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A computer-aided framework for subsurface identification of white shark pigment patterns

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Subsurface video footage can be used as a successful identification tool for various marine organisms; however, processing of such information has proven challenging. This study tests the use of automated software to assist with photo-identification of the great white shark *Carcharodon carcharias* in the region of Gansbaai, on the south coast of South Africa. A subsurface photo catalogue was created from underwater video footage. Single individuals were identified by using pigmentation patterns. From this catalogue, two images of the head for each individual were inserted into automated contour-recognition software (Interactive Individual Identification System Beta Contour 3.0). One image was used to search the database, the other served as a reference image. Identification was made by means of a contour, assigned using the software to the irregular border of grey and white on the shark's head. In total, 90 different contours were processed. The output provided ranks, where the first match would be a direct identification of the individual. The method proved to be accurate, in particular for high-quality images where 88.24% and 94.12%, respectively, were identified by two independent analysts as first match, and with all individuals identified within the top 10 matches. The inclusion of metadata improved accuracy and precision, allowing identification of even low-quality images.

Keywords: *Carcharodon carcharias*, computer-aided identification, contour recognition, mark-recapture, photo-identification, underwater

Introduction

White sharks *Carcharodon carcharias* are highly migratory marine predators and the oceans' largest carnivorous fish (Compagno 2002). Electronic tagging has shown that this species makes extensive oceanic migrations throughout its distribution range, which includes South Africa (Bonfil et al. 2005), Australia (Bruce et al. 2006), New Zealand (Duffy et al. 2012), and USA and Mexico (Boustany et al. 2002; Domeier and Nasby-Lucas 2008; Curtis et al. 2014). Despite these vast movements, site fidelity is a common behaviour, with individuals returning to key aggregation areas (Klimley and Anderson 1996; Bonfil et al. 2005; Domeier and Nasby-Lucas 2007; Jorgensen et al. 2010; Anderson et al. 2011).

The fact that white sharks migrate across a multitude of national borders confounds their conservation due to varying national laws and threats. The species has been categorised as 'Vulnerable A2cd+3cd' since 1996 in the IUCN Red List of Threatened Species (Fergusson et al. 2009). It is also listed on international agreements such as UNCLOS (United Nations Convention on the Law of the Sea), CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) Appendix II, and CMS (Convention on the Conservation of Migratory Species of Wild Animals) Appendices I and II, and is protected nationally in Australia, Croatia, the European Union, Mexico, Namibia, New Zealand, South Africa and all US waters (Camhi et al. 2008). Given their highly mobile nature and threatened status, the need for further study on this shark species is imperative.

Photo-identification (photo-ID) is one approach used to estimate population size and residency of marine organisms (Delaney et al. 2012). It is a non-invasive technique and has been used successfully on a variety of marine species (Langtimm et al. 2004; Huffard et al. 2008; Reisinger and Karczmarski 2010; Reisinger et al 2011). Photo-ID has provided information on white shark longevity (Anderson et al. 2011), site fidelity (Bonfil et al. 2005; Anderson et al. 2011; Nasby-Lucas and Domeier 2012), sexual composition (Nasby-Lucas and Domeier 2012), migratory behaviour (Bonfil et al. 2005) and population size (Chapple et al. 2011; Sosa-Nishizaki et al. 2012; Towner et al. 2013a). Dorsal fin identification of white sharks has been a widely used approach; however, characteristics of the fin are subject to changes over time, which may complicate the matching process (Chapple et al. 2011; Delaney et al. 2012; Towner et al. 2013a). Consistent effort is required to avoid re-identifying the same shark as multiple individuals (Towner et al. 2013a). In addition, the use of supplementary methods can increase the reliability of individual identification (Holmberg et al. 2009). In white sharks, pigmentation patterns or the irregular border between the grey dorsal and white ventral part of the body can be used to distinguish specific individuals under water (Domeier and Nasby-Lucas 2007). Final identification of individuals can then be made if both the left and right sides of each animal are catalogued, due to asymmetry in pigment patterns (Domeier and Nasby-Lucas 2007). Like the dorsal fin characteristics, these pigment patterns can change over time (Domeier and Nasby-Lucas 2007; Robbins and Fox 2012). This could influence their suitability for long-term studies and, although Nasby-Lucas and Domeier (2012) have identified individuals successfully using pigmentation patterns over a period of nine years, long-term studies should monitor these changes cautiously. Photo-identification methods must allow individuals to be distinguished and re-identified in subsequent years (Marshall and Pierce 2012).

