Aquatic Mammals 2020, *46*(5), 454-460, DOI 10.1578/AM.46.5.2020.454

Short Note

Dart Speed and Energy for Potential Cetacean Remote Sampling Devices

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Free-ranging cetaceans present challenges to researchers seeking to better understand their physiology and population dynamics. Given that cetaceans spend most of their time under the sea surface, it may be difficult to obtain tissue samples for analysis. Researchers desiring samples of cetacean tissue have developed a variety of "remote biopsy" techniques since the early 1970s (Winn et al., 1973). Samples obtained from free-ranging cetaceans can offer insights into a suite of biological analyses, including information about genetic relationships, foraging ranges, prey selection, environmental contaminants, stress levels, and reproductive health (Noren & Mocklin, 2012). The information gained can provide a window into the complex social and genetic relationships of marine mammal communities and assist managers with conservation efforts.

Many marine mammal scientists utilize similar remote biopsy sampling devices and techniques. Commonly, a stainless-steel biopsy punch affixed to a dart and fired from a projection device is used to collect a cylindrical plug of skin and blubber from free-ranging marine mammals. The biopsy punch is designed to suit the integument thickness of the target species. Among some dart projectors reported in the literature are recurve crossbows (Lambertsen, 1987; Palsbøll et al., 1991; Clapham & Mattila, 1993; Patenaude & White, 1995; Weller et al., 1997; Gauthier & Sears, 1999; Hooker et al., 2001; Gorgone et al., 2008; Kiszka et al., 2010; Kowarski et al., 2014; Reisinger et al., 2014; Sinclair et al., 2015; Fruet et al., 2017), pneumatic (CO_2) dart rifles with variable pressure regulation (Bearzi, 2000), a modified powder-actuated 0.22 caliber rifle with variable pressure regulation (Barrett-Lennard et al., 1996; Krutzen et al., 2002; Parsons et al., 2003; Tezanos-Pinto & Baker, 2012; Pagano et al., 2014; Liu et al., 2019), and a modified powder-actuated 0.22 caliber rifle without a pressure adjustment valve (Balmer et al., 2011; Sinclair et al., 2015; see also unpub. marine mammal research cruise reports at https://www.fisheries.noaa.gov/resource/publication-database/cruise-report-database-southeast-fisheries-science-center).

As remote biopsy technology has evolved, researchers should routinely consider the well-being and safety of the target species as they refine methods and research goals. Gales et al. (2009) recommended that remote biopsy device power be evaluated before sampling live animals, and Bearzi (2000) recommended researchers constantly review procedures and equipment out of an abundance of caution. Palsbøll et al. (1991) and Patenaude & White (1995) tested the tissue collection efficacy for a range of recurve crossbow power levels with certain biopsy dart designs in development, and Barrett-Lennard et al. (1996) measured the speed and energy of one device/dart combination. However, despite the widespread use of these different tools, there is relatively little detailed information available on the energy transferred to the sample subjects at impact. To assess the energy associated with some remote biopsy device/dart combinations in use and potentially other biopsy systems with similar parameters, the relationship between distance and dart speed/energy for five devices was evaluated using sampling gear and distance ranges reported for small cetaceans—in particular, common bottlenose dolphins (*Tursiops truncatus*).

Recurve crossbows (hereafter "crossbows") are among the least powerful hunting crossbows and are common among researchers for cetacean tissue sampling. When reporting crossbow power, some researchers cite the manufacturer's specifications of crossbow bolt (or arrow) speed (e.g., Jefferson & Hung, 2008; Wenzel et al., 2010), but the manufacturer specifications are intended to represent the estimated speed of some standard hunting arrow weight (e.g., 400 grains) and are not useful for inferring the speed of remote biopsy darts with greater mass and relatively poor aerodynamic profiles. Manufacturers may discontinue and introduce new crossbow models that are unfamiliar to researchers; for example, of the crossbow models specified in the literature reviewed by this author, none of the specified devices are currently available from the manufacturers (e.g., Palsbøll et al., 1991; Gorgone et al., 2008; Jefferson & Hung, 2008; Cunha et al., 2010; Kiszka et al., 2010; Wenzel et al., 2010; Kowarski et al., 2014; Reisinger et al., 2014). Crossbow draw-weight (the amount of force needed to draw the bow string into firing position) is often specified when researchers describe their respective biopsy methods in publications, but the power stroke (the length by which the crossbow string must be pulled back to engage with the trigger latch) is typically not reported. The power stroke bears on device power and may be different for each crossbow model.

