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Collision risk and impact study: Field tests of turbine blade-seal carcass collisions

Sea Mammal Research Unit
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Contents

1 Executive Summary

In the absence of any field data, collision risk models currently assume that all collisions between marine mammals and tidal turbines will be fatal. This precautionary assumption is not likely to be true and will lead to over-estimation of mortality rates. Estimated mortality rates are likely to be a serious constraint on turbine deployments and reducing the uncertainty should have the effect of reducing these rate estimates.

To address this issue a series of collision trials were carried out with grey seal (*Halichoerus grypus*) carcasses using a shaped, rigid bar fixed to the keel of a jet drive boat to simulate the leading edge of a turbine blade. The blade profile chosen represented a section near the tip where it is narrowest/sharpest and therefore most potentially damaging. The boat was driven at and collided with a number of previously frozen grey seal carcasses at a range of speeds. The angle at which the carcass was struck influenced the effective speed of that collision. This was accounted for by measuring the angle of the centre line of the keel to the water's surface (which varied with the vessel's speed) using video cameras and incorporating this into the effective speed calculations. Carcasses were impacted at a range of effective speeds from 1.95 m/s to 5.32 m/s. Resulting injuries were assessed via inspection of radiographs and by detailed post-mortem analysis. These data and the estimates of effective collision speeds were used to assess the likelihood of injury or death in real collisions.

Post-trial x-rays and post-mortems revealed no evidence of skeletal trauma. Neither were there obvious indicators of trauma such as tears, avulsions or rupture in the integument, musculature or organs, in any of the test subjects as a result of the collision trials. However, due to the difficulties in assessing soft tissue damage such as bruising and tissue oedema in previously frozen carcasses these soft tissue assessments were not considered reliable indicators of trauma in this experiment.

The results of the trials suggest that slow speed collisions with the tips of tidal turbines, at less than the maximum 5.32 m/s measured in this test, are unlikely to produce serious or fatal injuries in grey seals. It seems likely that a significant proportion of impacts would not be fatal, given the range of speeds tested in this set-up and the speeds with which wild seals will be exposed to when interacting with tidal turbines (see Data derived collision risk assessment). These are however, preliminary results and should be treated with caution as they are limited in their inability to assess soft-tissue damage or to determine potential unconsciousness as a result of collisions.

2 Introduction

The potential for renewable energy installations to directly and indirectly affect marine mammal populations has been studied from many different perspectives (Wilson *et al,*. 2007, Merchant *et al.*, 2014, Russell *et al.*, 2014). Short and long term effects of distribution changes and population trajectories directly related to offshore devices can be monitored through acoustic and visual observations, as well as telemetry based studies. However, to understand the results of physical impact between marine mammals and turbine blades, the likelihood of interactions (taking movement overlap and probability of evasion into consideration, akin to a simple predator-prey model) must be coupled with some measure of the severity of these interactions on individuals. This can only be achieved by combining observational and experimental data.

Tidal turbines pose a potential risk to marine mammals. The speed of movement of these devices is controlled by the ambient flow of the system. However, existing turbine systems are designed so that the rotational tip-speed is held at around 4.5 times the speed of the current and limited by manufacturers to an approximate maximum of 12 $m.s^{-1}$.

Information on the ability of marine mammals to evade turbine blades is not yet available. Results of telemetry studies with harbour seals in and around the MCT SeaGen device in Strangford Narrows suggest that there may be a small but significant avoidance effect (Royal Haskoning, 2011). However, because of the mitigation requirement to stop the turbine whenever marine mammals approach the device there was no evasion information and little understanding of how distribution and movement patterns might change as a result of the operation of these installations (Hastie, 2013). Collision risk modelling has therefore been adopted as the primary means of assessing the potential for impact. An implicit assumption that any contact is effectively fatal means that the models produce high take estimates. This can be moderated by applying avoidance and evasion factors, but the lack of relevant data means that these have to be based on data from other taxa, primarily birds evading wind turbines (Wilson *et al.*, 2007). The lack of relevant data on evasion and the assumption of fatality in all collisions results in these models being highly conservative and highly sensitive to evasion assumptions. There is a clear requirement for data gaps to be filled to better inform the environmental impact assessments of renewable energy devices.

A collision in these models is defined as any interaction which may result in physical damage to the organism. However, these species-specific models are largely based on spatial usage patterns and abundance data and assume mortality in the event of a collision. If the worst case scenarios are determined to be non-fatal (i.e. at a tip-speed of $12m.s^{-1}$ an impact does not immediately kill, remove the ability to successfully forage and reproduce or render the animal unconscious), direct collisions between renewable energy devices and marine mammals are of little concern. This seems unlikely; such high speed collisions are likely to be damaging. However, lower speeds may not be and excluding such low speed collisions from the estimated mortality may produce lower and more realistic assessments of impact.

The absence of any information on the effects of collisions was identified as a clear and important data gap. It is not ethically or practically possible to subject live seals to such impacts so the physical damage incurred by grey seal carcasses at various impact speeds was tested. An initial experimental set-up is described below that, with appropriate modifications, could be applied to different species to inform the damage aspect for future collision risk models.

