blade impacts

5.1 Final trials

A total of 59, 80 and 75 seal models were recorded and analysed for the ducted propeller, open propeller and Voith-Schneider propeller treatment groups respectively (Table 4). The ducted propeller treatment group exhibited a greater number of individuals displaying any characteristic injuries than either the open propeller or Voith- Schneider propeller treatment groups (Table 5). This trend could be seen when comparing propeller speeds and model sizes between propeller types with the exception of large models which were not included in the ducted propeller analysis. Furthermore no spiral lacerations (the most heavily weighted scoring criteria) were observed in either the open propeller or Voith-Schneider propeller treatment groups (Table 5).

Table 4. Number of trials in each treatment group. Size is indicated by an S, M or L to denote small, medium and large seal models respectively. Ranked propeller speeds are denoted by the integer values between 1-4. Lower integer values denote the slower speeds. No trials were carried out with large seal models and ducted propellers because in all attempts, the seal models stuck to leading edge of the propeller.

Propeller type	**Seal model size (ranked propeller speed)**												**Total**
	S(1)	***S(2)***	***S(3)***	***S(4)***	***M(1)***	***M(2)***	***M(3)***	***M(4)***	***L(1)***	***L(2)***	***L(3)***	***L(4)***	
Ducted Propeller	7	***9***	***8***	***7***	***7***	***7***	***7***	***7***	***0***	***0***	***0***	***0***	**59**
Open Propeller	6	***6***	***6***	***6***	***7***	***7***	***6***	***6***	***7***	***7***	***8***	***8***	**80**
Voith-Schneider Propeller	6	***6***	***6***	***7***	***6***	***7***	***6***	***6***	***7***	***6***	***6***	***6***	**75**

Table 5. Percentage of cases displaying any characteristic attributes for each treatment group.

Propeller type	**Ranked propeller speed**				**Seal model size**			**Mean weighted score**
	1	**2**	**3**	**1**	**Small**	**Medum**	**Large**	
Ducted Propeller	78.57%	75%	33.33%	21.43%	51.61%	53.84%	N/A	5.19
Open Propeller	0%	0%	0%	15%	0%	0%	15%	0.045
Voith-Schneider Propeller	0%	0%	0%	0%	0%	0%	0%	0

Table 6. Percentage of cases displaying single curvilinear lesions rotating at least once around the body; the most heavily weighted criteria.

Propeller type	**Ranked propeller speed**				**Seal model size**		
	1	**2**	**3**	**4**	**Small**	**Medium**	**Large**
Ducted Propeller	78.57%	75%	26.67%	0%	51.61%	42.86%	N/A
Open Propeller	0%	0%	0%	0%	0%	0%	0%
Voith-Schneider Propeller	0%	0%	0%	0%	0%	0%	0%

5.2 Ducted propeller

All seal models passing through the ducted propeller at 200 rpm and 400 rpm which demonstrated any characteristic damage received single curvilinear lesions (see example in Figure 9 and Figure 10). Lower proportions received characteristic lesions at higher propeller rotation speeds (Table 5). No single curvilinear lesions were seen at 1200 rpm (ranked propeller speed 4) however 21.43% did receive at least one characteristic injury at this speed.

Interestingly, the rotation of some of the seal models against the duct wall and the angle of the blades meant that the blade cut towards the front of the model. Fourteen seal models out of twenty-nine (48.28%) demonstrated this pattern. This is in contrast to the pathology of corkscrew cut seals where the cuts appear to start at the head, usually the face and progress backwards along the seal.

