Thermography of respiratory activity in cetacea

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Abstract

This paper describes thermography of the thermal energy carried in water droplets in the cetacean exhaled 'blow' as a tool for which may add objective data on respiratory activity in cetacea. The core body temperature of many cetacea is around 37.5 °C (99.5 °F 310.5 °K). Sometimes the sea water in which whales live is very cold. In the Northern Pacific, the Norwegian Sea and the Arctic Ocean, and in the Southern Oceans in the South Atlantic and Weddel Sea, the main body of seawater can be at a temperature as low as –1 °C (30.2 °F, 272 °K) and this can provide the potential for a significant contrast between core body temperature and sea water temperature. At the core body temperature of a whale, thermal energy in the Infra Red part of the spectrum is emitted with a peak emittance at a wavelength at about 9.6µm. Using a thermographic camera sensitive in the infra red spectral band 7.5 – 13 µm we have explored the thermal energy emitted by the thermal emissions from the respiratory blow of cetacea at the Sea World facility in San Diego, USA .

A Flir systems thermaCAM^{TM} E4 camera was used to make thermal images of Beluga, killer whale and pilot whales and the images captured direct onto the hard disc of a laptop computer. Additionally, thermal recordings of the ocular temperature of three species of captive whale (killer, pilot and beluga) were made. The thermal contrast between the eye and the skin around the eye was analysed using an infra red thermometer. The temperature of the surface of the eye (TE) was recorded with a Raytek ST^{TM} remote sensing infra red thermometer.

It is concluded that thermography may have the potential to;

1) Permit remote measurement of respiratory frequency in cetacea, particularly in very cold seas.
2) To add information to the decision as to whether a hunted animal is vital, or if it is dead – information which may be of value in the discussions on humane killing carried out by the IWC.

INTRODUCTION

Invisible heat

The core body temperature of many cetacea is around 37.5 °C (99.5 °F 310.5 °K). Sometimes the sea water in which whales live is very cold. In the Northern Pacific, the Norwegian Sea and the Arctic Ocean, and in the Southern Oceans in the South Atlantic and Weddel Sea, the main body of seawater can be at a temperature as low as –1 °C (30.2 °F, 272 °K). Although sea water freezes below –1.9 °C (this depends a little on its salinity) if it is not moving, the sea surface temperature may fall to –5 °C without freezing if it is kept in motion by waves and the wind.

At the core body temperature of a whale, thermal energy in the Infra Red part of the spectrum is emitted with a peak emittance at a wavelength at about 9.6µm. Using a thermographic camera sensitive in the infra red spectral band 7.5 – 13 µm we can, in principle, capture images of the thermal energy emitted by the warm body of a whale. However, this is usually not possible for two reasons.

1) Whales & dolphins are, for the most part, immersed in sea water. Thermal imaging can only measure the temperature of the surface of a solid or liquid. If a thermal camera is directed at a whale in the sea, although it may be possible to visualise the animal below the surface with a camera using visible light, only the thermal emission of the immediate sea surface can be measured and the animal remains thermally 'invisible'.

2) Whales in good condition are well insulated by a thick layer of blubber which may account for 40% of the animals weight. Blubber is made up of fat-filled panniculus adiposus tissue, which is held together in a matrix of collagen and elastin fibres, and acts not only as insulation, but also as an energy store, and also sculpts the smooth hydrodynamic shape of the animal. The core temperature of the whale is also protected by mechanisms which prevent warm blood from losing heat to the cold water. One of these mechanisms is the presence of arteriovenous anastomoses (shortcuts between arteries and veins) and counter-current heat exchangers (cold blood receiving heat from warm blood, maintaining heat in warm tissues), both of which preserve body heat. Many species of whales live a part of their lives in the warm subtropical and tropical seas, and these same thermoregulatory mechanisms also operate to maintain body temperature in these conditions.

The adaptive insulation of cetacea, and the fact that they are almost always immersed in water makes it very difficult to see how thermal imaging can be of any use in studying these species. However, there are situations when a whale cannot avoid releasing small amounts of thermal energy, even into the coldest sea, and this paper describes the use of thermography based on these possibilities.

Can you not tell water from air?