3 Aims and objectives

The overall aims of this section of the project were:

- To describe the physical effects of collisions between tidal turbine blades and seals.
- To estimate the likely mortality rate from such collisions.

These aims were accomplished by:

- Conducting a series of controlled collisions between simulated turbine blades and seal carcasses at a range of speeds.
- Assessing the injuries inflicted on the carcasses.

- Using these data and estimates of realistic collision speeds to assess the likelihood of injury or death in real collisions.

4 Methods

4.1 Simulated turbine blade

To assess the physical damage inflicted upon a seal when struck by a turbine blade a series of collision impact tests was carried out on seal carcasses using a simulated turbine blade attached to the keel of a jet drive boat, driven over the carcasses at known speeds.

The turbine blade was simulated by fitting a profile similar to the leading edge of a tidal turbine blade to the keel of a high speed, jet propelled boat. The profile was based on the shape of the leading edge of the tip of a standard blade profile (Hammerfest HS1000, NACA 1, data courtesy of EWTEC). An initial design using a straight leading edge was constructed but abandoned because the leading edge protruded too far forward from the keel and therefore had the potential to produce large lateral forces at the high speeds required for the collisions. This posed potential safety concerns and would have prevented accurate positioning of the boat during high speed collision trials.

A replacement profile that protruded 40mm from the keel was moulded to follow the keel of the boat (Figure 1). Three lengths of PVC piping, arranged in a triangular structure, were fixed to the centre line of the hull (Figures 1 and 2). Each 20mm diameter pipe was attached to the adjacent pipe with a polyethylene weld. The pipes were filled with a vulcanised silicon rubber for rigidity (Figure 2).

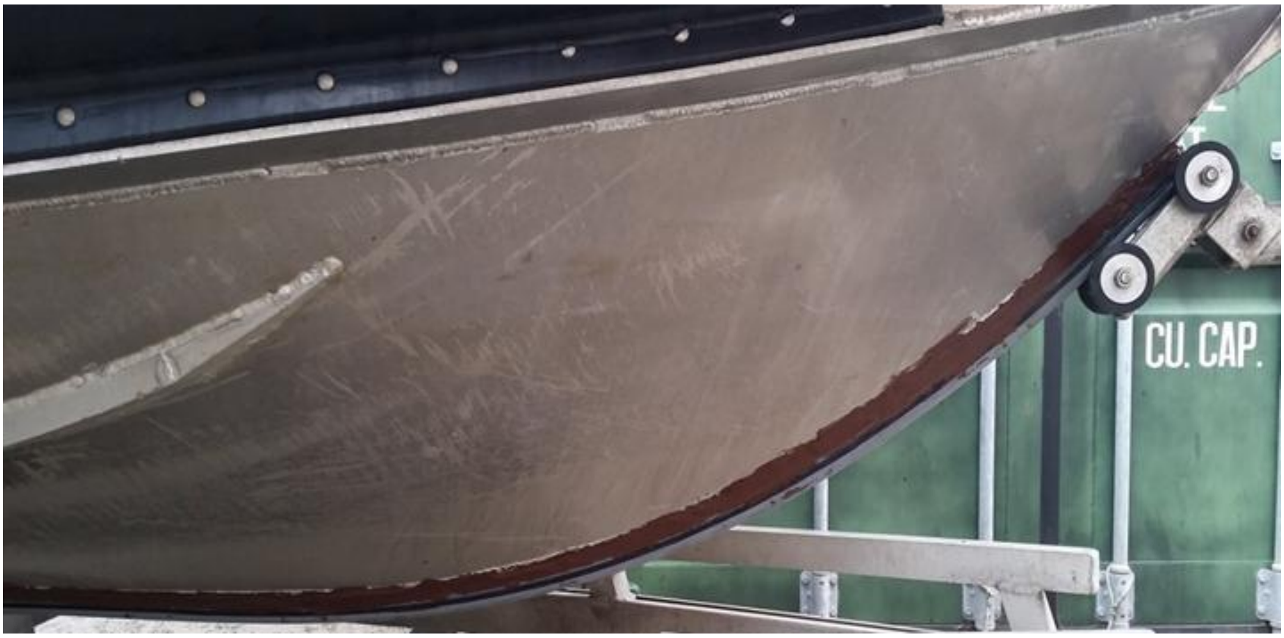

Figure 1. The model turbine blade fixed to the boat hull at the mid-line.

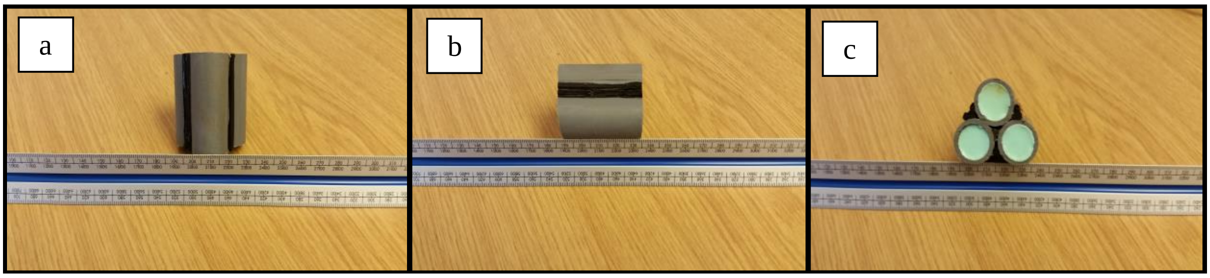

Figure 2. An example length of the model turbine blade (a) a head on view, (b) a side view and (c) a cross-sectional view.