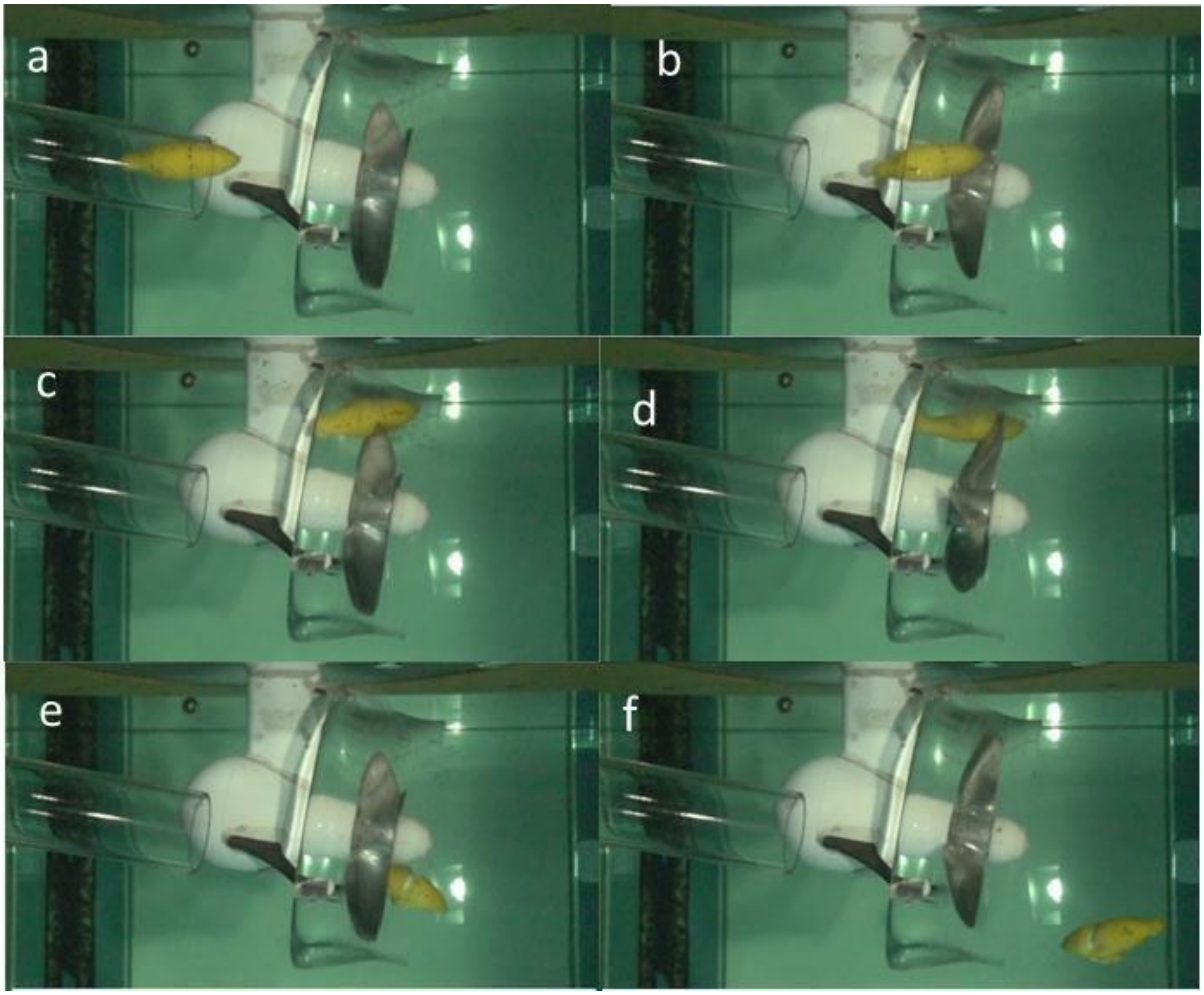

Figure 9. A sequence of still images from a high speed video of a seal model passing through the blades of a propeller in a Kort nozzle. In image (a) the seal model is shown leaving the launch tube, travelling at approximately 1.5 body lengths per second. In image (b) it accelerates into the gap between two blades before being hit by the following blade and pushed against the Kort nozzle in (c). In image (d) the blade can be seen cutting into the wax layer and in (e) the seal model has been rotated against the blade as it rolled around the inside of the Kort nozzle before being expelled in (f).

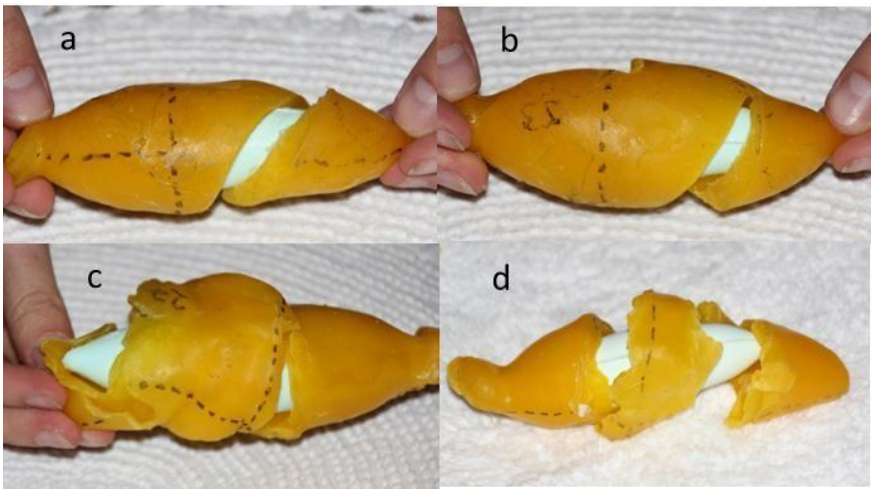

Figure 10. Damage resulting from replicates passing through a Kort nozzle. Figures 10a & 10b are images of the model shown in Figure. Note the damage comprised of a single smooth edged slice that cut through the wax layer and continued around the seal model in a spiral that rotated through approximately 450o. Images (c) and (d) show other examples of the damage resulting from the ducted propeller.

5.3 Open propeller

No seal models received characteristic damage in the three slowest propeller speeds (Table 5). Of the seal models subjected to the fastest propeller speeds, 15% demonstrated any characteristic damage, but none demonstrated a single curvilinear lesion (the most heavily weighted criteria). Large seal models were the only size class demonstrating any characteristic damage. Most trials resulted in individuals being knocked away from the propeller after a single strike or being rotated 180^0 along the dorso-ventral axis upon initial impact and then being knocked away from range of the propeller by the second strike (see examples in Figure 11, Figure 12 and Figure 13).

