Multi-year validation of photographic identification of grey nurse sharks, _Carcharias taurus_, and applications for non-invasive conservation research

Carley S. Bansemer\textsuperscript{A,B} and Mike B. Bennett\textsuperscript{A}

\textsuperscript{A}School of Biomedical Sciences, University of Queensland, St Lucia, Queensland 4072, Australia.  
\textsuperscript{B}Corresponding author. Email: s3339916@student.uq.edu.au

Abstract. Captive and wild _Carcharias taurus_ were used to assess whether spots present on their flanks were suitable as natural tags for individual shark recognition. Photographic images of seven captive sharks taken at monthly intervals for 14 months and at 3 years after the start of the study indicated that spot numbers, positions and sizes did not change. Eighty-nine wild sharks were photographically re-captured at least once subsequent to their initial image-capture; fourteen were re-photographed at least 23 months subsequent to their initial image-capture and a single individual after 14 years. Unique physical marks (e.g. partial fin loss) on six wild sharks were used to validate the pattern recognition process by providing unambiguous identification of individuals independently of their spots. Preliminary visual identification data on the eastern Australian _C. taurus_ population show how spatial and temporal information on individual sharks can be collected without recourse to conventional tagging to address key questions about this species’ ecology and population biology.

Additional keywords: natural marks, photo-identification, spot, tag.

Introduction

Conventional tagging methodologies are commonly used to collect data for use in models to estimate population size, as well as life history information (e.g. growth rates and gross movement patterns) (Cliff et al. 1996; Strong et al. 1996). Although the relatively recent use of electronic tags has allowed the collection of different data (e.g. real-time locations and diving profiles), their role in determining population sizes and structures is limited as few tags are deployed (Kohler and Turner 2001; Bruce et al. 2006; Wilson et al. 2006). Photographic identification (PID) studies of elasmobranch species have been used successfully to gain information on population size, structure and survival trends of the whale shark (_Rhincodon typus_) (Arzoumanian et al. 2005; Meekan et al. 2006; Graham and Roberts 2007), population estimates of the nurse shark (_Ginglymostoma cirratum_) (Castro and Rosa 2005) and site-fidelity and population-structure of an aggregation of great white sharks (_Carcharodon carcharias_) (Domeier and Nasby-Lucas 2006).

The grey nurse shark (_Carcharias taurus_) appears on the World Conservation Union’s Red List of Threatened Species as Vulnerable, with the population along the eastern seaboard of Australia listed as Critically Endangered (A2abcd) based on population declines (Cavanagh et al. 2003; IUCN 2007). Nationally, the east coast population is listed as critically endangered under the _Environmental Protection and Biodiversity Conservation Act 1999_ (EPBC 1999), which along with the _EPBC Regulations 2000_ identified the need for a recovery plan for this species in Australia. The Australian Recovery Plan for _C. taurus_ was released in 2002 (Environment Australia 2002), resulting in the introduction of protection measures for _C. taurus_ at key aggregation sites in Queensland and New South Wales (Bennett and Bansemer 2004), although their effectiveness in facilitating recovery of the population is unknown.

A mark–recapture study of _C. taurus_ using dorsal fin-attached Rototags on the east coast of Australia conducted in 2003 resulted in an estimate of between 410 and 461 individuals (Otway and Burke 2004), but subsequent tag-biofouling compromised their use for individual shark identification. A review of tagging research on this species concluded that permanent physical tagging cease (Department of the Environment and Heritage 2003). Consequently, we considered the possibility of using natural marks as a means to identify individual grey nurse sharks, as PID studies do not involve physical contact with the species studied. Photographic identification methodologies are therefore generally considered to be non-invasive, although the possibility remains that the presence of photographers in proximity to the study-species may affect its behaviour.

The overall aim of the current study was to determine whether spots on the flanks of _C. taurus_ could provide a reliable, non-invasive method to unambiguously identify individual sharks under natural conditions. To achieve this we aimed to (1) assess the temporal stability of spots in a captive population of _C. taurus_ housed in a public display aquarium over a 3-year period, and (2) use photographic images spanning 16 years to examine the long-term stability of spots in natural populations.