The coastal region south-east of Gansbaai on the south coast of South Africa makes a model location for photo-identification and mark-recapture studies on white sharks because several individuals show fidelity to this site (Bonfil et al. 2005; Towner et al. 2013a). However, given the large number of sharks that aggregate in the study area (Towner et al. 2013a), identification techniques must be able to process and quantify extensive datasets. Computer-based identification reduces the identification time and thus is a suitable application (Van Tienhoven et al. 2007).

The objective of this study was to provide a computer-aided subsurface identification tool for white sharks, which complements dorsal fin identification and potentially reduces processing time. Specifically, we tested whether the individual identification process can be automated using pigment patterns.

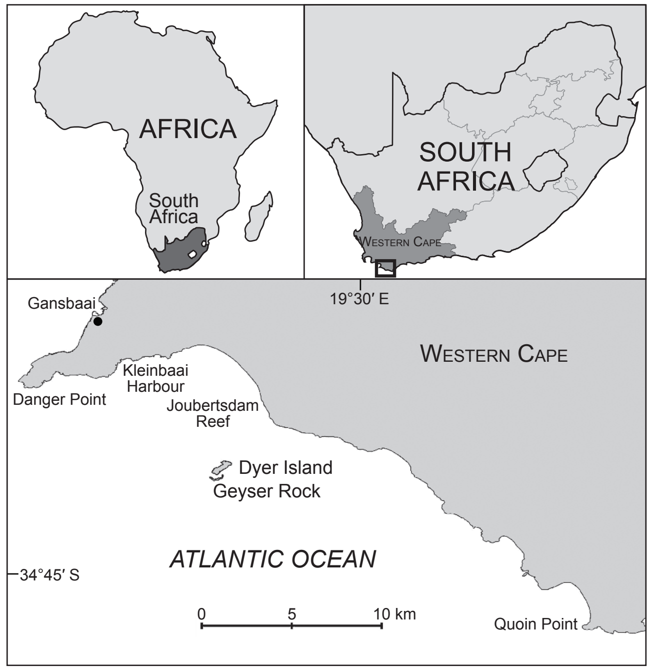

Figure 1: Map of study site, Western Cape, South Africa

Material and methods

Study site

The study site is situated on the south coast of the Western Cape, South Africa (Figure 1). It is relatively exposed, with the western and eastern boundaries being Danger Point (34°37.50′ S, 19°17.30′ E) and Quoin Point (34°47.28′ S, 19°39.15′ E), respectively. In this area, eight operators are permitted to conduct white shark cage diving, which began in South Africa in the early 1990s (Kroese 1998). White sharks are observed most commonly around the periphery of Dyer Island and Geyser Rock (34°40.67′ S, 19°23.86′ E), which are located 8 km offshore of the nearest harbour town, Kleinbaai.

White shark abundance peaks seasonally from April to July (Ferreira and Ferreira 1996; Towner et al. 2013b), which coincides with the breeding season of Cape fur seals *Arctocephalus pusillus pusillus* and more-stable water temperatures (Towner et al. 2013b). This is also the optimal time for increased underwater visibility, which averages 5–10 m (AVT pers. obs.). The size of white sharks at Dyer Island ranges from 1 m to 5.5 m total length (TL), with most individuals being 3–3.3 m (AVT unpublished data). The sex ratio is equal in winter and there is a higher ratio of females and unsexed juveniles in spring and summer (Ferreira and Ferreira 1996; Towner et al 2013b).

Data collection

Observations were made on 13 boat trips during 12 days in May 2011, with trip durations of between 2 and 4 hours. Filming of the sharks took place from a 12-m shark cage diving vessel, which was permitted to use both chum and bait – a mixture of teleost-based fish oils and heads – as a method to attract sharks (for further details of the method see Strong et al. 1992). Underwater video footage was taken from the boat deck, 1 m above sea level, by deploying a handheld pole with a custom-mounted GoPro high definition (HD) camera using the widest-angle format. In addition to these videos recorded by MD, 660 minutes of underwater footage was sampled by L Fourie (Fasttrax Marine, Hermanus) in the same region from July and August 2008, and from June until September 2009. Those videos were also recorded from a shark cage diving vessel by handheld pole, but they lacked HD resolution and used a narrower angle of view. Sex was determined by the presence or absence of claspers, which were clearly visible when present. Sex and permanent trauma-induced markings, such as damaged fins, were used as further identification features between years. Other features (e.g. bite marks and fishing hooks) were recorded and contributed to identification within short time-periods, as wound-healing is known to be rapid in the species (Domeier and Nasby-Lucas 2007; Towner et al. 2012).