The ‘spout’ or ‘blow’ can reach up to 7m in height in some species like the fin whale (*Balaenoptera physalus*), but is ‘short and bushy’ in all of the toothed whales. Most cetaceans have a single blowhole opening, but the baleen whales (those with no teeth but with keratin plates for filter feeding) have two openings to the blowhole. The spout is an important part of the visual detection of whales during many hunts, and ‘*Thar she blows’* - called out from the barrel at the masthead of a whaler is linked strongly with the language and fokelore of whaling.

You have seen him spout; then declare what the spout is; can you not tell water from air? My dear sir, in this world it is not so easy to settle these plain things. I have ever found your plain things the knottiest of all. And as for this whale spout, you might almost stand in it, and yet be undecided as to what it is precisely. (Herman Melville, Moby Dick, 1850)

Although the blow consists mostly of air, the air itself has almost no thermal emissivity at atmospheric temperatures, and even ‘warm air’ cannot be detected directly using thermal imaging. Fortunately, this means that we can ‘look through’ air to make images of warm objects.

During the respiratory cycle in whales, the inhaled air is heated close to body core temperature as it passes through the air passages and lungs. Some of this heat is scavenged by blood vessels in the upper airways as the air is exhaled. Cetacea have a high tidal volume, changing up to 85% of the air in their lungs at each breath, whilst humans only change about 15% in a breath. The air in the blow is forced out rapidly and with some force. The visible spout is a mixture of this warm expired air and sea water droplets from the water which enters the blowhole and the blowhole depression. The spout also contains cell debris and bacteria from the lungs (the blow in many whales is quite foul smelling) and also contains fresh water droplets, created by condensation of the warm moist air from the lungs when it meets cold environmental air.

The water droplets in the spout have high emmisivity - sea water has an emissivity in the range 0.989 to 0.954, and fresh water condensed from the humid expired air, has an emissivity of 0.987. Objects with high emissivity values (approaching 1) are very effective sources for thermal imaging. The droplets formed are likely to be mixture of small and larger droplets with a maximum size of about 4mm in diameter. The droplets formed by condensation of the humid air from the lungs are likely to be warmer initially, but quite small, as condensing vapour starts as microscopic droplets 10 – 20 microns in size before coalescing into bigger macroscopic drops. The initial stages of the blow will see a very rapid mixing of warm air, condensing droplets and sea water droplets. The temperature of the water droplets in the ‘main body’ of the blow are likely to be much lower than the core body temperature of the animal, and these droplets will only remain above environmental temperature for a very short time (seconds, or fractions of a second) as they have a large surface area, are small (and so do not contain much thermal energy), and are moving through cooler air. For this reason, the cloud of warm droplets will appear as a short lived thermal ‘flash’ against the background of a cold sea, and will be most detectable at night when there is no reflection of solar heat from the sea surface. In warmer seas and in warmer air, the thermal contrast between the blow and the background will be reduced.

A warm cetacean eye

Like other mammalian eyes, the cetacean cornea, the outer layer of the eye, has a good blood supply and, although small, in relation the body mass, the eyes of the giant whales are large, the globe being about 10cm in diameter for minke, fin and other baleen whales. The eye must maintain a blood supply and cannot be insulated by blubber on its visual surface. For these reasons, the eye has the potential to be an anatomical ‘window’ displaying warmer temperatures than the surrounding well insulated tissues of the head.

Materials & methods

Three species of large toothed whale in captivity were studied. Protocols for the ethical application of the tests to conscious toothed whales were developed in discussion with veterinary and animal care staff at Sea World, San Diego, USA.
A number of animals from three cetacean species - pilot whales *(Globicephala melas),* beluga (*Delphinapterus leucas*) and killer whales (*Orcinus orca*) were observed at night and in the very early morning in their pools. Thermography of the spout was carried out as the animals swam, and close range thermography of the eye, and use of an infra red thermometer was carried out when the animals came to the poolside following the commands of their trainers.

A Flir systems thermaCAM^{TM} E4 camera was used to make thermal image movies by capture direct onto the hard disc of a laptop computer. The camera was supported on a tripod and a simultaneous video was also taken to so that the thermal and video movies could be related to one another. The sequence of individual recorded images which made up the thermal recordings were then used to provide colour enhanced images. The time base provided with the images was used to record the duration of the blow, the interval between blows and to provide an estimate for the swimming speed of the animal.

The thermal contrast between the temperature of the eye and of the skin around the eye was measured. The temperature of the surface of the eye (TE) was recorded with a Raytek ST^{TM} remote sensing infra red thermometer. The temperature of the surface of the skin (TS) approximately 10cm from the eye was also recorded at the same time.