Some factors to consider when assessing the suitability of sampling equipment include physical characteristics of the target species, behavior, time at surface, practical distance to target, and capacity of the device for consistent, repeatable sampling to address the research questions (Gales et al., 2009). Large cetaceans (e.g., mysticetes) may present a larger target area, are potentially at the surface for a relatively longer period, and possess thicker integument relative to small odontocetes that may present a narrow spatial and temporal sampling window and a thinner blubber layer relative to large whales. Some researchers report sampling common bottlenose dolphins as close as 2 m with a variable-power dart rifle (Krutzen et al., 2002), while others report sampling bottlenose dolphins as far as an estimated 32 m distant with a crossbow (Fruet et al., 2017). Wenzel et al. (2010) suggested a safe sampling distance for remote biopsy devices would be consistent with the power of the sampling device and specified a minimum sampling distance of 4 m for one crossbow. In a review of cetacean biopsy methods, Noren & Mocklin (2012) found most researchers estimate sampling distances between the range of 4 to 15 m for small odontocetes.

The minimum amount of power required to successfully collect a sample at a typical sampling distance is not clear, but if device power is too low, it may potentially fail to provide enough energy to collect a sample with some species (e.g., Guiana dolphins [*Sotalia guianensis*]; hand-held crossbow, 34 kg draw-weight; Cunha et al., 2010). If device power is too high, darts may be damaged upon impact (e.g., 68 kg draw-weight; Kowarski et al., 2014), with the potential to inflict unintended injury. Palsbøll et al. (1991) found a crossbow with a 68 kg draw-weight performed best in their assessment, similar to Gauthier & Sears (1999) and Hooker et al. (2001) who used crossbows with 57 or 68 kg draw-weights to sample four species of northwestern Atlantic balaenopterid whales and northern bottlenose whales (*Hyperoodon ampullatus*), respectively. Fruet et al. (2017) recommended no device with a draw-weight greater than 68 kg fo r common bottlenose dolphins. Other researchers have recommended using lesser-powered crossbows to sample smaller cetaceans such as beluga whales (*Delphinapterus leucas*; 23 kg draw-weight; Patenaude & White, 1995). Weller et al. (1997) and Kowarski et al. (2014) found crossbows with draw-weights of 40 to 45 kg to be effective for common bottlenose dolphins and long-finned pilot whales (*Globicephala melas*), respectively. The projection device used by Barrett-Lennard et al. (1996) to sample killer whales (*Orcinus orca*) and humpback whales (*Megaptera novaeangliae*) had three power level settings, similar to the variable-power devices used by other researchers to sample polar bears (*Ursus maritimus*; Pagano et al., 2014) and bottlenose dolphins (*Tursiops* spp.; Krutzen et al., 2002; Parsons et al., 2003). However, even if all devices in use were identical, the weight and style of darts and the biopsy punches used may differ considerably among research programs and, thus, the energy calculated for one device/dart combination may not be applicable to the equipment of another researcher or appropriate for a different species. For example, the dart and biopsy punch described in this study are the same type described in Sinclair et al. (2015) for small cetaceans but is dissimilar to other dart designs (Barrett-Lennard et al., 1996; Krutzen et al., 2002; Pagano et al., 2014). To standardize the terms for consideration, an objective evaluation of these tools should consider the kinetic energy of a dart resulting from a specific device/dart/punch combination. Kinetic energy is the energy of a projectile in motion and is calculated (neglecting wind resistance) as

$$KE = \frac{1}{2}mv^2$$

where the units of mass (m) are in kilograms, the units of velocity (v) are in meters per second, and the resulting kinetic energy (KE) is expressed in joules (J).