Validation of a PID approach would allow for intensive, non-invasive monitoring of the shark population and could, importantly, replace invasive approaches to gain information on...
Photographic identification of *Carcharias taurus*

Marine and Freshwater Research 323

population size and structure, growth rates, mortality, habitat occupancy, sex ratios, sexual segregation and the timing, scale and patterns of individual shark movements.

**Materials and methods**

**Features used for shark identification**

*Carcharias taurus* has bronze-grey skin, is paler ventrally, with some individuals displaying dark margins to their fins. Dark spots are found on all body surfaces, including the fins, but are most abundant posterior to the first dorsal fin and anterior to the caudal peduncle. Spots vary in size, shape, density, number and position on left and right flanks of individuals and between individuals. Two spot-types were observed on sharks; small, very dark spots (Fig. 1a) and, more commonly, larger spots comprising pigmentation that was slightly darker than that of the general body surface (Fig. 1b). Both spot-types were visible in photographic images and proved suitable for mapping their distributions on the flanks of *C. taurus*.

Several sharks exhibited additional features that assisted in their identification. Puncture wounds and lacerations to the body and fins of female sharks (Fig. 1c) were observed during the mating season, whereas other injuries appeared to be permanent, such as the loss of significant portions of fins (Fig. 1d) and jaw damage (Fig. 1e). Other features for unambiguous identification of individuals included the appearance of tag-insertion sites and fouled tags (Fig. 1f), embedded fishing hooks (Fig. 1g) and attached fishing-line (Fig. 1h).

*Carcharias taurus*: in captivity

**Study site**

The captive study population of seven *C. taurus* was maintained in a 2.2-megalitre (ML) public display aquarium at Underwater World (UWW) Mooloolaba, Queensland, Australia. Fresh seawater was supplied at ambient ocean temperature at a rate of 0.9 ML day$^{-1}$, resulting in a seasonal variation in water temperatures between 18$^\circ$C and 29$^\circ$C. The aquarium was fully enclosed, with artificial lighting from 0800 to 1900 hours each day.

The study population comprised two female and three male sharks captured from southern Queensland waters and two female sharks captive-born at UWW. All sharks were mature, between 2 and 3 m total length ($LT$), similar to those routinely encountered by divers at UWW aggregation sites, and exhibited some behaviours (e.g. seasonal mating activity) similar to those displayed by individuals in the natural environment.

**Image capture**

Photographic images of sharks at UWW were obtained using digital cameras in underwater housings (Video = DSR-HC1000 & MPK-PHP, Sony, Tokyo, Japan; Still = DSC-100, Sony, Tokyo, Japan & SLR-DC, Ikelite, USA; EOS 400D, Canon, Tokyo, Japan & Invader, Amphibico, Canada). Digital images of the left and right flanks of the seven captive grey nurse sharks were taken from inside the aquarium by the primary author and UWW staff over a period of 3 years (February 2004–February 2007), and included a focussed study in which images were taken monthly for 14 consecutive months (February 2004–March 2005).

**Analysis of images**

All spots identified in images taken at the start of the study were compared with all spots identified in subsequent images and assessed by eye for changes in spot number, spot appearance, spot location and other body surface features (e.g. scars, fin damage or mating injuries). Additionally, all individual spots on one flank of each captive shark were allocated an identification number in images taken at the start of the study. The presence/absence, appearance and relative position of each numbered spot was determined in all subsequent images. We ensured that the same spot was being compared by using relative inter-spot distances and distances from spots to fixed features (e.g. origin of the first dorsal fin, insertion of the pelvic fins, etc.). Images of *C. taurus* were not used if spots could not be clearly discerned owing to poor image quality (e.g. significant presence of backscatter, poor contrast, lack of resolution or because the image was out of focus).

*Carcharias taurus*: in the natural environment

**Study sites**

Two sites in southern Queensland waters (Flat Rock; 153$^\circ$33.129′E, 27$^\circ$23.445′S and Wolf Rock; 153$^\circ$33.129′E, 25$^\circ$54.630′S) were used to explore the applicability of PID-based tagging and recognition of sharks in the natural environment. Flat Rock is characterised by two rock formations that break the surface and a sandy bottom at a depth of 25 m from which steep granite walls rise to form distinctive gutters (Ford et al. 2003). Images of *C. taurus* were taken at Flat Rock in the ‘shark gutter’ between 1991 and 2006. Wolf Rock comprises four steep-walled pinnacles, two of which are exposed under all tidal conditions. Individual sharks were photographed at depths of 10–35 m between 2003 and 2007. The study population comprised mature male and female *C. taurus* between 2 and 3 m $LT$.