The difference in the eye and the skin temperature (TD) was then calculated; temperature difference TD = TE - TS (ºC)

Results

Table 1 gives basic biological data for the animals studied.
Figure 1 shows a sequence of timed images of the opening and closing of the blow hole in a pilot whale.
An example of the thermal emission form the eye of a killer whale (*Orca orcinus*) can be seen in Figure 2.
The thermal differential (TD) between the eye temperature, and that of the adjacent skin is provided in table 3.

Discussion - A warm flash in a cold sea

The general proposal was that these techniques could be of value to;

1) Detect whales and measure respiratory frequency.
3) Determine whether a hunted animal is vital, or if it is dead.

The study of the difference in the measured temperature of the surface of the eye and the skin of the area surrounding the eye indicate that a consistent differential between these temperatures can be shown, even at the comparatively high temperatures experienced in San Diego during April. Table 2 shows the mean value of this difference (TE) for Pilot, Killer and Beluga whales measured. It is proposed that, as with other animals, after blood circulation has stopped, the surface of the cetacean eye will cool very rapidly, particularly if in contact with seawater.

Figures 1 and 2 show examples of the thermal images made in captive conditions. These images support the proposal that, with the high thermal sensitivity that can be achieved with thermal imaging, it is possible to detect the heat energy in the blow from a significant distance in clear air. In sea that is not rough, and without cloud or fog, it is likely to be possible to detect the thermal energy of a blow over a considerable distance and to measure the frequency of respirations from an individual, or a group of animals by studying recorded thermal images.

Relevance for the IWC debate on humane killing

The minke whale is the largest animal on earth hunted for commercial sale. This hunt is carried out under the regulation of the International Whaling Commission (IWC), and Time to Death (TTD) is an established measure in the IWC deliberations on the efficiency of killing and welfare considerations for these animals. The larger baleen whales, the Blue, Fin & Sei are now, in general, protected, although a small number may still be taken illegally, and there are aboriginal hunts for grey whales, and bowhead whales in Russia, bowhead whales in Alaska, minke and fin whales in Greenland and humpback whales in St Vincent & the Grenadines.

The current IWC criteria for determining that a whale is dead, and so the TTD, are that the animal should show relaxation of the lower jaw OR no flipper movement OR sinking without active movement (Anon 1980). These measures were reviewed at a workshop on sentience and potential suffering in hunted whales (RSPCA 2001) and were felt to be insensitive and largely inadequate for determining insensibility and death with any precision, and have been the subject of working groups papers at the IWC since the 1980's (IWC, 1980) and the focus of a recent IWC resolution (IWC, Resolution 2004-3 Resolution on Whale Killing Issues) which identifies that there are significant concerns about the adequacy of the existing IWC criteria.

The time from impact of the harpoon to the death of the whale is called the time to death (TTD). This information is recorded by the whalers, or by observers supported by the whaling industry, and is reported to the IWC. This TTD data has, over the last 20 years, been used by both sides in the arguments for and against whaling.

The whaling nations propose that there have been improvements in the percentage of animals immediately killed in the Norwegian hunt from 17% in 1983, to 80% in 2002 (Øen, 2003). Groups opposed to whaling on animal welfare grounds identify that, even using the most humane TTD data, 1 in 5 (20%) of whales do not die rapidly.

For animals not clearly killed immediately by the harpoon, it is common for the whalers to shoot the whale with large calibre rifles once it is held by the harpoon line. Table 3 provides figures for the numbers of 'secondary' shots required in addition to harpooning in recent Norwegian and Japanese hunting seasons. In a recent studies by Knudsen (2003a, 2003b) it is suggested that one round from the rifles used in the Norwegian hunt is highly efficient at causing permanent and very severe brain damage when it hits 'in', or 'near', the brain or in the upper cervical spine. However, this finding does not fit with the reported data that the mean number of bullets required during secondary killing in the Norwegian hunts 1998 – 2002 was 2.3 (IWC/55/WK22 2003), and published figures for gray whale and bowhead 'aboriginal' hunts provided by the Russian Federation for the 2002 season, which indicate that an average of 52 (small calibre) bullets were used per animal (IWC/55/WK13 2003)

This paper presents 'spout thermography' as a potential tool for detection of whales and dolphins for population calculations, and that thermography of the respiratory activity and of the eye of hunted animals could add objective data to IWC discussions on time to death. It might also be suggested that thermography might be used as an aid to detect whales during the hunt, but it is the authors clear intent that the technique has potential as a scientific tool rather than an aid to commercial whaling.