Subsurface identification

Domeier and Nasby-Lucas (2007) found that three body regions were most suitable for the identification of white sharks on account of the high variability between individuals. These regions were: (i) the extension of the interbranchial septum, known as the gill flaps; (ii) the area around the pelvic fin; and (iii) the lower lobe of the caudal fin. We assigned different pigment pattern types, using the definitions of Domeier and Nasby-Lucas (2007), to each of these regions. With regard to the gill flaps, white colouration on only the first gill flap was classified as Type I, on the first and second gill flaps as Type II, and on the first, second and third gill flaps as Type III. Regarding the pelvic fins, grey colouration extending continuously from the body onto a pelvic fin was classified as Type I. Type II showed a discontinuous grey colouration, and in Type III the grey colouration on a pelvic fin was completely separated from the grey body colouration. With regard to the caudal fin, an entirely grey lower lobe was classified as Type I, Type II had a small white islet on an otherwise grey lower lobe and Type III showed white pigmentation only on the leading edge of the lower lobe, but no white islet. Type IV caudal fins showed white along the leading edge of the lower lobe extending to the centre, either as a small white islet or a larger patch. Final identifications were made through visual comparison. We concluded that each of the three regions could be used for the identification process.

Computer-aided identification

The software Interactive Individual Identification System Beta Contour 3.0 (I3S Contour), available from http://www.reijns.com/i3s, was used for the computer-aided identification process. I3S Contour is based on the spot-recognition program I3S, initially developed as an identification tool for the natural variation in spot patterns of spotted raggedtooth sharks *Carcharias taurus* (Van Tienhoven et al. 2007). Additionally, this software was found to be a reliable identification tool for whale sharks *Rhincodon typus* (Speed et al. 2007). The updated contour software contains a new function called 'generic'. This function was especially designed for the single contour per image and side exhibited by an animal such as the white shark. The software requires start and end points assigned by the user. To process new images or load images from known individuals into the database, the user selects reference points along the irregular border of the shark's head by using a computer mouse. The contour is automatically assigned between the points. The optimal contour between these reference points is compared using a semi-automatic tracing algorithm. The search function then compares the annotated individual image against all images within the database. The program lists the results, ranked in descending order, with the most likely matches being assigned the highest rank. Final matching is achieved visually. Furthermore, I3S allows the user to include metadata in the search process, thus reducing processing time and improving accuracy. For further detail see Den Hartog and Reijns (2011).

Data analysis

Images were taken as snapshots from videos and saved as JPEG-files. Each shark was logged with an individual number. Identification of new individuals was made by the visual comparison of images already taken, using the subsurface identification method of Domeier and Nasby-Lucas (2007). This resulted in a subsurface photo catalogue with clearly known individuals. The subsurface identification process was conducted by two people independently, to decrease the likelihood of processing

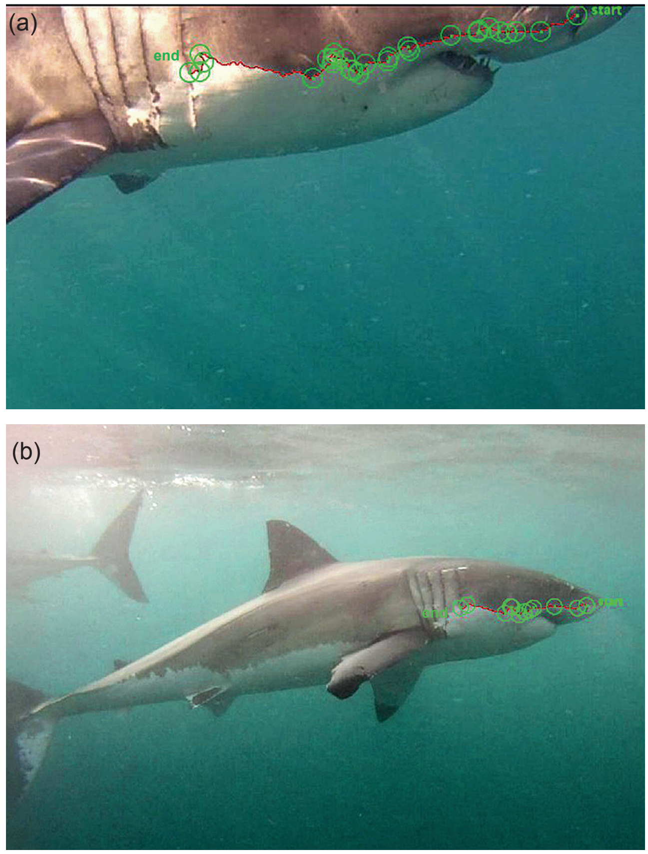

Figure 2: (a) An example of a white shark reference image and (b) the counterpart image used to search the database, showing the contour along the irregular border computed by the software and used for the computer-aided identification process