**Image capture**

Photographic images of wild *C. taurus* used in the present study were taken by the primary author (2001–2007) and by recreational divers (1991–2007). Free training workshops conducted over 6 years (2002–2007) were used to encourage the general diving community to participate in the supply of data on shark numbers at aggregation sites. In addition, contributions of images of sharks were specifically solicited from divers (2004–2007). To aid this process, regular presentations were held at dive shops and dive clubs to provide information on how to dive responsibly with grey nurse sharks and aspects of the species’ biology, while simultaneously recruiting volunteer underwater photographers for the study. These divers submitted high-resolution digital images together with dive locations and dates to the primary author. In 2004 and 2005 a monthly prize was awarded to the photographer of a randomly selected *C. taurus* image to encourage the diving community to provide images for this project.

**Analysis of images**

Images of sharks in the natural environment were catalogued by flank (left or right), sex, date of image-capture and geographical locality. A subset of images from 12 fieldtrips involving nine photographers was analysed to determine the approximate
Fig. 1. Features of use in shark identification. (a) Small, black pigment spots (infrequent); (b) variable-sized dark grey spots (common); (c) mating scars (seasonally common); (d) fin damage; (e) jaw deformity/damage; (f) tag insertion site (labelled I) fouled tag (labelled F), and abrasion caused from fouled tag (labelled A); (g) embedded fishing hook and trailing line; (h) fishing line and related scarring.
proportion of images suitable for identification purposes. The
criteria used previously to determine whether images of captive
sharks were suitable for analysis were applied to this subset of
images. Photographic ‘recaptures’ of individuals were based on
matching the distributions and appearances of spots by compar-
ing all spots identified in the initial image with those identified in
the recapture images. Additionally, for sharks where the recap-

capture period exceeded 23 months all individual spots visible in
the initial image were numbered and compared with the corre-
sponding spots in the last image of that individual, as described
for captive sharks. Independent verification of these shark’s
identities was provided by the presence of permanent scars,
derformities and other unique body or fin features.

Results

Verification of spot persistence: Carcharias taurus
in captivity

Fig. 2. Paired images of individual captive sharks showing the persistence of spot-patterns. (a) February 2004 and (b) February 2007 = female Carcharias taurus, showing a subset of nine matched spots and tissue loss to the trailing edge of the first dorsal fin (labelled ‘∗↑’) (c) March 2004 and (d) February 2007 = male C. taurus, showing a subset of nine matched spots.

Images of both flanks of the seven captive sharks showed that
spots were consistent with respect to their relative sizes and posi-
tions throughout the 3-year study period (Fig. 2a–d). Although
individual spots appeared to vary in density, multiple images
of the same shark taken on a single day showed that this was
strongly influenced by ambient light conditions (Fig. 2a, cf. b),
the angle of the shark relative to the focal axis of the camera and
the amount of particulate matter in the water causing backscatter
(Fig. 2c, cf. d). The clearest images were obtained under
uniform, diffuse light in clear water conditions with the shark’s
flank perpendicular to the camera’s focal axis.

Under suboptimal lighting conditions, such as the dap-
pbled light in Fig. 2a, spot visibility was diminished. Similarly
backscatter as seen in Fig. 2c, may result in false spots being iden-
tified. Small or pale spots falling in areas of deep shadow or high
reflectance were either difficult to resolve or were not visible.
Some variation occurred in the visibility of specifically identi-
ified (numbered) spots that were monitored on a monthly basis
for 14 months (Table 1). This apparent variation was a result of a
combination of suboptimal lighting conditions or when an image
was taken that inadvertently failed to include part of the spotted
flank rather than a real change in spot presence. In four of the
captive sharks all of the spots that were identified and numbered
in the initial image were identified in all subsequent images. The
Table 1. Individual spots matched through time for captive Carcharias taurus