Herein, dart speed was measured and energy was calculated for four crossbows, including the Barnett Panzer V and the Barnett Wildcat III (Barnett Outdoors, Tarpon Springs, FL, USA), the MK-150A2 and MK-180B (Man Kung, Taichung City, Taiwan, Republic of China), and one customized 0.22 caliber powder-actuated dart rifle without a pressure regulating valve (Table 1). The Panzer V (Reisinger et al., 2014; Sinclair et al., 2015; Fruet et al., 2017), Wildcat III (Gorgone et al., 2008), MK-150A2 (pers. obs., Pensacola Bay, August 2016; Timbalier/Terrebonne Bay, June 2016), and dart rifle (Balmer et al., 2011; Sinclair et al., 2015) have been used to collect remote biopsy samples from common bottlenose dolphins in the field, while the MK-180B was effectively used to collect samples on a bottlenose dolphin carcass in a laboratory setting at up to 10 m distant (pers. obs., 25 June 2015). The darts used in this study were obtained from Ceta-Dart (Copenhagen, Denmark). The crossbow dart (total length and weight = 60 cm, 61 g/935 grains) was similar to that pictured in Figure 2 of Sinclair et al. (2015) for use in small boat, small cetacean sampling and consisted of an Easton ACC carbon-aluminum shaft, a custom plastic half-moon nock, a 12-cm plastic fletching, and a custom-made threaded stainless-steel flanged head enclosed in a 10 × 3 cm cone-shaped high-density polyurethane cast foam backstop, which also serves as flotation. The sampling end of the rifle dart was identical to the crossbow dart, but its shaft was trimmed and modified with an aluminum base.Rubber o-rings were placed around the dart shaft and base (#7 and #83, respectively; Danco, Irving, TX, USA) to form a pressure seal within the barrel (total length and weight = 46 cm, 52 g/809 grains; see Figure 1 of Sinclair et al., 2015). Rifle darts were propelled by an explosive charge commonly used in fastening devices (0.22 caliber single shot powder loads, green, level 3; Ramset Fastening Systems, Glendale Heights, IL, USA). A 10 × 25 mm stainless steel biopsy punch (also from Ceta-Dart) of the same size and style used in established remote biopsy protocols (Sinclair et al., 2015) was threaded onto the sampling end of the darts.

Dart speed was measured indoors with a shooting chronograph (Competition Electronics, Rockford, IL, USA). The chronograph detects disruption of light as projectiles pass over its sensors and measures the elapsed time between disruptions in meters per second (m/s). The manufacturer specifies an accuracy of ± 1% of measured speed or better. Darts were fired indoors over the chronograph on a tripod (90 cm height) and into a target backstop at marked distance intervals of 3, 5, and 10 m, measured from the front edge of the chronograph to the toe line of the shooter's lead foot. A 3 to 10 m sampling range was chosen because other researchers reported an estimated sampling distance for bottlenose dolphins in the 2 to 10 (4.6 ± 1.2 m, N = 408 [Krutzen et al., 2002]; 3 to 10 m [Kiszka et al., 2010]; or 5 to 10 m [Gorgone et al., 2008] range); and the mean (± SD) remote biopsy sampling distance visually estimated in the field was 4.98 ± 2.0 m (N = 923; NMFS SEFSC Permit No. 14450, Pascagoula, MS, USA; unpub. data, 2010 to 2013). New strings were installed on each crossbow at the start of the speed tests and were replaced every 30 shots or when string integrity reached minimum acceptable safety standards (e.g., early indications of fraying or separation of string strands). Crossbow wax was applied every few shots to the string and bow stock. The rifle speed test began with a thorough cleaning of the rifle bore and combustion chamber. Data output was recorded into the internal memory of the chronograph and uploaded to a computer where it was tabulated and kinetic energy values were calculated. Data analyses were completed in *R* statistical software (R Core Team, 2018) using a 95% confidence level for all tests ($\alpha = 0.05$). The dart speed and kinetic energy at each distance factor level for all devices did not meet assumptions of normality ($p < 0.05$; Shapiro-Wilk test), so a one-way Kruskal-Wallis test was used to determine if there were statistically significant differences between any distance factor levels, followed by iterative pairwise Mann-Whitney tests to determine the specific distances at which dart speed/energy differed significantly.

In total, 30 shots at each of three distances—3, 5, and 10 m—were measured on each device (N = 450; Figures 1 & 2; Table 2). Mean dart speeds from all devices from 3 to 10 m ranged from 35.4 to 49.4 m/s, and mean kinetic energy ranged from 37.9 to 74.0 J. Significant differences in speed/energy among some distances were found for all devices except for the dart rifle (crossbows: $p < 0.001$; dart rifle: $p = 0.69$; Kruskal-Wallis test). *Post hoc* Mann-Whitney tests indicated speed/energy was not significantly different from 3 to 5 m for the Panzer V ($p = 0.43$) and Wildcat III ($p = 0.17$), but indicated statistically significant differences in speed/energy between 3 to 10 m ($p < 0.001$) and 5 to 10 m ($p < 0.001$). Statistically significant differences in speed/energy for all distance factor levels (3, 5, and 10 m)