error. For the purpose of the computer-aided identification process, a second catalogue with known individuals from the subsurface photo catalogue was constructed. This catalogue required two images of the same individual, recorded at different times, one being a reference image and the other a counterpart image used to search the catalogue. If the quality of a corresponding pair of images differed, the higher quality image was used for reference and the other, the counterpart image, was used for purposes of searching the database. The body region selected for the computer-aided identification was different from the regions used to assign pigment pattern types by Domeier and Nasby-Lucas (2007), because the software requires fixed start and end points to assign a contour between these points. Therefore, the contour along the irregular border between the ventral white and dorsal grey colouration from the posterior edge of the nostril (start point) to the first gill slit (end point), was used for computer-aided identification (Figure 2). Consequently, only images of the head and the gill regions of the shark from the subsurface photo catalogue (all individuals had an assigned gill pattern type) were used. If the border was not separated by the nostril, the point on the border directly above the nostril was used. If the border was not separated by the first gill slit, the point directly below the first gill slit was used.

Images in which the border was not clearly and completely visible were categorised as 'low' quality (Figure 3a), those where the border was completely visible but the image resolution was low were categorised as 'medium' (Figure 3b), and those where the border was completely and clearly visible and the resolution was high were categorised as 'high' (Figure 3c).

The shark's orientation was recorded as 'angled' or 'near-perpendicular' to the camera, to investigate whether its position would affect the performance of the software.

Three runs were made. In the first run, only the contour assigned by the software was used to search the database, whereas in the remaining runs, metadata were used as further criteria. The second run contained metadata about gill pattern type (Type I, II or III), sex (male, female, unknown), the presence of permanent trauma-induced markings (yes, no) and the side of the shark shown in the image (left, right). The last run contained additional information about the pelvic (Type I, II, III) and caudal fin pattern type (Type I, II, III, IV) and more detailed information about the permanent marks (i.e. location on the shark's dorsal or pelvic fin).

The difference between the rank assigned by the software and the true match, known from the number assigned in the subsurface catalogue, was then investigated. To test the performance and accuracy of the software, the rankings obtained were categorised as top 1 (direct match), 5, 10, 20 and above top 20. The complete analysis was performed by two persons independently to allow for variations in assigning the contour, as well as to test the precision of the software. A Wilcoxon signed-rank test was applied to test whether the two datasets differed significantly.

Results

Subsurface identification

In addition to the 660 minutes of video material recorded between July 2008 and September 2009, over 880 minutes of video were captured in May 2011. In total, 136 different sharks were catalogued, including 55 images where at least one pigment pattern type from one side was missing. However, it was possible to enter them as distinct from each other due to the comparison of the remaining patterns and the presence of distinct permanent trauma-induced markings. Approximately 62% (n = 85 sharks) were females and 37% (n = 50 sharks) males. Sex was unknown for one shark. Of the total, 83 sharks were re-identified at least once, including 10 that occurred in two different months, 22 in different years and 5 in all observed years. Seven individuals were recorded in 2008 and returned in 2011. Among the re-identified sharks, both the pigment patterns and the border between the grey dorsal and white ventral part of the head area did not show any obvious changes. Most of the sharks were symmetric in pigment pattern types, but the detailed appearance of the border was asymmetric. Of the sharks that had asymmetric pigment pattern types, 17 had asymmetric gill pattern types, 36 had asymmetric pelvic fin pattern types, 14 had asymmetric caudal fin pattern types and one had asymmetric pigment pattern types in all three body regions.

Computer-aided identification

The irregular border in the head region for at least two images of the same shark was available for 69 individuals from the subsurface catalogue. For 21 of these individuals, both left and right side images were available, leading to a total of 90 different contours due to asymmetric patterning (i.e. where the border between the grey and white part of an individual shark's head was different between the left and right side). Hence the database contained 180 images in total that were used for the identification process, i.e. one reference image and one counterpart image with which