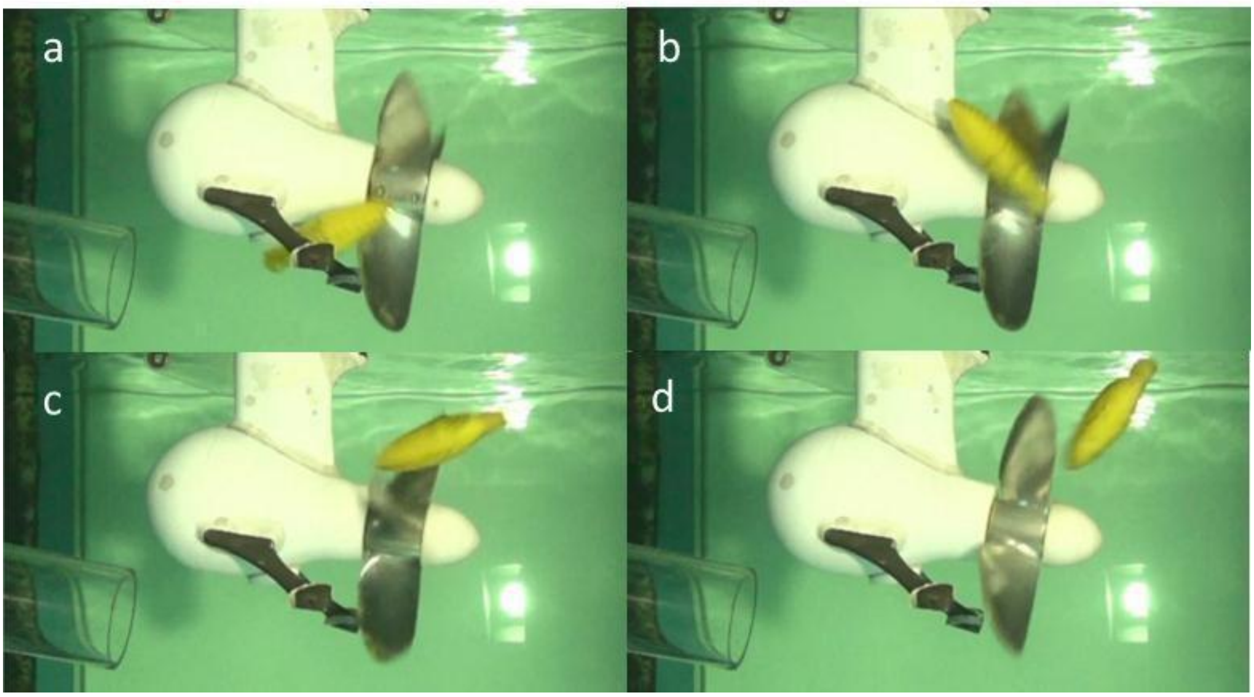

Figure 11. A sequence of still images from a high speed video of a seal model passing through the blades of an open propeller, the same seal model as used in the Kort nozzle. In this trial the propeller was rotating at a medium speed of 600 rpm. In image 11(a) the seal model is shown accelerating into the gap between two blades, close to the centre of the propeller, and being hit by the following blade. In image 11(b) the seal model is shown having been flipped through $180^0$and is now passing backwards and spinning. In image 11(c) the seal model has been struck by the following blade but has now been pushed to the edge of the propeller and in 11(d) it has been expelled.

Many of the seal models passing through the open propeller received superficial wounds, often resulting from multiple blade impacts. Twelve trials, all at 1200 rpm, resulted in wounds which cut through the wax layer. In five of these cases, the seal model jammed against the struts of the main support of the propeller and suffered additional tear wounds. These wounds can be assumed to be fatal damage given the depth and severity of the lacerations.

Figure 12. An example of damage resulting from a model passing through an open propeller. Note three separate impact marks: one indicated by the pointer, one on the front of the seal model and one at the rear. None of them resembled a spiral, curving wound and all were notably superficial with none cutting deeply into the wax layer.