<table>
<thead>
<tr>
<th>Shark</th>
<th>Sex</th>
<th>Cumulative month from start of study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>C1</td>
<td>♂</td>
<td>19</td>
</tr>
<tr>
<td>C2</td>
<td>♂</td>
<td>21</td>
</tr>
<tr>
<td>C3</td>
<td>♂</td>
<td>20</td>
</tr>
<tr>
<td>C4</td>
<td>♂</td>
<td>26</td>
</tr>
<tr>
<td>C5</td>
<td>♂</td>
<td>(8)</td>
</tr>
<tr>
<td>C6</td>
<td>♂</td>
<td>(7)</td>
</tr>
<tr>
<td>C7</td>
<td>♂</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2. Total number of image resights for individual wild Carcharias taurus

<table>
<thead>
<tr>
<th>Sex/Flank</th>
<th>TS</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>♂/Left</td>
<td>57</td>
<td>1</td>
</tr>
<tr>
<td>♂/Right</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>♂/Left</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>♂/Right</td>
<td>32</td>
<td>9</td>
</tr>
</tbody>
</table>

Verifying spot persistence: Carcharias taurus in the natural environment

Of a subset of 800 images of grey nurse sharks, taken at Wolf Rock and Flat Rock on 12 different occasions and by nine different photographers, 615 (77%) were of sufficient quality for an individual to be recognised. Four hundred unique flanks were identified based on their spots, with 40% (162 out of 400) photographically recaptured at least once subsequent to their initial documentation. The minimum possible number of individual sharks in the recapture analysis was 89, assuming that the 48 right flanks of female sharks belonged to the same sharks for which there were 57 left flank views and vice versa for male sharks (Table 2). Six female sharks were unambiguously matched for both flanks. Consequently, the maximum possible number of individual sharks in the analysis was 156. About half (44%) of the sharks were resighted within a month of their initial sighting and image capture, with the remaining sharks resighted up to nine times over a period of 5115 days (Tables 2, 3). There was no indication of spots changing over the inter-observation periods in regard to the 162 flanks that were recorded on at least two occasions. Fourteen sharks were photographically recaptured between 23 months and 3 years subsequent to their initial images being captured, with one shark matched after 14 years. Individual spots were numbered on the initial images of these fourteen sharks and no change in the presence, relative position or size of spots was observed when compared with the same spots in the final images (Table 4). Additionally, six of these fourteen sharks had another permanent feature (e.g. fin notches, scars, embedded hooks) that allowed for verification of a shark’s identity independent of its spots. These six sharks were successfully matched using both their spots and the other identifying feature(s), for example, images of a shark with a particular mouth deformity obtained 23 months apart clearly showed the same 38 prominent spots in both images (Fig. 3a, b). Similarly, 22 distinct spots did not change demonstrably over 14 years on a less heavily spotted shark that could be identified by a prominent scar along its right flank (Fig. 3c, d).

Several female sharks had mating related injuries comprising tooth punctures and superficial lacerations. While healing, tooth punctures caused from mating could be mistaken as ‘additional
Table 3. Total number of resights for different times at liberty for wild Carcharias taurus

<table>
<thead>
<tr>
<th>Sex/Flank</th>
<th>TS</th>
<th>&lt;1</th>
<th>1-2</th>
<th>3-4</th>
<th>14+</th>
<th>TR</th>
</tr>
</thead>
<tbody>
<tr>
<td>♂/Left</td>
<td>57</td>
<td>78</td>
<td>9</td>
<td>8</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>♂/Right</td>
<td>48</td>
<td>71</td>
<td>16</td>
<td>3</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>♀/Left</td>
<td>25</td>
<td>34</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>♀/Right</td>
<td>32</td>
<td>39</td>
<td>15</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4. Individual spots matched through time for wild Carcharias taurus