The blade tip was used for the model as it has the “sharpest” leading edge profile and the smallest frontal surface area; it therefore represents the most potentially dangerous area due to the narrower and therefore smaller area impact zone. For example, a typical 9 metre turbine blade displays a 2 metre chord at its widest point, 3 m from the blade root at a twist angle of 10.8° compared to a 0.75 metre chord at a twist angle of 4° at the tip (Figure 3). Furthermore the tip speed of a rotating object represents the fastest moving part and therefore will always represent the most potentially damaging area for a collision to occur.

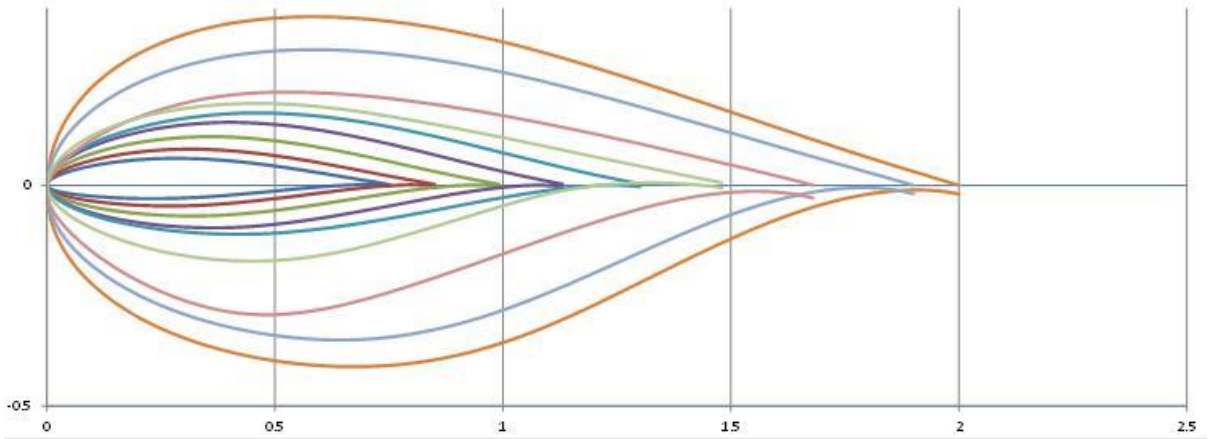

Figure 3. Scale drawings of the profiles of a typical tidal turbine blade at different distances from the centre. Widest profile is at 3m from the centre and profile becomes progressively narrower towards the tip. In reality the profiles are progressively twisted but this has been removed to make it easier to compare profiles.

4.2 Study subjects and collision set-up

Five grey seal carcasses (two adult and three juvenile) were subjected to collisions. Four of the carcasses, three juvenile grey seals and one adult male were stored frozen at -20ºC and defrosted over 4-5 days at ambient temperature. One adult male seal was stored in a chiller room at 2ºC for a period of 4 weeks. The three juvenile seals had been by-caught in trawl nets and the two adult males were stranded dead. All the juvenile seals were radiographed prior to the trial to rule out the presence of any pre-existing fractures. It was logistically not possible to image the adult seals due to the limitations of the available x-ray equipment

Seal carcasses were suspended either semi- or fully submerged just below the surface with the use of buoys to account for the natural buoyancy of the carcasses (Figure 4). The carcasses were tied at the neck, fore flippers and hind flippers to a horizontal line between two anchored buoys. Weights suspended from the anchor lines pulled the buoys apart and maintained the horizontal line under tension. The carcasses were held in a fixed position by strapping a cylindrical buoy to lie alongside the carcass to prevent rotation prior to collision. The attachments were not rigid, so the carcass was able to move in response to the collisions, but the tension in the horizontal line provided some resistance to horizontal rotation (pivoting) and to horizontal displacement. The buoy strapped to the carcass added resistance to rotation and to horizontal displacement by increasing the surface area and hence increasing the drag forces acting on the body.