Table 1. Crossbow manufacturer specifications (manufacturer specifications not available for the custom-made dart rifle)

Device	Speed (m/s)	Draw-weight (kg)	Power stroke (cm)
Barnett Panzer V	75	68	31.8
Barnett Wildcat III	72	68	25.4
MK-150A2	64	68	26.7
MK-180B	50	59	25.4

were found for the MK-150A2 ($p < 0.001$) and MK-180B ($p < 0.001$). Darts ejected from the rifle had the widest range of speed (13.4 to 72.5 m/s [$\mu = 47.1 \pm 9.6$ m/s]) and energy (4.7 to 137.7 J [$\mu = 60.6 \pm 20.7$ J]).

Although statistically significant differences in dart speed/energy at different distances from the target within 3 to 10 m were found for the crossbows, there was little practical significance (Table 2). Mean dart speed between 3 and 10 m decreased by less than 2% for the Panzer V, MK-150A2, and Wildcat III; and mean dart speeds decreased by 3.3, 1.1, and 4.4% for the MK-180B between 3 to 5, 5 to 10, and 3 to 10 m, respectively. Given the small changes in dart speed/energy observed for each of the crossbows tested, it may be inferred that there would be little difference in the energy carried by the dart or dart penetration depth in sample subjects with similar anatomical parameters in the 3 to 10 m range for each crossbow. However, the same assumption may not apply across all devices as dart energy varied more widely among devices. The Wildcat III ejected the biopsy darts at ~90% of the speed and ~80% of the energy of the Panzer V, despite both devices having the same draw-weight (68 kg). The lower dart speed/energy of the Wildcat III is likely due to the shorter draw-length, resulting in less energy transfer to the dart (Table 1). The MK-150A2 (manufacturer specified speed of 64 m/s) should rank below that of the Wildcat III (manufacturer specified speed of 72 m/s) yet was measured as potentially more powerful (~3%) than the Wildcat III in this study, likely due to the longer power stroke of the MK-150A2 (Tables 1 & 2). In terms of consistency, the small variance in dart speed/energy indicates that the Panzer V and Wildcat III were the most consistent at 10 m distant, while the dart speed for the MK-150A2 and MK-180B was more variable at the same distance, and the dart rifle speeds were highly variable overall (Figure 1). Dart rifle speed values ranged from inadequate to obtain a sample (lowest recorded speed = 13.4 m/s) to much greater than the highest crossbow speed (145%; maximum recorded speed of dart rifle, 72.5 m/s, and Panzer V, 50.0 m/s). Unlike the crossbows, the mean dart speed for the dart rifle increased (~4 to 10%) and variability decreased with each distance iteration from 3 to 10 m (Table 2). Several factors may bear on the dart rifle performance observed here. Over