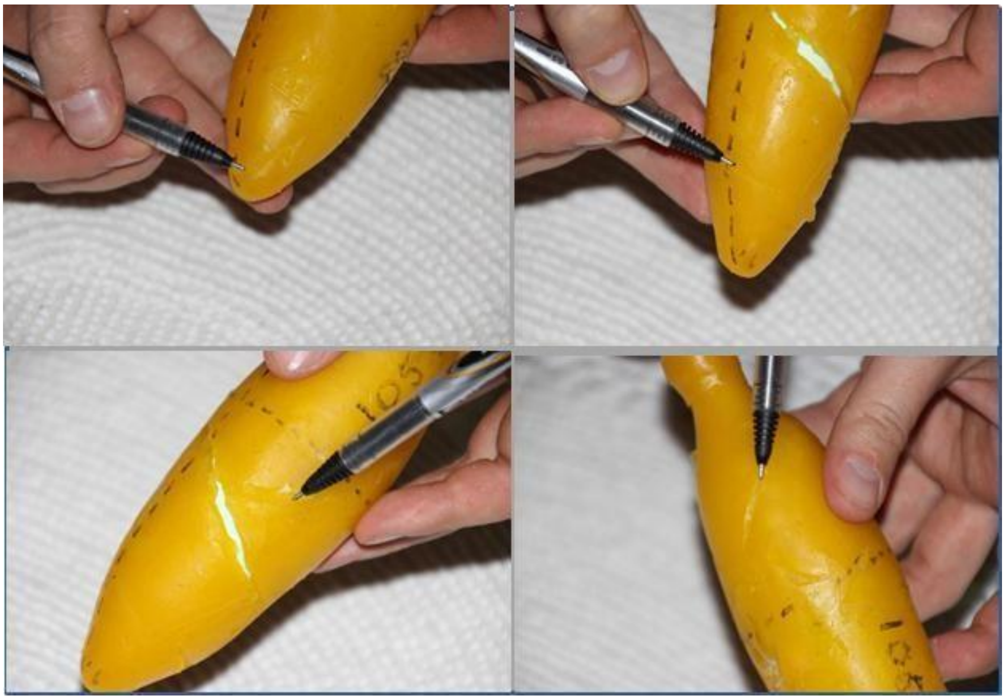

Figure 13. Multiple slice wounds, at different orientations due to passage through an open propeller.

5.4 Voith Schneider propeller

No characteristic lesions were observed on any seal models passing through the Voith- Schneider propeller. Many of the seal models received only superficial wounds, often resulting from multiple blade impacts. However, unlike the previous two mechanisms, no models tested with the Voith-Schneider propeller showed any visible signs of significant impact and did not demonstrate deep slicing damage. Seal models often received multiple blade impacts however were invariably knocked out of range of the rotating propeller and into the wake without sustaining significant or observable damage (Figure 13 and Figure 14).

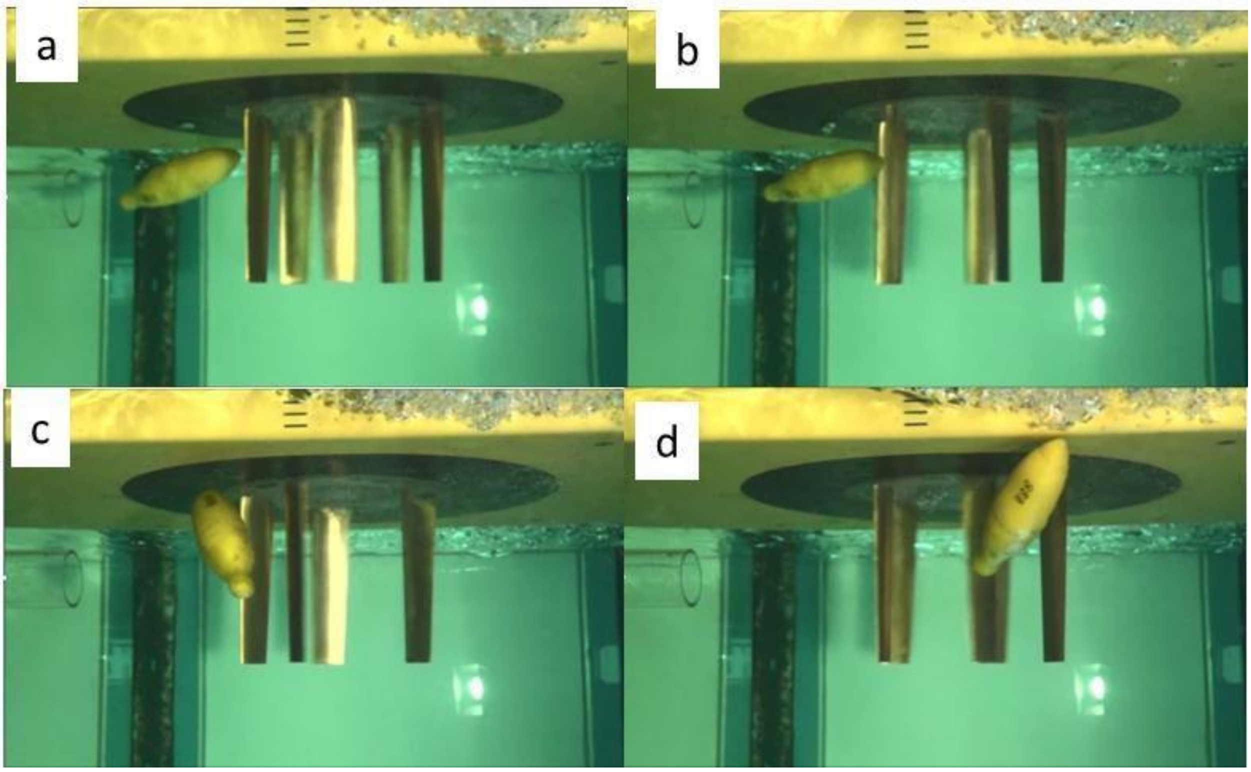

Figure 14. A sequence of still images from a high speed video of a seal model passing through the blades of a Voith Schneider propeller. In this trial the VS drive was at maximum rotation speed of 320 rpm. In image (a) the seal model is shown accelerating towards the blades and has started to turn in the direction of rotation. In image (b) the seal model has continued to turn in the direction of rotation and is shown being struck on the front by the blade. As a result of the impact the seal model has been flipped through 180^{o} and is now moving backwards and is struck by a second blade pushing it away from the VS drive (c). In (d) it has moved clear of the blades.