These initial studies confirm that thermal imaging of the small amounts of heat energy which escape the whale in the spout, and via the surface of the eye is possible. It is proposed that thermal imaging may be able to differentiate between an animal which is vital and one which is dead;

1. Vital – continuous thermal output from the eye if it is not covered by water, and from the blow when respiratory activity is present.

2. Dead – no thermal output from the eye, no respiratory thermal energy detected over a significant time period by thermal imaging.

The change from 'vital' to the 'dead' state marks the time of death, and could be used to calculate the time it took the animal to die, the TTD. Where TTD data is being collected by the whaling nations, this data should be as accurate and reliable as is possible if reports of improvements in the efficiency of the methods used to kill these giant mammals are to be considered credible. It is proposed by the authors of this paper that thermal imaging techniques might provide additional objective data on the TTD for hunted animals, and so inform the activities of the IWC. The following caveats clearly apply to these studies.

- The work was carried out under ideal conditions on captive animals.
- The test methodologies were developed on relatively small, toothed whales, and although the transfer of heat to the blow is likely to be universal amongst all species, the technique would need to be tested in baleen whales before it could be concluded that the tests are universally applicable.
- The study was carried out only on fully conscious animals. These techniques remain untested in use in animals during whaling activities. To confirm the hypothesis that thermography could provide information on value in determining consciousness and death would require further study on animals during whaling activity.
- Such studies might be of value in the interpretation of the dying process in hunted cetacea, and assist in the discussions and debate on welfare aspects of the hunt, as well as providing additional data on the rate of improvement in efficiency presented by whaling countries.

Table 1. Biological data for the animals studied.

Species	sex	weight kg	age years
Pilot Whale (*Globicephala melas)*	f	818	24
Pilot Whale	f	1250	44
Killer Whale (*Orcinus orca*)	f	3673	41
Killer Whale	m	2382	13
Killer Whale	m	2282	10
Killer Whale	f	2241	26
Killer Whale	f	1920	11
Beluga (*Delphinapterus leucas*)	f	922	36
Beluga	m	582	17

Table 2. The mean difference in the eye and the skin temperature for the three species (temperature differential) TD = TE (eye) - TS (skin) (ºC) (individual values in brackets)

	Pilot Whale	**Killer Whale**	**Beluga**
Mean eye / skin temperature differential (actual values) TD = TE - TS (ºC)	5 (5,5)	7.3 (5,9,8)	6.5 (5,8)

Table 3. Use of secondary killing methods during Norwegian Commercial Whaling and Japanese JARPA hunts (IWC/55/WK22 2003).

	Season	% of total whales killed on which rifles were used
Norway	1999	57%
	2000	43%
	2001	45%
Japan	1998/99	60.7% (mean bullets 2.6)
	2000/2001	63%(mean bullets 2.2)
	2001/2002	68.4% (mean bullets 2.2)