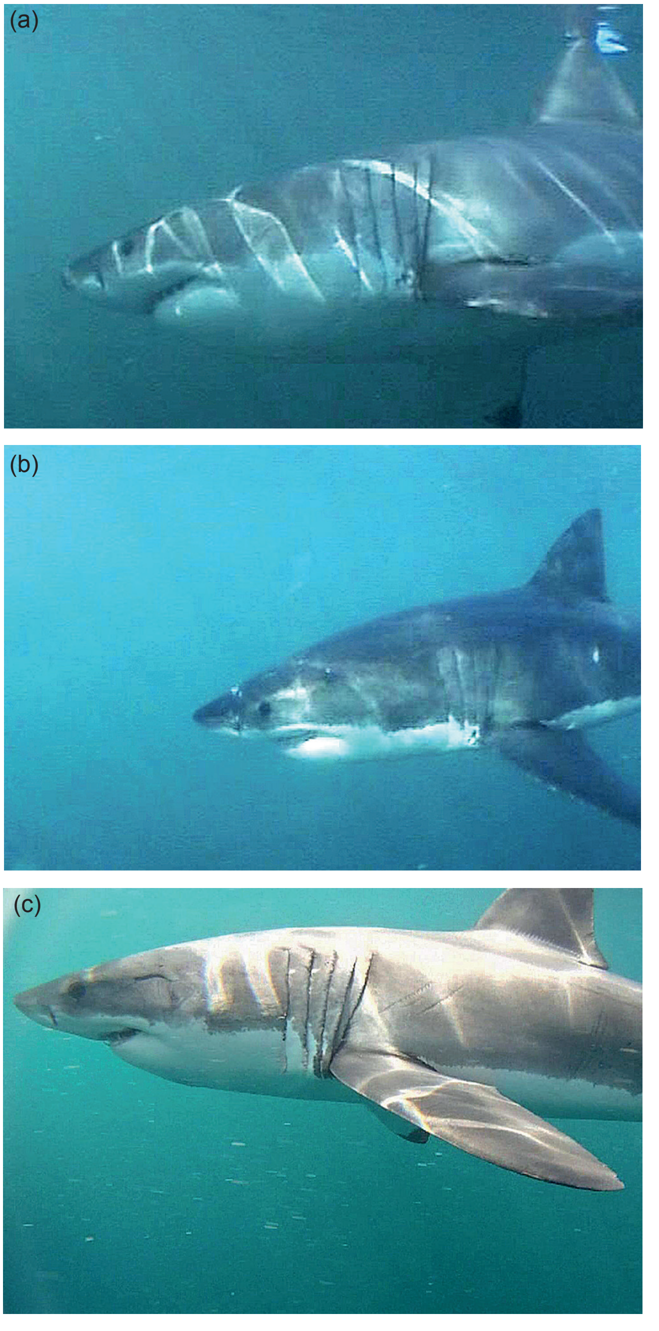

Figure 3: Examples of white shark images rated as (a) low quality (as a result of uneven/reflected light, the irregular border is not entirely visible), (b) medium quality (the irregular border is visible, but the image resolution is low), and (c) high quality (the irregular border is visible in detail)

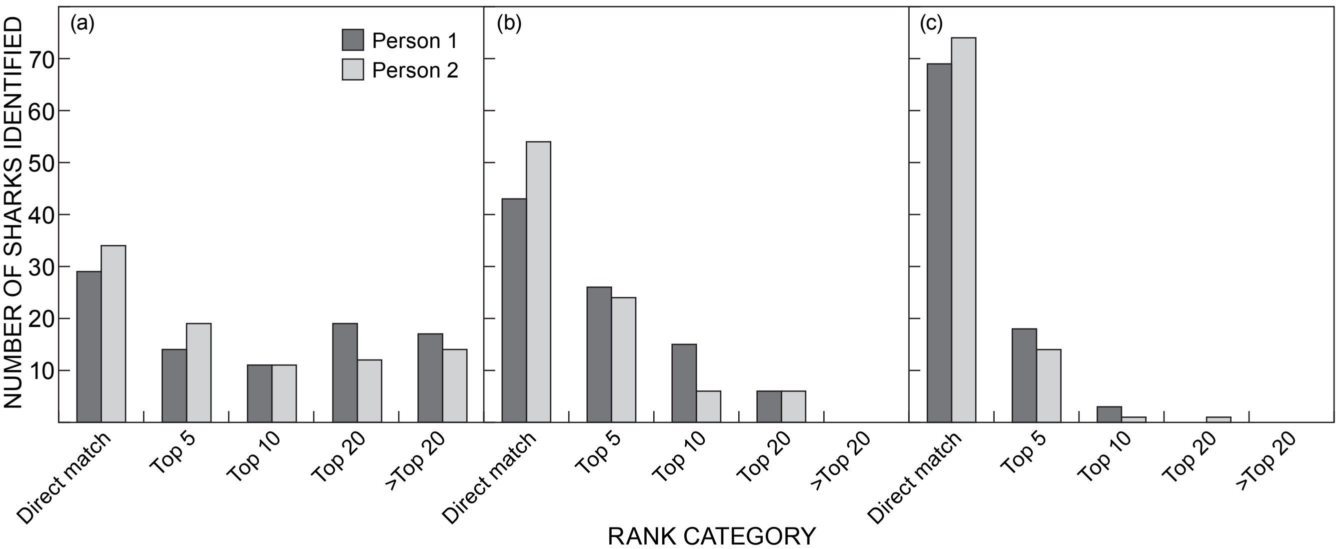

Figure 4: Results of the computer-aided identification process performed by two persons independently of each other, expressed as the frequency of identified individuals per rank category when (a) only the contour assigned by the software to the irregular border along a shark's head was used; (b) partial metadata were included; and (c) additional metadata were included. Direct match = all individuals ranked at first position; top 5 = ranks 2–5; top 10 = ranks 6–10; top 20 = ranks 11–20; >top 20 = ranks >20

to search for each of the 90 different contours. In all, 40 images were rated as low quality, 93 as medium quality and 47 as high quality. Of the 47 high-quality images, all except two were recorded in high definition via GoPro HD camera. Although 72 images were recorded in HD resolution, some of these images were assessed as low or medium quality, due to water turbidity reducing visibility. In 81 images the shark was not completely perpendicular to the camera.