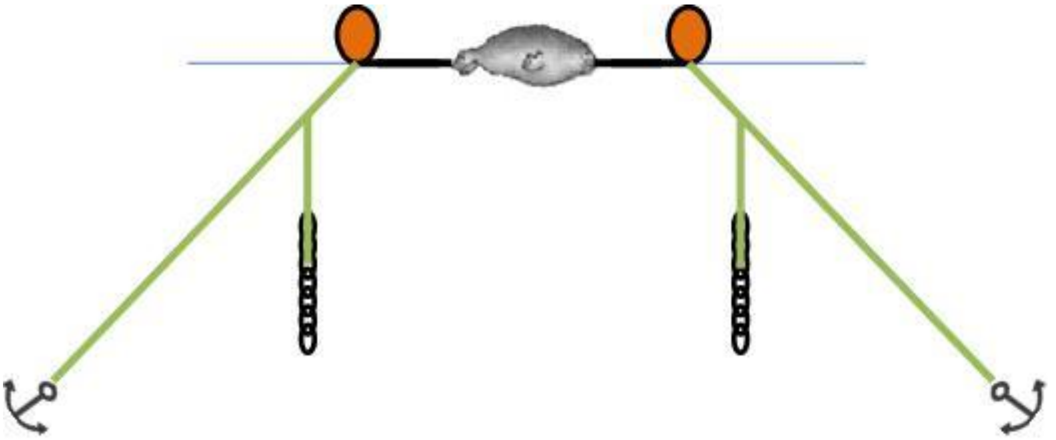

Figure 4. Diagram of the experimental set-up. Two buoys, weighted with chain and fixed in position at the surface with support anchors are connected by a 3 metre length of rope. The carcass under test is attached to this rope with further flotation buoys attached if the carcass displayed negative buoyancy.

Collisions were inflicted once on the head, torso (rib-cage and scapulae) and pelvis of each carcass by the simple method of driving the jet boat at the target at known speeds. Trials were carried out in a large sheltered artificial harbour at Ardersier Point in the Inner Moray Firth. This site provided a sheltered, effectively enclosed area, 2 km x 0.25 km with no appreciable currents or wind driven waves in the inner harbour where the trials were conducted.

The location of the point of collision was assessed by a vertically mounted video camera (30 frames per second) attached to the bow along the centre line. A frame grab from the video is shown in Figure 5 immediately before impact with the seal carcass. This allowed an accurate identification of the impact point in each collision. In practice it was relatively easy to hit the carcasses at pre-determined spots. An additional underwater video camera attached to one of the anchored buoys was oriented to face along the carcass to observe the point of impact and movement of the carcass (Figure 6). In practice only the point of impact was consistently observable as turbulence in the water caused by the wake of the boat significantly reduced visibility immediately after impact in many trials.

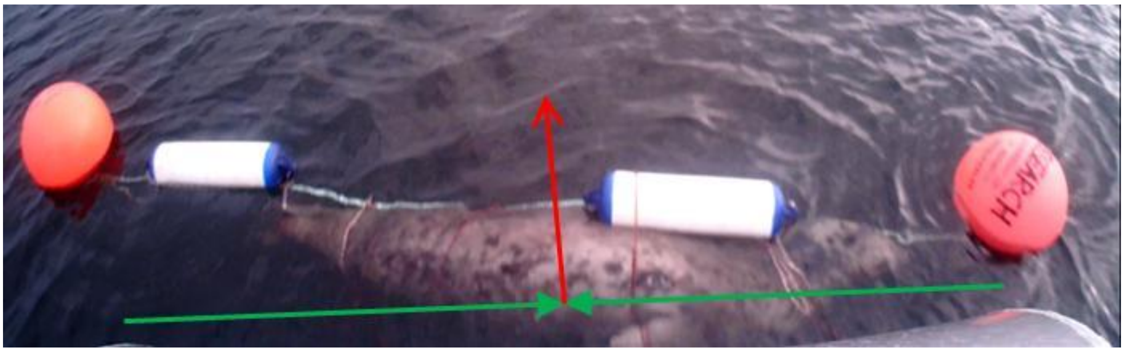

Figure 5. View from bow mounted camera indicating direction of movement and line of impact during an abdomen impact trial. The green arrows indicate the centre point of the boat given the position of the nose piece and the red arrow indicates direction of movement. The point at which the green arrows converge indicates the point of impact on the animal.

Figure 6. Underwater images of a collision to the abdomen showing (a) the seal suspended just below the surface, (b) the moment of impact with the carcass rolling away (clockwise in the 2D perspective) and (c) the carcass being pushed away and down into the water column by the continued momentum of the boat coupled with the angle of attack.

With the blade attached to a boat it able to was possible to accurately control point and speed of impact, but the curvature of the keel combined with changes in the trim angle of the boat at different speeds meant that the angle of attack and therefore effective collision speed varied between trials. Figure 7 demonstrates the elevation and angle of attack with relation to the water line for the ‘blade’ profile at the two different speeds used in the trials (3m.s^{-1} (6 kt) and 12m.s^{-1} (24 kt)).