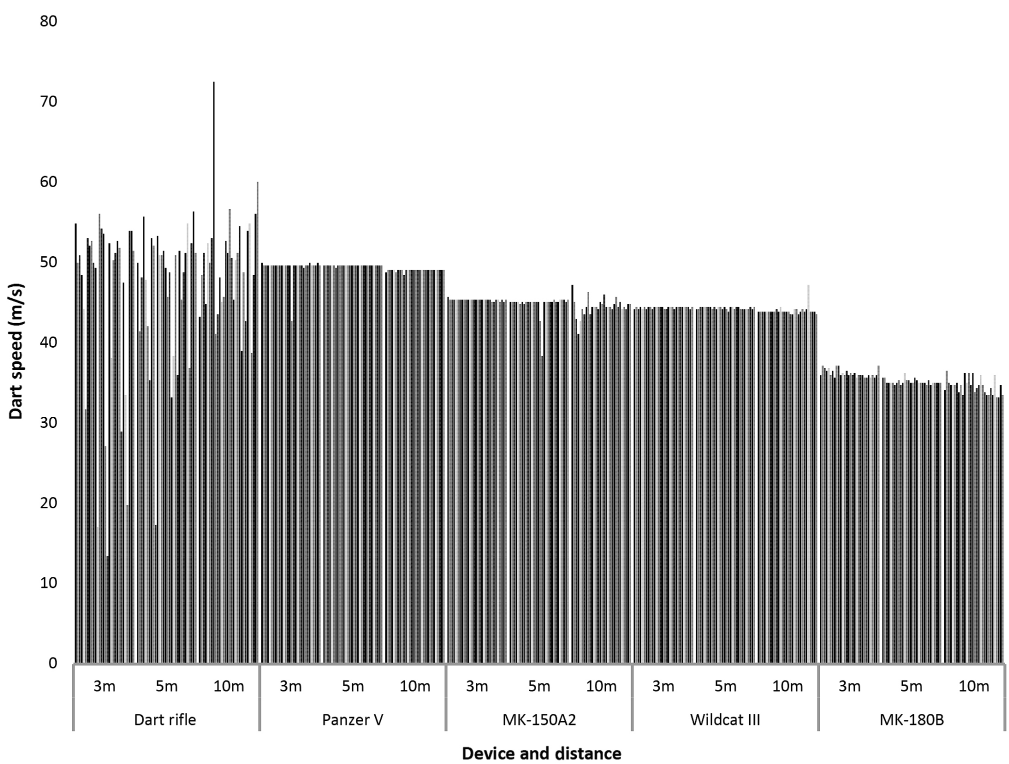

Figure 1. Speed test results in meters per second (m/s) for the dart rifle, Barnett Panzer V, MK-150A2, Barnett Wildcat III, and MK-180B ($N = 450$; 90 samples per device)

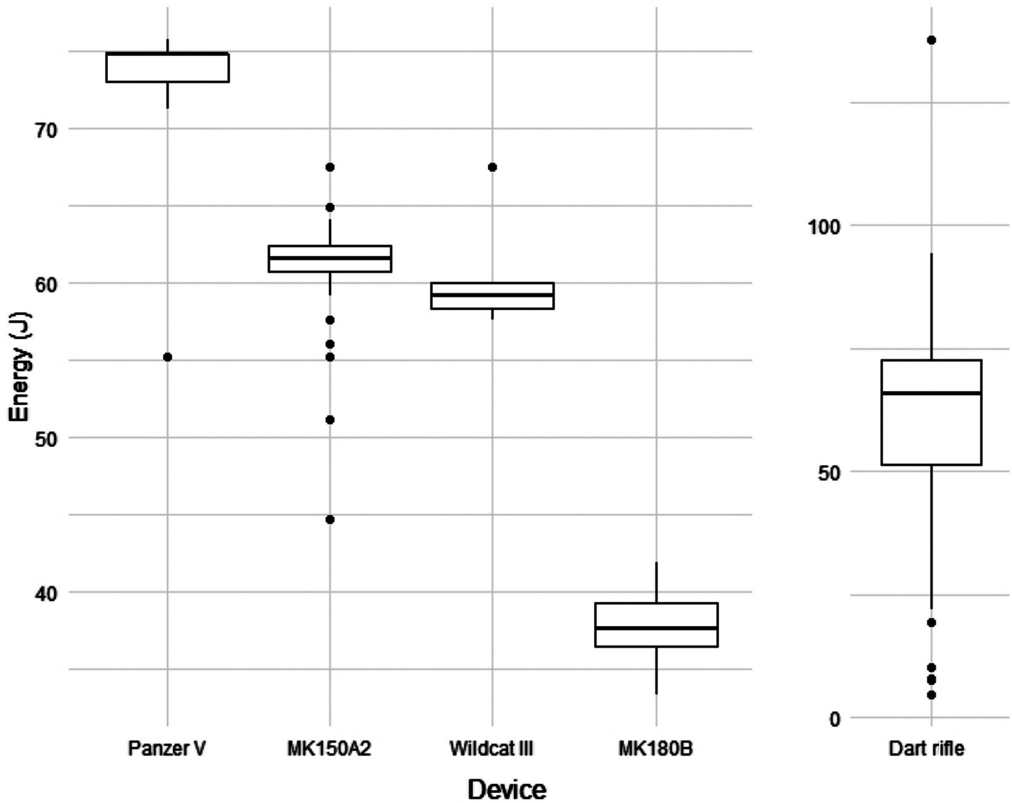

Figure 2. Boxplot of energy values for each device over the 3 to 10 m range (*N* = 450; 90 samples per device); note different Y-axis scale for the dart rifle.