The software alone ranked 81.11% of the sharks within the top 20 matches for Person 1 and 84.44% for Person 2 respectively (Figure 4a). The median rank of all individuals was 3.5 with a median absolute deviation (MAD) of 3.7. Ranks ranged from 1 to 96. All of the shark images ranked outside the top 20 either represented sharks that were at an angle to the camera or cases where at least one of the two images was of low quality. In cases where sharks were outside the top 20 ranking for both persons, the angles was measured with ImageJ 1.46r (http://imagej.nih.gov/ij/). The angles of sharks that were outside the top 20 ranking for both persons were at least 16° (16°–27°) for either the reference or the search image and between 20° and 43° for the sum of both images. The use of metadata improved the identification process significantly. The first metadata run using gill pattern type, sex, the presence of permanent marks and the side of the shark as additional information identified 100% of the sharks within the top 20 matches for both people (Figure 4b). The median rank was 1 with MAD of 0 and a range of 1–18. The second metadata run, which contained the most information, identified all sharks within the top 10, except one individual, with 76.67% and 82.22% of the sharks directly identified by Persons 1 and 2, respectively (Figure 4c). The median rank was 1 with MAD of 0 and a range of 1–13.

There were 17 cases where both images (i.e. the reference image and the image used to search the database) were of high quality. Here, by comparing the contours alone without any metadata information, the software achieved a direct identification of 88.24% and 94.12% for Persons 1 and 2, respectively (Figure 5). The median rank for high-quality images was 1 with MAD of 0 and a range from 1–6. Of the images not directly identified, the shark was not perpendicular to the camera in either the reference or the search image, or both. However, all high-quality images were successfully identified after the first metadata run.

In the 13 comparisons where both images were of low quality, the rate of direct identification by the software alone was low, with 15.36% and 7.69% for Persons 1 and 2, respectively. The median rank for low-quality comparisons was 12 with MAD of 14.8, and the ranks ranged from 1 to 96. For Person 1, 23.08% were outside the top 20, and 46.15% in the case of Person 2. After the first metadata run, all individuals were identified within the top 20. The median rank was 3 with MAD of 3 and ranks ranged from 1 to 14. After the second metadata run, all individuals were identified within the top 10, with 69.23% and 61.54% of the individuals directly identified. The median rank was 1 with MAD of 0 and the ranks ranged from 1 to 9.

The use of metadata also improved precision of the software (Figure 6). The difference in ranks of the same individual investigated by the two persons ranged from 0 to 55, with 26.67% having no difference when only the contour assigned by the software was used (i.e. the rank found by Persons 1 and 2 was equal). After the first metadata run, the percentage with no difference in ranks increased to 41.11%, and increased further to 74.44% after the second metadata run. In addition, the ranks for each individual found independently by the two persons were not significantly different whether by using the software only (Wilcoxon signed-rank test: $V = 873.5$, $p = 0.139$), the first metadata run: $V = 543.5$, $p = 0.1272$) or the second metadata run ($V = 125$, $p = 0.6995$).

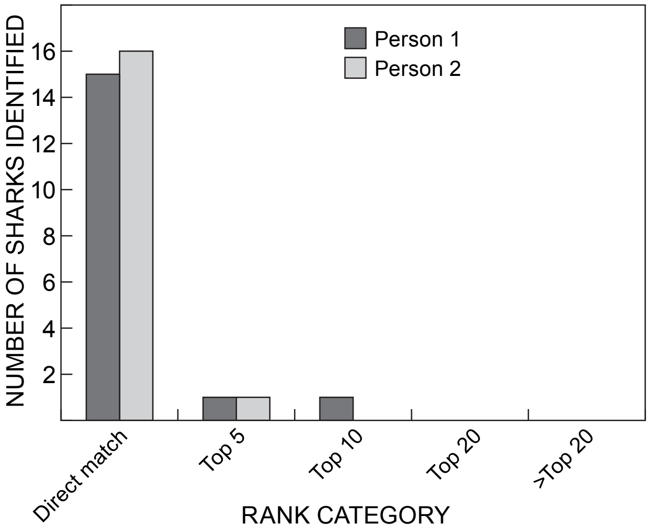

Figure 5: Results of comparisons of high-quality images only, expressed as the frequency of identified individuals per rank category when only the contour assigned by the software to the irregular border along a shark's head was used. Rank categories defined in Figure 4