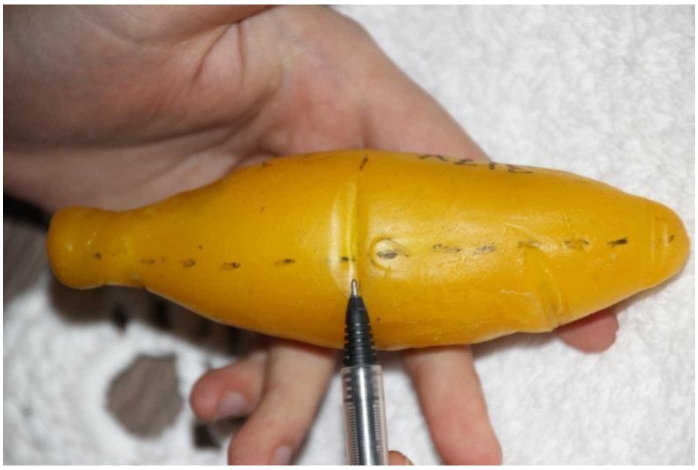

Figure 15. Figure shows the damage inflicted on the seal model by the collision with the Voith-Schneider Propeller

6 Data extraction and analysis

The scoring system (referred to in Section 3.1) provided two indices for each individual trial: a binary index score which highlighted which individuals demonstrated any of the characteristic marks, and a weighted index of how typical the damage to the individual was compared to the necropsy data.

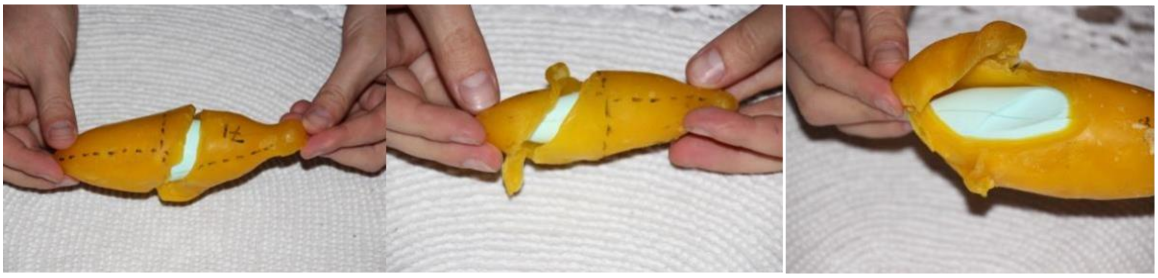

Figure 16. Examples of three differently weighted individuals. (a) the seal model demonstrated a single spiral lesion and peeling of the “blubber layer” however the lesion began mid-way down the “body”. (b) the seal model demonstrated all three characteristic markings. (c) The seal model demonstrated a lesion which began anteriorly and the “blubber layer” shows signs of peeling however a single spiral lesion was absent.

The Chi-squared test confirmed that the production of any of the attributes was affected by propeller type (χ^2= 15.52, p = <0.001). No trials within the Voith Schneider propeller treatment group displayed any characteristic attributes and so were excluded from further analysis; all quantitative results in this treatment were equal to 0. A demonstration of this result can be seen in the histogram in Figure 17.

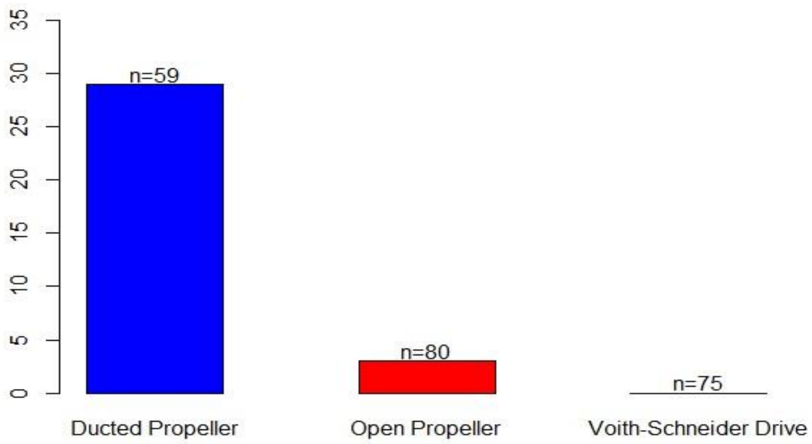

Figure 17. Histogram of the number of trials yielding a binary index score of one by propeller type.

Binomial GLM output showed propeller speed to be a significant predictor of production of any characteristic marks, between treatment groups (z = -3.285, p = <0.005) while seal model size did not appear to effect the outcome (z = 0.353, p = 0.724). Model results are summarised in Table 7. However, it must be noted that large seal models were excluded from the analysis because of the limitations of the experimental set-up. The response variable for this model was the binary index which, for each trial, was either 1 or 0 depending on whether the seal model incurred any of the characteristic attributes. The model predictors were propeller speed and seal model size.

The negative binomial GLM demonstrated that propeller speed significantly affected the weighted score in the ducted propeller treatment group (Table 8). Slower speeds produced more characteristic wound patterns than faster speeds with maximum rpm yielding no examples of single linear lesions comprising one or more rotations; the attribute with the largest weighting index (Figure 18). Changes in seal model size had no effect on the weighted scores (table 8). Fitted values from the negative binomial GLM are demonstrated in Figure 19. Confidence limits for weighted index values can be seen to overlap with regards to model size (Figure 19). This further supports the result that model size is not a good predictor of wound patterns. For both medium and small model sizes, weighted index can be seen to decrease from initially high values to zero at 1200 rpm. Furthermore, as propeller speed increases, weighted index values for both sizes begin to converge.