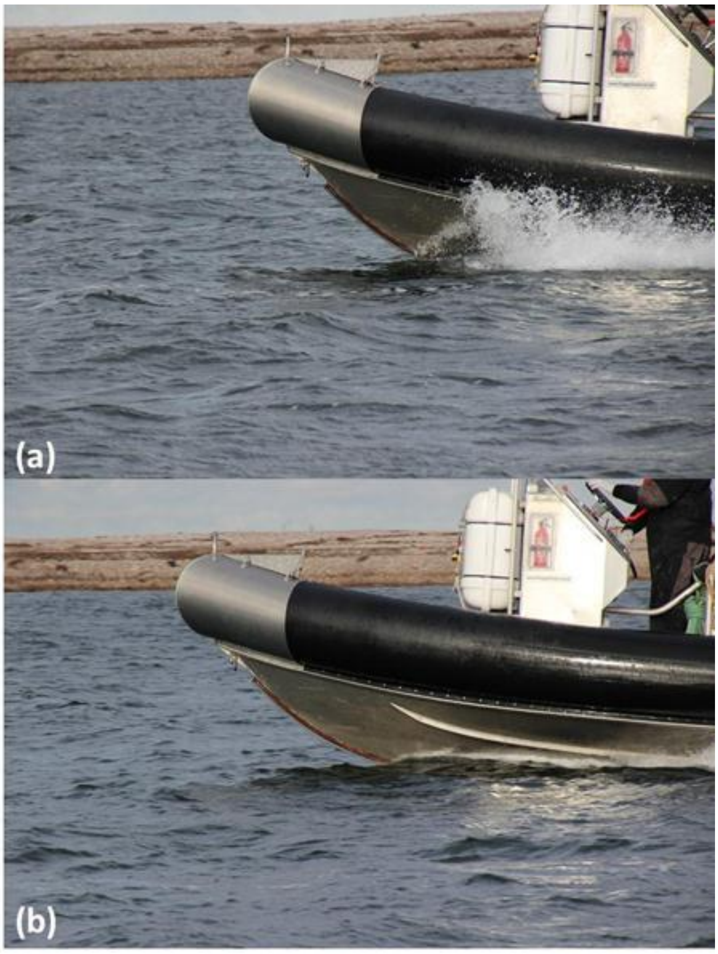

Figure 7. A perpendicular perspective of the blade profile at (a) 6 knots, and (b) 24 knots. Note the elevation of the boat hull with relation to the water surface and the resulting angle of attack of the blade.

4.3 Effective collision speeds

Photographs of the boat passing at known speeds (Figure 7) were used to calculate angle of the blade at the impact point, assuming that the initial contact with the buoyed carcass was at 30cm above the surface. With the water surface acting as a flat, adjacent side to a right angle triangle, the impact angles for 3 $m.s^{-1}$ (6 kt), 6 $m.s^{-1}$ (12 kt), and 12 $m.s^{-1}$ (24 kt) were 43.7°, 33.9° and 28.2° respectively. Several photographs, perpendicular to the boat were used to confirm the angles were consistent. These angles were used to calculate an effective collision speed for each trial, calculated as:

Effective speed = $V \sin \alpha$

Where alpha was the angle subtended by the blade at the water surface and V was the measured speed of the boat (see discussion for a description of important caveats). Table 1 shows the approach speeds, angles of attack and the resulting effective collision speeds imposed on the seal carcasses given the angle of attack. It was not possible to account for the vertical movement of the boat due to small wavelets.

Table 1. Adjusted displacement speeds at given angles of attack. All values were calculated using trigonometric functions assuming the carcass was struck at the absolute centre of mass.

Boat Speed ($m.s^{-1}$)	Angle of attack	Speed of displacement ($m.s^{-1}$)
3	43.7°	2.07
6	33.9°	3.34
12	28.2°	5.67

After each carcass had been subjected to a series of collisions at different points along the body, it was then transported to a veterinary clinic where a full series of digital radiographs were taken of the three juvenile grey seal carcasses. Each carcass was then necropsied by a veterinary pathologist with experience of marine mammal necropsies. For the four previously frozen carcasses both the radiographic images and the necropsy analysis were used to assess skeletal damage only, because the freeze-thaw process is known to produce pseudo-bruising and renal haemorrhaging in pinnipeds (Roe *et al*., 2012). As a consequence, any observed internal damage to the muscle tissue or organs could not be confidently attributed to the collision trial impacts. Clearly, it was not possible to perform any sort of internal examination before the trials as the structural integrity of the skin and blubber layer could not be ensured if incisions had been made; in such cases carcasses could have displayed signs of trauma that otherwise would not have been present if the skin and blubber layer was left intact. Therefore only one carcass of the five could be assessed for signs of trauma aside from skeletal damage.

5 Results

5.1 Pre-collision examinations.

Pre-collision radiographs were obtained for the three juvenile grey seals. Radiographs of the entire axial skeleton were taken using standard dorso-ventral or cranial oblique views. Special attention was paid to cranial, abdominal and pelvic regions due to the sensitivity of these areas to serious injury; these areas are most likely to cause death if significantly damaged. One carcass exhibited radiolucency in a section of rib. However, on subsequent inspection at necropsy this was confirmed to be a healed injury. No other skeletal irregularities or signs of pre-existing injuries were identified on the carcases pre-collision.

5.2 Effective collision speeds

The final impact speeds are detailed in Table 2. Two speeds were used, 6 and 24 kt (equivalent to 3 and 12 $m.s^{-1}$). In practice although the boat speed could be fairly accurately maintained, it did vary slightly during the trial runs. The final impact speeds were estimated from the boat's GPS readings just before impact. The observed speeds were close to the target speeds so the measured angles of attack at 6 and 24 kts were used.

All individuals were subjected to three separate collisions: to the head, torso and pelvis. Collision accuracy was assessed visually using the surface and sub-surface videos and remained consistent throughout the experiment (see Figures 4 and 5 for examples).

Table 2. Corrected impact speeds for each trial.