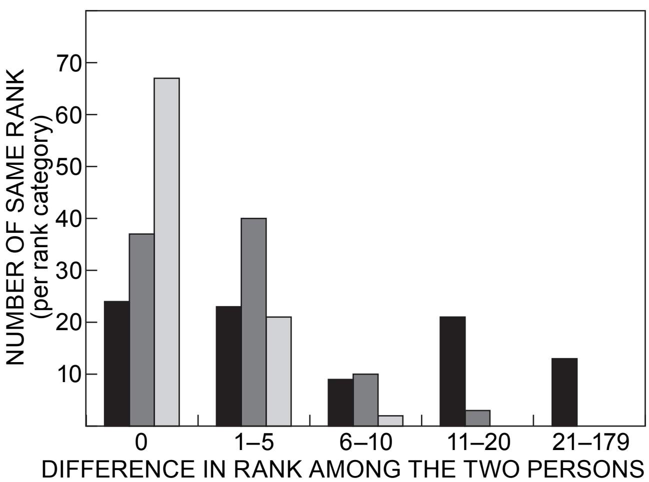

Figure 6: Results of the difference among the ranks between two persons who analysed the images independently from each other. The differences in ranks were categorised for visualisation purposes. Black bars – results of the software using only the irregular border along a shark's head to assign a contour; dark grey bars – results after the first run where partial metadata were included; light grey bars – results after a detailed metadata search that included more information than in the first metadata run

Discussion

Subsurface identification proved to be a suitable method to identify white shark individuals. The number of sharks identified ($n = 136$) in relation to the duration of the study (26 hours of filming between July 2008–May 2011) further highlights the importance of Dyer Island as a white shark aggregation site. The fact that 22 individuals were re-identified in different years and five individuals in all years supports site fidelity, a behaviour suggested by previous studies on white sharks (Klimley and Anderson 1996; Bonfil et al. 2005; Domeier and Nasby-Lucas 2008; Jorgensen et al. 2010; Anderson et al. 2011; Towner et al. 2013a).

The software was able to identify individuals in the subsurface catalogue by using the contour separating grey and white colouration between the nostril and the first gill slit, making it a suitable identification marker for this approach. Likewise, the use of automated software provided reliable results and, although quantification of processing time was not an objective of the study, images could be processed into the program in just a few minutes and analysis time thereafter was of the order of seconds.

From 69 sharks, 90 different contours qualified for the computer-aided identification method in total, due to asymmetry of left and right sides. The reduced sample size of 69 individuals is explained by the fact that the initial database of 136 sharks focused on subsurface identification via gill, pectoral and caudal fin pattern. Therefore, the head of the shark was not explicitly targeted and was apparent in only some of the images. Nevertheless, the sample size was comparable to those in other studies that have provided successful identification methods of white sharks (Domeier and Nasby-Lucas 2007). If the head and gill pattern are targeted by the videographer, the method presented here should not decrease the number of suitable images, but instead should increase it. Unlike the conventional subsurface method, the computer-aided approach does not necessarily require the three images of the gill, pectoral and caudal fin regions, but only one image per side showing the head and gill area.

Image quality was a major factor affecting the performance of both methods. The results showed that poor-quality images and an angled orientation of the shark relative to the camera resulted in individuals not being identified within the top-20 ranking. These images showed the lowest rate of direct matches, although manual identification was still possible. Van Tienhoven et al. (2007), using a previous version of the software, also found that it was able to identify images of moderate quality. However, this software has been shown to be much less effective at identifying low-quality images and images where the animal was in an angled position (Speed et al. 2007). Water turbidity reduces the image quality, making close-up videos essential. The camera deployed in May 2011 had HD resolution and a wide-angle function of 170°. This allowed sharks to be catalogued through the use of close-up images even if visibility was poor. Image quality also affected the identification results among users, but in general the results showed that different users will not have a large effect on the performance of the software. The main source of error between the two persons was when the image quality was low and the irregular border was not clearly visible. Under these circumstances the automatic recognition of the border by the software can fail and the user has to assign the contour manually, rather than start and end points only. We suggest using only high-quality images where the shark is near-perpendicular to the camera, i.e. at an angle of <15° and ideally <10°. The use of near-perpendicular, high-quality images in this study resulted in a high degree of direct identifications without any metadata information (88.24% and