Table 7. Coefficients of the Binomial GLM. The response variable was the presence or absence of any characteristic attribute (detailed in table 2). The model included small and medium seal models from all three propeller type trials.

	Estimate	Standard error	z-value	Pr(>|z|)
Intercept	0.449	0.54	0.825	0.409
Ranked RPM	-0.705	0.21	-3.285	0.001
Model Size	0.162	0.45	0.353	0.724

Table 8. Coefficients for the negative binomial GLM

	Estimate	Standard error	z-value	Pr(>|z|)
Intercept	2.824	0.282	10.007	<0.001
Ranked RPM	-0.003	0.001	-6.832	<0.001
Model Size	0.285	0.233	1.223	0.221

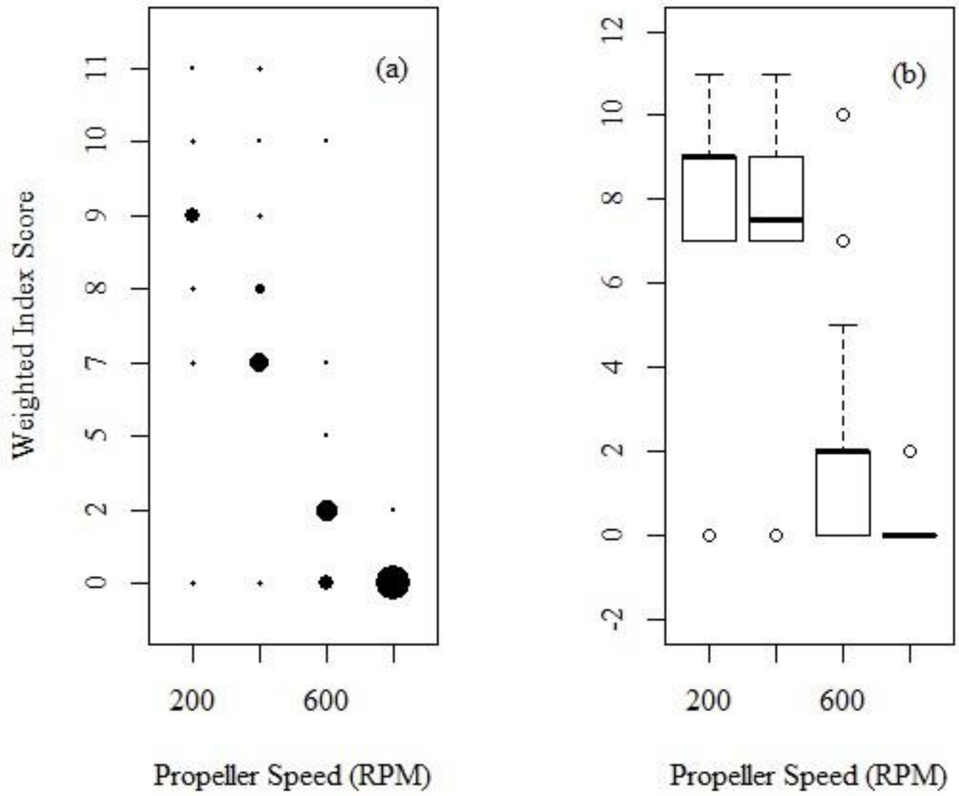

Figure 18. (a) Dot plot demonstrating the weighted index scores as a function of propeller speed in the ducted propeller treatment group. The size of the dot indicates the number of trials in that value. (b) Boxplot of weighted scores against propeller speed. A significant distinction between propeller speeds of below 400 RPM and above 600 RPM can be seen suggesting a threshold value of between 400 and 600 RPM under which characteristic corkscrew lesions are more likely.