Seal ID	Collision Speed (m/s)			Corrected Collision Speed (m/s)		
	Head	***Torso***	***Pelvis***	***Head***	***Torso***	***Pelvis***
Juvenile 1	3.19	3.09	3.19	2.02	1.95	2.02
Juvenile 2	12.4	12.3	12.24	5.3	5.25	5.23
Juvenile 3	12.24	12.45	12.29	5.23	5.32	5.25
Adult 1	3.34	3.24	3.24	2.11	2.05	2.05
Adult 2	12.35	12.45	11.99	5.28	5.32	5.13

5.3 Post-trial radiographs and necropsies

Post-trial radiographs of each juvenile showed no discernible evidence of skeletal damage; cranial, abdominal and pelvic bones remained intact (Figures 8, 9 and 10). This absence of skeletal damage was later confirmed by detailed necropsies.

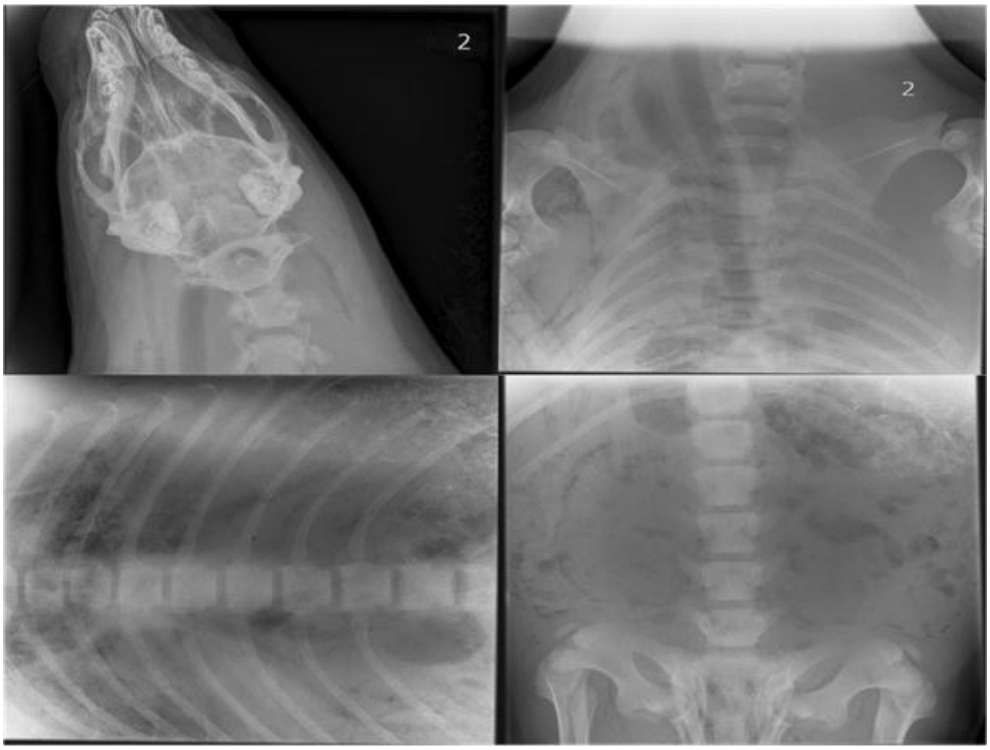

Figure 8. Radiographic images of the head, torso and pelvis of juvenile 1.

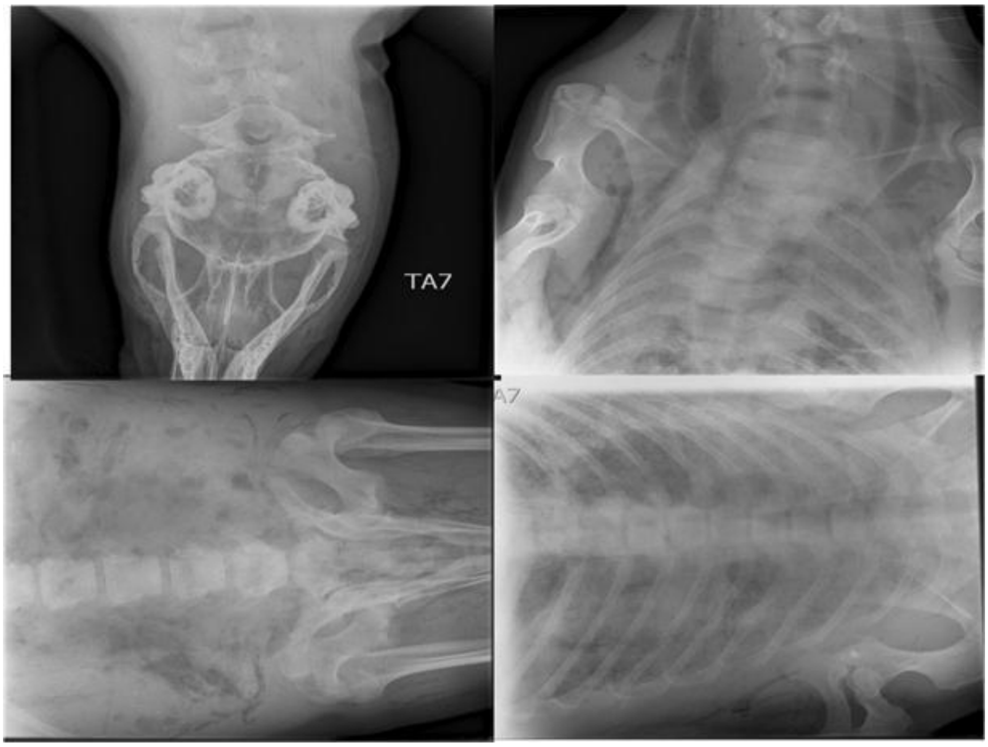

Figure 9. Radiographic images of the head, torso and pelvis of juvenile 2.