94.12%). Under these circumstances, a visual comparison of the first 10–20 ranks should therefore be sufficient to investigate whether a newly recorded individual is already present in a photo-ID database. In addition, the present study used only one reference image, although the use of multiple reference images can further increase the efficiency of the program (Van Tienhoven et al. 2007; Den Hartog and Reijns 2011). The inclusion of metadata significantly improved the identification results in terms of accuracy, precision, and the processing of poor-quality images. Thus it may be possible to process older images, if further information is present. These findings are in agreement with those of Van Tienhoven et al. (2007), who used a previous version of the software. However, for standardisation purposes in population or similar studies, metadata information has to be carefully chosen in order not to bias the assumption of equal probability of identifying an individual. We recommend that the following metadata be used in order to reduce the number of comparisons: (i) gill-pattern type (this is usually visible on images of the shark's head); (ii) sex (this is easily distinguished using underwater footage); and (iii) the side of the shark (left or right).

It is important to consider the caveats and limitations when using pigment patterns for individual identification and mark-recapture analysis. The assumption of equal recapture probability has been shown to be violated when pigment pattern photo-identification is used, which causes underestimation of the true population size; however, abundance indices can still be estimated (Sosa-Nishizaki et al. 2012). The caveats are discussed in detail by Sosa-Nishizaki et al. (2012). In addition, it is important to consider that pigment patterns can be asymmetrical. This is of particular relevance if only the contour is used, because minimal changes in the irregular border will cause asymmetry. A dorsal fin is bilaterally symmetrical along the trailing edge, requiring only a single photograph to identify an individual. Therefore, all individuals have the same probability of being captured from a single photograph. In using pigment patterns, one image for each side of the animal is needed and, unlike the dorsal fin method, multiple images must be recorded for final identification. This means that sharks that are less likely to return or remain around the boat have a lower probability of being photographed from both sides and hence a lower probability of being included in the catalogue. The conventional technique uses three regions on the shark's body to define different pigment patterns. The presented computer-aided approach requires only the head region from both sides, in particular when only high-quality images are processed. Hence, the capture probability should be less biased than is the case with the conventional technique. The chosen metadata can also affect the probability of recapture. This would be the case, for example, if sex cannot be recorded for all animals but is used for identification. For future studies, the best approach would be to use only the contour and those metadata that are always available. Furthermore, it is important that the individuals can be re-identified over time. Although patterning of white sharks can change over time (Domeier and Nasby-Lucas 2007; Robbins and Fox 2012) and injuries may change the appearance of the irregular border, no obvious changes were present among the 83 re-identified sharks, including seven individuals that returned after four years. Future studies should carefully monitor changes along the border, but reported changes are rare and have not affected the ability to re-identify individuals in previous studies (Domeier and Nasby-Lucas 2007). However, we recommend the use of this method in combination with dorsal fin identification, because supplementary methods can increase the reliability of identification (Holmberg et al. 2009). For example, if the fin experienced drastic changes in shape, an individual may still be identified from its subsurface catalogue.

In future studies, recording the length of animals would improve the information in the database. The length could be measured with reasonable accuracy using lasers or stereo camera systems (Klimley and Brown 1983; Costa et al. 2009; Rohner et al. 2011). This could provide valuable information for assessments and growth studies. With modern advances in camera technology, this method has the potential to become more effective, particularly when using high-quality perpendicular images. In addition, subsurface identification offers many advantages compared with traditional dorsal fin photo-identification, as more information is captured, making it an effective supplementary method. As an alternative to the use of video, still images, taken using digital cameras, of the head and gill region of the shark could be used. White sharks are surface-active predators, especially in the context of eco-tourism vessels using chum and bait. Hence the potential to collect data exists for anyone pursuing white shark encounters. These methods can also be used as a tool to make comparisons between different locations (Brooks et al. 2010) and therefore future research should include comparative studies between multiple aggregation sites across the global range of white sharks, where video footage is obtainable. This could provide further insight into their migration behaviour and habitat use, which is especially important given that the species is known to cross political boundaries (Bonfil et al. 2005; Jorgensen et al. 2012). However, it should be noted that the dataset used here was intended to investigate the performance of the identification technique and software and is not yet suitable for future population studies. Future work would require more individuals to be identified over a more consistent time-frame, and further consideration should be given to how the technique might affect assumptions associated with mark-recapture analysis. Changes in pattern (Domeier and Nasby-Lucas 2007; Robbins and Fox 2012) or dorsal fin appearance (Chapple et al. 2011; Delaney et al. 2012; Towner et al. 2013a) may result in a resighted animal being catalogued erroneously as new, which can lead to overestimates of abundance. The combination of dorsal fin identification with the method presented here could increase the reliability of these studies. In addition, more-complete databases can provide essential information for the protection of this vulnerable predator. The described method is likely to be applicable for all subsurface identification studies that capture distinct and stable contour regions on the subject animal's body.

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