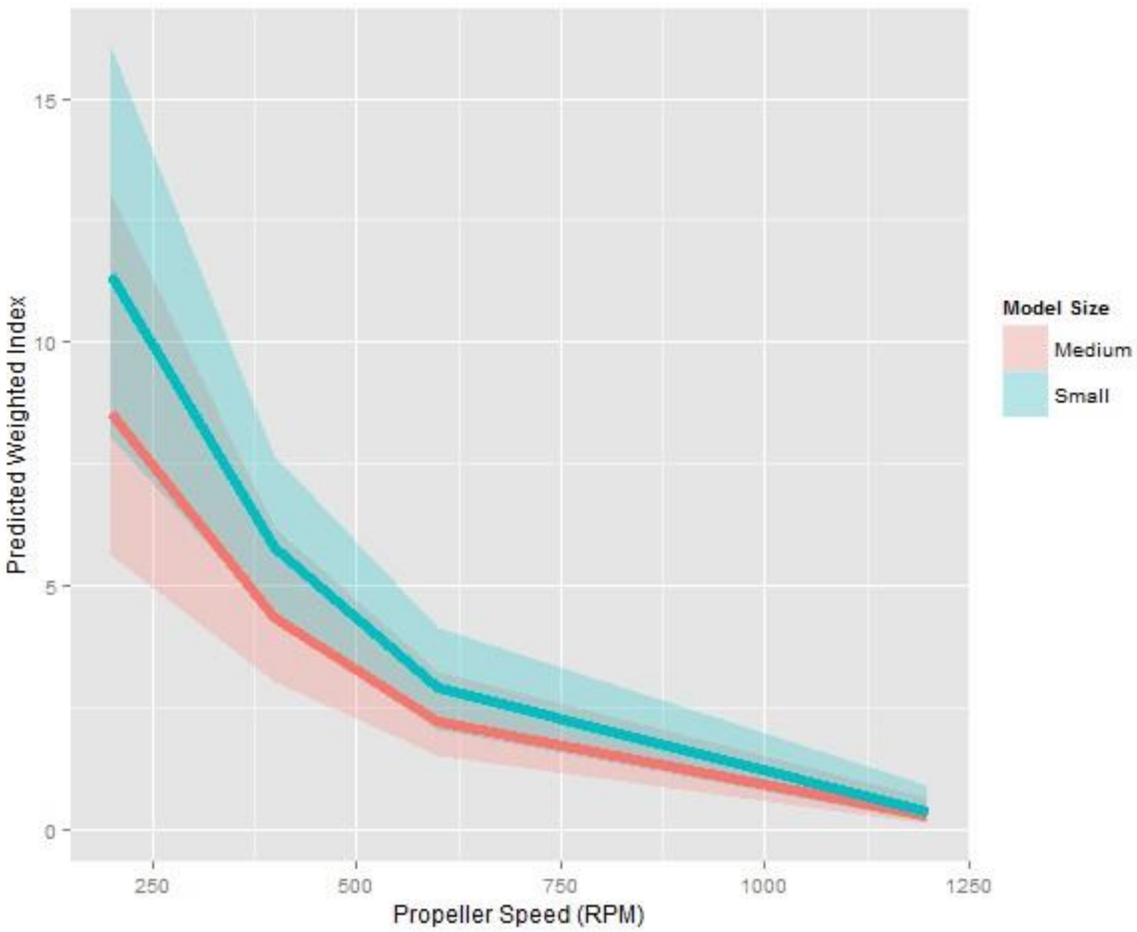

Figure 19. Fitted weighted index values from negative binomial regression.

7 Discussion

On the basis of these analyses there seem to be clear differences in the damage caused by the different devices. A large proportion of the ducted propeller trials produced spiral lacerations similar to the corkscrew wounds on seals, particularly at the lowest propeller speeds tested. Open propellers produced impact marks that were much less severe, and cuts were only apparent at high propeller speeds. Trials with the Voith Schneider propeller produced few marks at low speed and never produced cuts that penetrated through the outer wax layer. When subjected to the Voith-Schneider propeller at the highest speeds no additional markings were produced on the models, in all cases.

The majority of seal models passed through the various mechanisms and remained essentially intact. As only 34 out of the 214 trials yielded significant, characteristic lesions (with a further 12 demonstrating inferred 'fatal' damage) the result suggests that seals may be able to pass through fast spinning ship propellers without sustaining serious damage. Indeed, passing through faster rotating propellers appeared to be less detrimental to the model seals with less overall damage than when passing through slower rotating propellers. It must be noted that only wound patterns and superficial damage could be assessed here and skeletal trauma and internal damage such as haemorrhaging cannot be inferred. The silicone cores and wax coverings will not behave in exactly the same way as a seal's body when hit by a propeller blade. However, the fact that the silicone was flexible and relatively easily cut would seem to suggest that streamlined objects of similar flexibility and resilience could pass through propellers of similar relative sizes without being severely lacerated. The fact that some size/speed combinations produced spiral lacerations in a proportion but not all trials may indicate that there are further criteria which govern the interaction outcomes that were not controlled for in this experiment. Therefore, while it has been demonstrated that ducted propellers were able to produce these wounds and that open propellers and Voith Schneider drives did not, the frequency at which this occurs is still uncertain and what other variables could be important in determining the outcome of interactions. Given the fact that the outcome differed between seal models which were introduced to the experiment in an identical way, it may be that behavioural responses affect wound production in real seal-vessel interactions. Behavioural factors, as well as morphology, will be subject to individual variation and possible differences such as avoidance strategies, swim speed and body condition could alter the mechanism of interaction. Unfortunately this range of factors is difficult to replicate in its entirety under laboratory conditions and real-time observations would be required to assess these variables.

Interestingly, in the ducted propeller trials the behaviour of the seal models and the resulting damage patterns were different for a curved bladed propeller compared to a straight bladed propeller, with no clear spiral lesions inflicted by the straight blades. Where a model is stuck on the propeller blade it must still be assumed that this would equate to fatal damage due to the depth of the wound and the fact core damage is almost always observed. However this was an incidental observation during the initial development of the trial protocols. It warrants further investigation as it may indicate that only certain ducted propellers will inflict spiral lacerations. A proportion of the seal models passing through the ducted propeller at high rotation rates and through the open propeller at slow rotation rates suffered only superficial indentations in the wax layer. Clearly such damage is less severe than full thickness lacerations through the wax layer, but the indentations may indicate impacts that could have caused internal injuries when scaled up to real seals and propellers. While it is risky to extrapolate from damage to the wax layers up to actual wounds on real seals, the fact that the real, characteristic spiral lacerations rarely involve any skeletal damage would suggest that less violent impacts producing no cuts are unlikely to cause skeletal damage. Many such impacts are therefore likely to be survivable unless the animal is rendered unconscious.