Figure 10. Radiographic images of the head, torso and pelvis of juvenile 3.

Necropsies of the two adult carcasses also revealed no skeletal damage. Additionally muscle tissue and organs were assessed for haemorrhaging and ruptures. No trauma which could be associated with the trial collisions was apparent. In summary, no evidence of skeletal trauma was found. Neither was there obvious indicators of trauma such as tears, avulsions or rupture in the integument, musculature or organs, in any of the test subjects as a result of the collision trials. However, due to the difficulties in assessing soft tissue damage such as bruising and tissue oedema in dead, frozen and defrosted cases, soft tissue assessments were not considered reliable indicators of trauma in this experiment. Nonetheless, there were no indications of physical damage to any of the seals following the collisions described above.

6 Discussion

The results of the trials suggest that slow speed collisions with the tips of tidal turbines are unlikely to produce serious or fatal injuries in grey seals. This does not, however, assess the effect of other interactions, such as blunt cranial trauma leading to unconsciousness, which would also be likely fatal. Although death due to blows to the skull does occur without the presence of a skull fracture in humans, this is unusual and a skull fracture can be regarded as an indirect indicator of severity of the resulting trauma (Sulaiman *et al.*, 2014). No skull damage was observed in the trials. However, even a minor head injury leading to concussion or severe short term disorientation could be potentially lethal to a submerged seal which needs to be able to return to the surface to breathe.

None of the collision trials caused any skeletal damage. However, these preliminary results should be treated with caution. A correct interpretation of the effects of collisions with blades will require a modified set-up with a straight edged blade and collisions with fresh seal carcasses. These will be carried out in the near future. However, the results presented here can go some way towards assessing the likely injuries from collisions with turbine blades if the following factors are taken into account.

6.1 Effective collision speed

The effective collision speed, based on the angle of attack will probably overestimate the amount of energy transferred to the carcass that is available to cause tissue damage. The damage resulting from a collision will be due either to deformation, e.g. crushing and bending on the collision surface and extension and bending of the opposite surface, or to differential acceleration of body components leading to rupture and haemorrhage in internal structures. However, because the blade will not be normal to the direction of motion some of the energy transferred to the carcass will be used in rotational acceleration about the longitudinal axis of the seal. In addition, because the blade will not strike the carcass in line with the centre of mass the carcass will pivot in the horizontal plane and some of the energy will be used in rotational acceleration around that pivot point. These two acceleration components will mean that the observed effective collision speed is an overestimate of the equivalent blade impact speed for a collision with a real turbine.

To some extent this will be counteracted by the way that the carcasses were tethered. In order to hit specific points it was necessary needed to know the orientation of the carcass. In order to maintain a fixed orientation in the water it was tied at the neck, thorax and hind flippers to a horizontal line running between the surface buoys. This line was held under sufficient tension to keep the seal in a fixed orientation during the trials. The carcass did pivot when hit at the head or pelvis, but was not completely free to do so. In addition, to maintain the carcasses in a horizontal position at the surface they were strapped to horizontal, cylindrical floats, approximately 20 l volume. This prevented the seal from sinking at either end. During the collisions these floats added significant resistance to the rotational motion and simultaneously added significant resistance to the forward motion of the carcasses. There are no accurate estimates of the effects of these added resistances, but they would have increased the effective collision speed. Although measures of these competing effects were not available it seems likely that the resulting effective collision speed would be close to the estimate based on the angle of attack.

6.2 Mechanisms of injury

Whether an impact results in injury depends to a large extent on the kinetic energy transferred to the animal and therefore depends on the velocity of the blade. Resulting injuries are in part due to the ability of the moving object to accelerate the different tissues in the direction the object is moving. The top speeds used in the trial were limited by the speed of the boat and safety considerations. Because the angle of attack during collisions was acute the resulting effective speeds were lower than the speeds likely to be encountered at a real turbine. However, the estimated effective speeds of $5.3 m.s^{-1}$ would be higher than two thirds of estimated likely collision speeds (see below) for real turbine seal interactions.

Both the total amount of energy transferred to the victim and the rate of its transfer will affect the type and severity of traumatic injury. The extent of the area of collision will also have an effect (Chattopadyay & Tripathi, 2010). The potential destructive force of a collision may be expressed in terms of energy per unit area of impact. Therefore, the shape of the colliding object will be expected to have some influence on the extent and severity of the injuries. For a fixed speed of impact a narrower profile will have a smaller surface area of impact and will therefore concentrate the force. In collisions with hard structures this will increase the likelihood and severity of fractures. In the trials the blade profile was based on the shape of the tip of a turbine blade. Not only is this the narrowest and therefore most potentially damaging shape, it also represents the fastest moving part of the device. The profile becomes progressively more rounded (Figure 1) and therefore progressively less dangerous towards the base of the blade. As the collision speed necessarily decreases towards the centre it is clear that impacts towards the centre of the device will be less damaging.