<table>
<thead>
<tr>
<th>Shark</th>
<th>Sex</th>
<th>UF</th>
<th>D</th>
<th>S-1</th>
<th>S-2</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>♂</td>
<td>A</td>
<td>748</td>
<td>30</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>♂</td>
<td>P</td>
<td>742</td>
<td>12</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>♂</td>
<td>A</td>
<td>710</td>
<td>16</td>
<td>16</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>♂</td>
<td>A</td>
<td>1075</td>
<td>22</td>
<td>22</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>♂</td>
<td>P</td>
<td>1053</td>
<td>31</td>
<td>31</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>♂</td>
<td>A</td>
<td>918</td>
<td>26</td>
<td>26</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>♂</td>
<td>A</td>
<td>1438</td>
<td>22</td>
<td>22</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>♂</td>
<td>A</td>
<td>1374</td>
<td>13</td>
<td>13</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>♀</td>
<td>P</td>
<td>707</td>
<td>38</td>
<td>38</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>♀</td>
<td>P</td>
<td>735</td>
<td>30</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>♀</td>
<td>A</td>
<td>734</td>
<td>25</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>♀</td>
<td>P</td>
<td>1087</td>
<td>3</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>13</td>
<td>♀</td>
<td>P</td>
<td>5116</td>
<td>22</td>
<td>22</td>
<td>100</td>
</tr>
<tr>
<td>14</td>
<td>♀</td>
<td>A</td>
<td>952</td>
<td>13</td>
<td>13</td>
<td>100</td>
</tr>
</tbody>
</table>

Photographic identification of Carcharias taurus

Photographic identification is a successful non-invasive tagging method for studying the behaviour, ecology and population biology of elasmobranch species (Arzoumanian et al. 2005; Meekan et al. 2006; van Tienhoven et al. 2007). A review of grey nurse shark tagging research conducted on the Critically Endangered east coast population of Carcharias taurus concluded that future research involving tagging should be limited to short-term deployment, such as pop-off archival tags, and that permanent tagging cease (Department for the Environment and Heritage 2003). However, as one action of the Recovery Plan is to monitor the population’s status, application of non-invasive PID could be used to fulfil this requirement. The eastern Australian grey nurse shark population is particularly well suited for such an approach as the sharks are easily accessible and readily observed by divers at aggregation sites. Additionally, as a shark-dive ecotourism

spots’ (similar to those identified in Fig. 1a). However, they are temporary marks that on close inspection are different in colour and can be distinguished from permanent spots. In eighteen sharks first sighted with mating wounds, resightings indicated that these wounds healed within about 3 months of the initial injury. Other injuries, such as those that resulted in tissue loss to the caudal or pectoral fins (Fig. 4) showed evidence of tissue regrowth, although damage was still apparent after 22 months (Fig. 4c cf. d).

The appearance of fin notches (defined as healed, minor ‘v- or c-shaped’ tissue loss to the leading or trailing edge of fins) was highly variable. Of 10 sharks that had fin notches on their first sighting, three were seen to have healed completely before their subsequent resighting (two within 1 month and one within 23 months), whereas in two individuals the fin notches were still clearly visible after 2 and 3 years respectively. Fin notches observed on the remaining sharks were unchanged in subsequent observations, which ranged between 2 weeks and 1 year. Large, obvious, fully healed scars resulting from considerable tissue damage or loss (e.g. Fig. 1d, e) exhibited minimal change through the course of the present study.

Observations of fishing tackle attached to seven sharks indicated that its persistence varied considerably. A hook remained embedded in a caudal fin (Fig. 1g) for 1 month only, whereas a hook with trailing line remained embedded in the jaw of another shark for at least 1 year, although it was no longer evident after 2 years. Fishing line seen protruding from a gill slit in one shark persisted for at least 35 months.

Discussion

Photographic identification is a successful non-invasive tagging method for studying the behaviour, ecology and population biology of elasmobranch species (Arzoumanian et al. 2005; Meekan et al. 2006; van Tienhoven et al. 2007). A review of grey nurse shark tagging research conducted on the Critically Endangered east coast population of Carcharias taurus concluded that future research involving tagging should be limited to short-term deployment, such as pop-off archival tags, and that permanent tagging cease (Department for the Environment and Heritage 2003). However, as one action of the Recovery Plan is to monitor the population’s status, application of non-invasive PID could be used to fulfil this requirement. The eastern Australian grey nurse shark population is particularly well suited for such an approach as the sharks are easily accessible and readily observed by divers at aggregation sites. Additionally, as a shark-dive ecotourism
industry has operated for many years, there is an extensive photographic archive that allows us to conduct retrospective analyses on this population.