Table 2. Mean (± SD) dart speeds at each distance in meters per second (m/s), and mean (± SD) speed and energy values for each device over the 3 to 10 m range (*N* = 450; 30 shots per device at each distance)

	Speed (m/s)				Energy (J)
Device	3 m	5 m	10 m	3-10 m	3-10 m
Barnett Panzer V	49.5 ± 1.3	49.7 ± 0.1	49.1 ± 0.1	49.4 ± 0.8	74.0 ± 2.2
Barnett Wildcat III	44.4 ± 0.1	44.4 ± 0.2	44.0 ± 0.6	44.3 ± 0.4	59.4 ± 1.1
MK-150A2	45.4 ± 0.1	44.8 ± 1.3	44.5 ± 1.1	44.9 ± 1.0	61.1 ± 2.7
MK-180B	36.3 ± 0.5	35.2 ± 0.3	34.6 ± 1.0	35.4 ± 1.0	37.9 ± 2.0
Dart rifle	44.8 ± 12.4	46.7 ± 8.4	49.8 ± 6.8	47.1 ± 9.6	60.6 ± 9.6

the course of the first 40 shots with the dart rifle, the chronograph recorded abrupt decreases in speed; and several shots were of such low power that the darts fell short of the chronograph, and, thus, speed could not be measured.

The dart rifle was cleaned after each of these incidents and thereafter when dart speed decreased to 30 m/s or less. The frequent cleaning of the dart rifle bore and barrel as sampling progressed from 3 to 10 m distant may have been responsible for the apparent positive correlation between dart speed and distance for the dart rifle. Also, the darts were fired in relatively quick succession in contrast to the occasional sampling attempt during field operations. It is possible the unusual use of the rifle in these tests affected dart rifle performance, confounding the statistical test. Finally, the potency of the power loads used to propel the dart may vary. Some power loads (or "charges") failed to properly ignite in the rifle combustion chamber ("duds"); and although the charges used in this study were considered fresh, it is possible the charges were affected by humidity or age prior to purchasing (Barrett-Lennard et al., 1996; Krutzen et al., 2002). The highest rifle dart speed was recorded in the next shot after experiencing a dud charge (72.5 m/s; Figure 1), likely due to residual gun powder remaining in the chamber. The energy of that dart was measured at ~138 J, nearly twice as much energy as that calculated for the most powerful crossbow in this study, the Panzer V (maximum energy ~75 J). It should be noted that in the field, experienced samplers are aware of the potential for excessive dart speed after cleaning the dart rifle or a dud charge, and they routinely fire a blank charge without a dart in the barrel as a safety measure to prevent excessive dart speed.

Notably, most of the dart speeds recorded herein are within the range of dart speeds (or less) recorded by Barrett-Lennard et al. (1996) for their powder-actuated variable-power rifle; however, the mean energy of the darts ejected from the devices in this study (37.9 to 74.0 J) were well above the energy values reported (10.6 to 32.8 J) by them. The large difference in kinetic energy may be attributed to the much lighter dart used in Barrett-Lennard et al., which was about 1/5 (~12/61 g) the weight of the dart used in this study and other research programs using similar equipment. Less dart mass should result in less energy absorbed by the animal at impact and, presumably, this would be a safer tool for remote biopsy sampling, yet the only published account of a marine mammal fatality related to remote biopsy sampling occurred while using equipment thought to transfer the lowest energy at impact (Bearzi, 2000). In that case, a pneumatic variable-power dart rifle was set to the minimum power setting, the dart was similar to that described in Barrett-Lennard et al. (1996), and it was fired from an acceptable distance (~6 m). A confluence of factors is thought to have influenced the outcome of that sampling event (Bearzi, 2000).

This study could not duplicate the variety of potential platform conditions (e.g., crosswinds and variable platform heights), and, thus, even with the same or similar tools, the kinetic energy of a dart in the field may somewhat vary from what is presented here. The highly variable results of the dart rifle may prompt further questions, but the results for the crossbows indicate that the differences in dart speed/energy for each crossbow are small for the type of equipment and distance range tested here, and, thus, distance (as it pertains to the sampling device) would likely not be a factor to influence behavioral responses or wound healing for samples collected from an animal within the 3 to 10 m range. This short note contributes supplemental performance information for a small cross-section of potential marine mammal remote biopsy tools and may be useful in the future as a reference aid to researchers in refining their choice of sampling technology to one that consistently and effectively collects the desired sample with minimal disturbance to the target species.

Acknowledgments

Thanks to Keith Mullin and Kevin Barry at the National Marine Fisheries Service, Southeast Fisheries Science Center laboratory in Pascagoula, Mississippi, for supporting this work. Thanks to the three anonymous reviewers who improved this manuscript with their constructive comments. No endorsement of any specific device or dart configuration is implied from this work.

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