The severity of injuries will also depend to a large extent on the composition of the blade. Blades are usually hard and relatively inflexible. However, if the collision surface is flexible and/ or compressible, such as the abdomen of a seal, the effective time over which the kinetic energy is transferred to the victim will be increased and will be relatively less likely to cause structural damage. The type and severity of injuries will also depend on the tissue underlying the point of the impact. Even if there is no surface trauma, the resulting motion of the underlying tissues or organs may cause extensive damage and severe haemorrhage.

6.3 Effects of carcass storage

As described above, the fact that the carcasses had been previously frozen or held in a chiller for a long period means that the post mortem results from soft tissue examinations cannot be easily interpreted. Degradation of muscle and internal organs means that apparent bleeding could be due to the storage method. However, it could be expected that such freeze-thaw damage and post mortem autolysis would make organs more susceptible to tearing and avulsion. The absence of gross damage such as tearing, rupturing or avulsion of major organs suggests that such gross internal damage to freshly killed or live seals would be limited. However, the freeze-thaw damage and post mortem autolysis make it impossible to detect other trauma related tissue damage to intact organs such as the liver and brain that could easily be fatal.

6.4 Likely impact speeds

The impact speed will be a function of the rotation rate of the turbine and the distance of the impact point from the centre of rotation. The rotation rate of the blade through the water will be a nonlinear function of the current speed; being stationary below some device specific stall speed and reaching a maximum at some intermediate current speed set by the specific design of the turbine and the local flow conditions. In addition, the speed of any particular point on a blade will be linearly related to the distance from the centre of rotation, being close to zero near the centre even at high rotation rates.

In the absence of other information, the available collision risk models assume that marine mammals will not react to the presence of a turbine. Therefore it is assumed that the impact point will be at some random point on the blade. The probability that a collision occurs on any particular section of blade will be equal to the proportion of the total swept area that is swept by that section and will be a related to the distances from the centre (e.g. the outer 10% of the blade sweeps 19% of the total area, while the inner 10% sweeps only 1%).

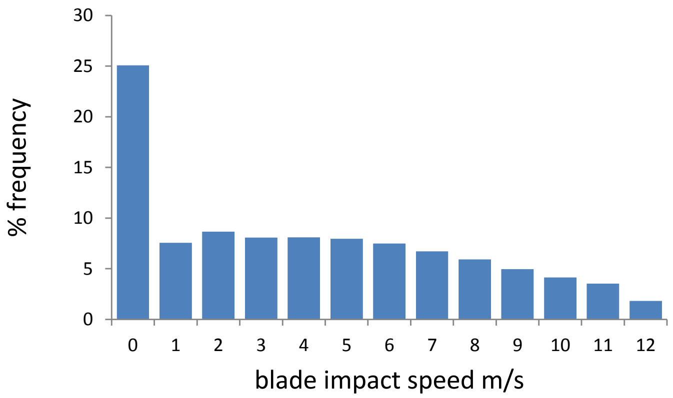

Figure 11: Frequency distribution of estimated blade speeds during collisions with randomly moving seals. Data provided by EWTEC)

To illustrate the combined effects of the temporal patterns of flow and the position on the blade a frequency histogram of expected collision speeds was generated (Figure 11). The POLPRED package was used to generate estimates of the current speeds at 10 minute intervals over the period 4/3/2014 to 1/4/2014 for a site in the Sound of Islay. These current data were used to generate estimates of the blade speed assuming that the turbine stalls at a current speed of 0.8 $m.s^{-1}$ and reaches a maximum tip speed of 12 $m.s^{-1}$ for current speeds of 2.5 $m.s^{-1}$ and higher. This is broadly similar to the pattern for the SeaGen device in Strangford. Figure 11 shows the frequency histogram of estimated blade speeds for collisions with seals swimming randomly with respect to the turbine position. It is apparent that most collisions would be with slowly moving blades. Under these assumptions, the blade speed in the majority (57%) of collisions would be less than 4 $m.s^{-1}$ (14$km.hr^{-1}$ or 7.8 kt). Again, under these assumptions, the blade speed observed in the fast collision trials (5.3 $m.s^{-1}$) would be expected to be faster than 67% of collision speeds in random collisions with turbines.

7 Conclusion

The results of the trials suggest that slow speed collisions with the tips of tidal turbines are unlikely to produce serious or fatal injuries in grey seals. None of the collision trials caused any skeletal damage. The relationship between the collision speeds and the realistic situation in a real life collision is not clear. However, these preliminary results do suggest that many collisions with the more rounded and slower parts of the turbine will be unlikely to kill or seriously injure grey seals. Further trials with harbour seal carcasses would be necessary to comment on any species-specific effects of collisions. However, if the estimate of effective collision speed is realistic these results suggest that more than two thirds of impacts are unlikely to directly kill seals.

8 Acknowledgements

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