Our study is the first to use both captive and wild *C. taurus* to examine the persistence of spots over many years. The use of captive animals allows the identity of the sharks studied to be known with a certainty that is difficult to achieve using animals in the wild. The captive population also allows images to be collected at specific times and under controlled conditions, rather than relying on opportunistic observations in the natural habitat. Our study of captive and wild *C. taurus* confirms that spots remain fundamentally unchanged for at least 3 years. Additionally, a single wild shark that was unambiguously matched from a unique scar across its flank and whose spots showed no change in relative position, size or appearance for at least 14 years supports the likelihood of long-term spot-persistence.

Healed wounds on the fins and tail are used as unique identifiers in PID studies of basking sharks (*Cetorhinus maximus*), nurse sharks (*Ginglymostoma cirratum*), great white sharks (*Carcharodon carcharias*), dolphins and whales (Hammond 1990; Strong *et al.* 1996; Castro and Rosa 2005). However, Auger-Méthé and Whitehead (2007) report that a small dorsal notch on a long-finned pilot whale (*Globicephala melas*) visible in 1998 was no longer apparent in 2000. Other concerns about the loss of distinguishing marks are noted in respect to fin damage in *C. carcharias*, where subsequent injuries can remove features previously used for individual identification (Domeier and Nasby-Lucas 2006). In our study *C. taurus* can be seen with fresh, superficial wounds resulting from mating activities at certain times of the year. Most of these wounds appear to heal completely within about 3 months and even in sharks with more severe tissue loss there appears to be tissue regrowth that changes the appearance of the wound over time. These observations reinforce the importance of using spots or other natural patterns in conjunction with other potential identifying features for recognition of individuals.

Considerable variation can occur in the utility of images for identification purposes due primarily to issues of image

---

**Fig. 3.** Paired images of individual wild sharks showing persistence of spots over 23 months. (a) August 2004, and (b) July 2006 = male *Carcharias taurus*, showing a subset of five matched spots, and over 14 years, (c) July 1991 and (d) July 2005 = male *C. taurus*, showing a subset of five matched spots.
resolution and contrast, artefacts and subject orientation. Most modern (film or digital) cameras can easily provide images of sufficient resolution for image analysis, although a shark that only takes up a small proportion of the image area may still prove unusable. Similarly, individual frames taken from a video sequence may lack sufficient resolution for accurate analysis. The spots on *C. taurus* can sometimes appear muted; under these circumstances digital image enhancement software is useful in increasing image contrast to make spots more obvious. Further possible confounding factors relate to lighting conditions and mating wounds. Suspended particulate matter in the water may produce artefacts that could be mistaken for natural spots or which may obscure spots. Similarly, healing puncture wounds (that often result from mating) can resemble small dark spots that could be mistaken for permanent spots or which may obscure permanent spots. Dappled light may obscure spots (see Fig. 2) and is most likely to occur in shallow, sunlit waters (e.g. some spots were obscured in images of captive sharks where substantial artificial lighting was present). This is not a significant problem in regard to wild *C. taurus* as there is a more even light environment at depths of 10–30 m, where sharks are generally photographed. Finally, the orientation of a shark with respect to the focal axis of the camera is of importance, particularly if automated spot-recognition programs (Arzoumanian *et al*. 2005; van Tienhoven *et al*. 2007) are to be used. The position of spots will appear to change relative to one another and to fixed features as the obliquity of view increases and will be compounded by flexion of the body if the shark is swimming. Our decision not to use automated spot-recognition software was related, in part, to these factors and to the fact that there are no data to suggest that automated methods, although possibly faster, are more accurate than manual pattern matching.

Fig. 4. Images of individual wild sharks showing tissue regrowth on the caudal fin over 2 months (*a*) December 2006 and (*b*) February 2007 = female *Carcharias taurus*, and on the pectoral fin over 22 months, (*c*) March 2005 and (*d*) January 2007 = female *C. taurus*. 