Large seal models introduced to the ducted propeller invariably became stuck in the system and did not pass through into the wake. Initial blade impacts showed frontal damage in all cases, with some wounds penetrating as deep as the seal model core. While these trials were discontinued to prevent damage to the engineering models, this is a result which requires further investigation. Almost all spiral-cut seals found around the UK have been either adult harbour seals or juvenile grey seals (Thomson *et al*,.2010; Bexton *et al.,* 2012) indicating a size threshold may exist, above which spiral lacerations are highly unlikely with the vessels active in inshore waters. Given the largest axial girth measured on a spiral cut seal in the UK is 1280 mm, the scaling ratio in these trials would suggest a propeller diameter of no less than 2443 mm would be necessary to cause characteristic spiral lacerations in these larger animals. Smaller individuals would not require such large diameters to display these damage patterns therefore these data would suggest a range of vessels are potentially involved in these interactions. Given the size threshold for spiral lacerations lies between medium and large seal models, in this experiment it can also be inferred which individuals would be susceptible to spiral lacerations for a given propeller size. For example, as the scaling ratio in table 2 suggests, the threshold would lie between an axial girth of 890 mm and 1052 mm when interacting with a ducted propeller of 1700 mm diameter. As no adult grey seals have been found with these wound patterns and the size range of ducted propulsion systems is represented extensively throughout UK waters, it can ultimately be assumed that vessels equipped with ducts large enough to accommodate an adult grey seal do not operate at necessary speeds to produce spiral lacerations, in coastal regions of the UK.

An alternative explanation of this observation could be that larger ducted propulsion systems, seen on deep water support vessels such as anchor handlers and platform suppliers, are more commonly associated with offshore rather than coastal regions. A seal killed whilst interacting with a propeller operating below the presumed rotation speed threshold in an offshore region would be less likely to make landfall. It may therefore be that lack of reports of spiral cuts on larger seals may be due to the geographical distribution of the events in areas of poor monitoring. Interestingly, reports of decapitated seals are common in the UK and these observations are almost exclusively positively confirmed as adult grey seals; the size class which is not represented in the records of spiral-cut seals. The edge of the decapitation wounds are usually smooth edged and similar to those found on spiral-lacerated seals. Further analysis of these individuals coupled with trials on a greater size range of seal model and propeller may aid in the determination of a size threshold and provide a mechanism whereby larger seals could be decapitated or spiral cut.

The Voith-Schneider propeller did not produce any cuts and most seal models suffered only minor indentations or no impact marks at all. This suggests that collisions between seals and Voith-Schneider propellers are not involved in the corkscrew seals issue. Furthermore, the lack of severe damage to seal models may indicate that even if collisions do occur they may not cause serious injuries except at high rotation rates. However, as previously stated, internal damage is difficult to infer from these model trials.

The ink traces depicting the patterns of water flow into and through the ducted propeller show that there is no rapid acceleration of flow until the ink stream is close to the propeller, within a range approximately equivalent to one propeller diameter. This clearly demonstrates that objects are not drawn into the propeller from long ranges and suggests that a conscious seal should be capable of turning and avoiding the propeller at any time during its approach until it was within a few metres of, and less than a second, before impact. This implies that seals are voluntarily swimming towards the devices or at least making no attempt to avoid them until immediately before the impact.

Analysis of the high frame rate videos suggests spiral lacerations can be caused by two different mechanisms: (a) an initial blade impact on the posterior of the seal, travelling forwards towards the head in a spiralling motion, or (b) an initial blade impact on the anterior of the seal travelling backwards towards the tail. This is contrary to current necropsy data where all wounds begin at the head and spiral down the body. Anterior blade impact is surmised during necropsy from to the consistent pattern of initial blunt force trauma to the muzzle of the seals. The spiral lacerations then show no signs of secondary blade impact but rather a continuous cutting and sheering action after initial blade impact. This may be the result of some unidentified scale effects, structural differences between models and real seals such as the absence of pectoral flippers on seal models or behavioural changes in live seals such as evasion attempts or swimming gaits which cannot be replicated in scale trials. However it is interesting to note that, even in the instance where seal models were rotated along the dorso-ventral axis prior to incurring characteristic damage, spiral patterns could still be pronounced.

8 Future work

The results of the scale seal model tests highlight several issues that require further investigation:

- Investigate the influence of the shapes of blades in ducted propellers on the types and frequencies of damage to seal models.
- The results presented here suggest a threshold exists in seal model size, below which spiral lacerations are unlikely. An additional series of trials should be undertaken to determine the relative sizes of seal models that will and will not pass through a particular size of ducted propeller.
- Investigate the conditions (propeller speed, relative size of propeller and seal model etc) under which propellers inflict other types of damage such as decapitation.
- Repeat a series of trials with seal models modified to produce an equally resilient, but more flexible core and include morphological characteristics such as pectoral flippers to investigate whether this increases or decreases the incidence of spiral lacerations.
- Begin vessel based observations on vessels with ducted propellers to identify possible visual cues to these interactions and provide further insight into the seals' behaviour prior to collision.

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