Figure 1 Example Sequence of thermal images of the spout of *Orcinus orca*

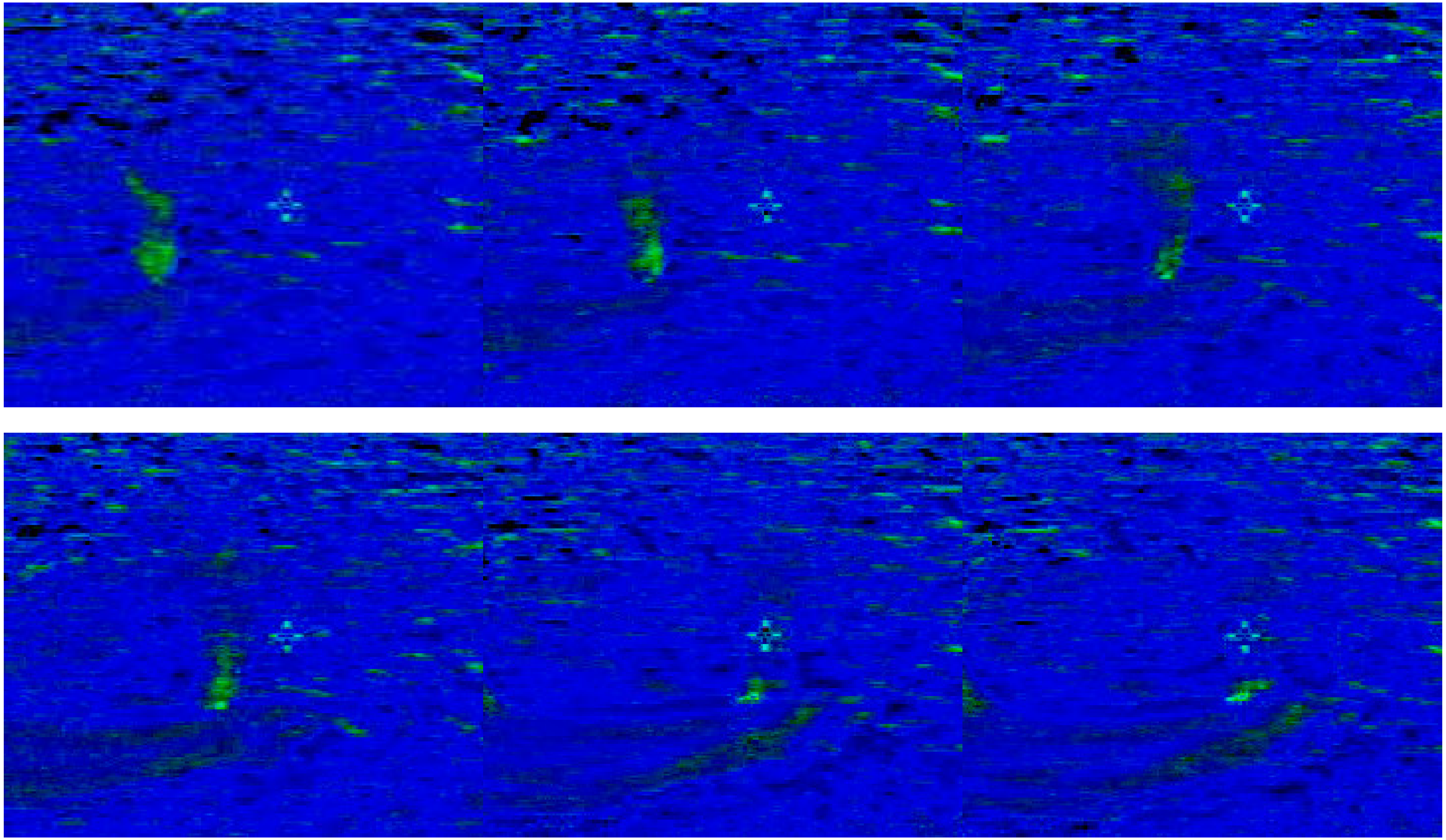
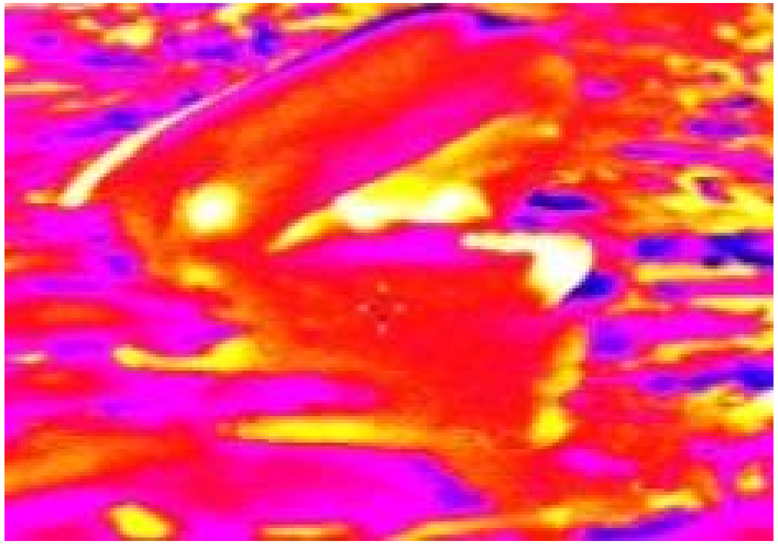


Figure 2. Thermal image of the head of a killer whale (Orcina orcus) showing the thermal emission (hottest) white → yellow → pink → black (coldest). **The eye, and the warmer open mouth can be clearly identified.**



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