Photographic identification of *Carcharias taurus* Marine and Freshwater Research 329
A potentially serious limitation of the PID process for *C. taurus* and other sharks lies with the ability to match images of the left and right flanks of an individual. When bilateral images are available the individual can theoretically be identified, irrespective of camera position. However, uncertainties arise if a shark is known only from a single view, for example of the left flank, as any image of a shark’s right flank may or may not be of that individual. This uncertainty can compromise estimates of population size where it is necessary to ensure that the number of individuals counted at a particular time and place is accurate. This uncertainty relating to the identity of individual sharks reduces the value of a PID approach for population estimates, unless (a) the appearance of both flanks of each individual is known or (b) images of a single (e.g. left) flank of the body are only collected for analysis. When possible, an image pair, comprising left and right flanks of an individual was recorded, but this was only possible when a specific shark was photographed from each side without having left the observer’s field of view or when the shark could be identified unambiguously by a feature visible from both viewpoints, such as jaw-embedded hooks with trailing fishing line. Importantly, unmatched left and right flank images can still provide valuable data on aspects of the shark’s biology, such as duration of occupancy, minimum abundance and sex ratios at specific sites and movements between sites.

 Globally many elasmobranch species are suitable for the application of PID. Whale sharks (*Rhincodon typus*), great white sharks (*C. carcharias*), manta rays (*Manta birostris*), zebra sharks (*Stegostoma fasciatum*), tiger sharks (*Galeocerdo cuvier*) and the grey nurse shark (*C. taurus*) are important species for ecotourism and have obvious spots/pigmentation patterns, making them suitable for the collection of photographic images. In addition, many less iconic elasmobranch species have pigmentation patterns and habits that would likely make them well suited to PID studies. Prime candidates for a PID approach are shallow water species that are easily photographed or captured; for instance, the Hemiscylliidae (longtailed carpet sharks), Orectolobidae (wobbegong sharks) and Heterodontidae (bullhead and horn sharks) contain many highly patterned species that inhabit a variety of shallow water habitats (Last and Stevens 1994; Campagno 2001). As these dermal species are relatively sedentary (e.g. Huveneers et al. 2006; Heupel and Bennett 2007) they lend themselves to future PID studies of their biology, although pigmentation pattern stability over time would need to be verified for each species.

 Two important aspects of using PID methodology in studying the east Australian population of *C. taurus* are that it fosters strong community involvement in the collection of data and that the results can be used to examine questions relating to juvenile, sub-adult, male and female (pregnant or not) sharks across the species’ range. This ability to collect such data using a non-invasive approach is of particular importance as conventional tagging methodologies have been shown to be unsuitable for this species owing to tag fouling and subsequent injuries (Department for the Environment and Heritage 2003; Dicken et al. 2006).

 We have verified the use of naturally occurring spots to identify and monitor individual *C. taurus* over multiple years along the east coast of Australia. The ongoing development of a comprehensive Australian east coast database and planned repeat surveys of aggregation sites along the east coast of Australia will provide for robust population estimates. Our investigations allow for the monitoring of the *C. taurus* population status through time, which is a key conservation requirement under the Australian Recovery Plan for the east coast *C. taurus* population.

**Acknowledgements**

We thank Professor A. Boulton and two reviewers for their constructive and helpful comments. We thank A. Kilpatrick, all the UWW crew, D. Harasti, N. Marsh, K. Holzheimer, A. Nel, K. and C. Phillips, A. Walsh, J. Foster and the numerous other volunteers for their support, field assistance and images of *C. taurus*. We thank B. Bruce for his support and feedback on earlier drafts. Underwater World (Mooloolaba), Sea World (Gold Coast) and the Queensland Parks and Wildlife Service supplied prizes to providers of shark images. Financial support was provided by the Department for the Environment and Heritage, the Queensland Government PhD Smart State Initiative and the Hermon Slade Foundation. In-kind support was provided by Queensland Parks and Wildlife Service – Moreton Bay District, Underwater World (Mooloolaba), Sea World (Gold Coast) and the Queensland Museum. This research was conducted in accordance with University of Queensland Animal Ethics Approval SBMS/196/04/DEH, SBMS/228/05/DEH, SBMS/560/06/DEH and SBS/640/07/HSF.

**References**


Manuscript received 12 October 2007, accepted 28 February 2008

http://www.publish.csiro.au/journals/mfr