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Evaluation of the Potential for Injury With Remote Drug-Delivery Systems

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Abstract

We evaluated the potential for different types of remote drug-delivery systems (RDDS) to injure target animals. We recorded dart velocity, time, and distance from projector muzzle at 8.5-millisecond intervals by Doppler radar chronograph for 4 types of RDDS. We used darts of different volume and unique combinations of charges, power settings, and distances in accordance to manufacturer's recommendations. Variation in the drop of repeated shots was >10 cm for 28 of 90 trials (5 replicates per trial) with heavy-mass darts having the lowest precision. Impact velocities were high (>50 m/sec) in many trials using heavy darts and some trials using light-mass, rapid-injection darts. We evaluated the permanent wound cavity (PWC) formed by firing dye-filled darts into ordnance gelatin covered tightly by a fresh elk hide and into the thighs of calf carcasses. Rapid-injection darts fitted with end-ported needles consistently 1) forced hair and skin beneath the hide; 2) formed a PWC that was 2–3× the needle length; and 3) pulled the hide away from the gelatin before the dye was completely ejected into the gelatin. We conclude injury to target animals is minimized in RDDS that use lightweight, slow-injection darts, fitted with side-ported needles and broad-diameter needle seals, and that impact target animals at moderate velocity (40–50 m/sec) with high precision. We recommend against using darts with rapid-injection mechanisms and end-ported needles because of their potential to cause deep, chronic wounds. (WILDLIFE SOCIETY BULLETIN 34(3):741–749; 2006)

Key words

dart, injury, ordnance gelatin, permanent wound cavity, precision, rapid-injection, remote drug-delivery systems, slow-injection, velocity.

The development of reliable remote drug-delivery systems (RDDS) in conjunction with safer anesthetic drugs over the past 4 decades has greatly facilitated the capture and handling of many different free-ranging species and the medical care of zoo animals (Harthoorn 1970, Bush 1992). Today, the large variety of commercial RDDS available creates a challenge to select the appropriate one. Some guidance can be obtained through published reviews and technical manuals that highlight the strengths and weaknesses of different RDDS (Jones 1976, Kock 1987, Bush 1992, Nielson 1999, Kreeger et al. 2002).

The possibility that RDDS can cause significant injury has been noted by some authors (Thomas and Marburger 1964, Smith and Huse 1980, Valkenburg et al. 1983, Spurlock and Spurlock 1988). However, most injury has been attributed to user inexperience or inappropriate use of the drug-delivery system (Jessup 2001). Minimal attention has been directed toward design features or manufacturer's recommendations that also might cause injury. An exception is the study by Valkenburg et al. (1999) in which the velocity, consistency, and penetration of darts was compared between CO_2- and powder-charge-propelled darts.

Despite widespread use of RDDS, the potential for injury in target animals remains largely unknown because the contributing factors have not been clearly identified. Further, it is likely the frequency of injury is underestimated because many dart injuries go undetected, concealed well by fur and skin. Although the development of RDDS has progressed over the years, more controlled laboratory studies and experimentation in the field are needed to further reduce morbidity or mortality caused by this equipment.

Using techniques employed to study wound ballistics in humans (Fackler 1988, MacPherson 1994, Haag and Haag 2002), we determined, in a controlled laboratory study, some of the characteristics of RDDS that could contribute to injury in target animals. We then used this information to assess the potential for injury using different types of RDDS selected primarily on the basis of dart mass and mechanism of drug injection.

Methods

We conducted the study on an indoor firing range at the Royal Canadian Mounted Police (RCMP) Forensics Laboratory at Regina, Saskatchewan, Canada (50°27′00″N–104°37′00″W) in September 2003. We tested 4 different remote drug-delivery systems selected to represent both a wide range in dart mass (heavy vs. light) and 2 different mechanisms of drug injection (rapid vs. slow; Table 1). The rapid-injection darts expel their liquid content by means of a powder charge placed between the rubber plunger and tailpiece that detonates upon impact and quickly advances the plunger. The slow-injection darts rely upon compressed air to

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Table 1. Classification and description of remote drug-delivery systems[a] used in a study conducted in Sep 2003 to evaluate the potential for different types of remote drug-delivery systems to cause injury.

	Relative mass of dart[b]	
Injection speed	**Heavy (1.00)**	**Light (0.48–0.73)**
Rapid		
Manufacturer	Cap-Chur®	Pneu-Dart®
Dart volumes	3, 5, 7, 10 ml	3, 5, 7, 10 ml
Dart projector	extra-long-range projector	model 196 projector
Charges	brown, green, yellow, red	brown, green, yellow
Power settings	not applicable	2, 3, 4, 5
Slow		
Manufacturer	Cap-Chur®	Paxarms®
Dart volumes	3 and 5 ml	3, 5, 6 ml
Dart projector	extra-long-range projector	MK24C* .509 projector
Charges	brown, green, yellow, red	red
Power settings	not applicable	10, 20, 30, 40, 50, 60 m

[a] Darts and charges provided by Palmer Cap-Chur & Equipment Company, P.O. Box 867, Douglasville, GA 30133, USA; Pneu-Dart Inc., 1 West Third Street, Suite #212, Williamsport, PA 17701, USA; and Paxarms NZ Ltd., 37 Kowhai Street, Timaru, New Zealand.

[b] Mass of light darts expressed as a proportion of the mass of heavy darts at an equivalent volume.

advance the plunger. All systems tested use 0.50-caliber darts (12.5 mm diameter).

We divided the study into 2 research phases. We determined the mass, precision, and velocity of the RDDS in phase I. We identified factors causing tissue injury in phase II.

Mass, Precision, and Velocity

We weighed all darts to the nearest 0.1 g, using a top-loading electronic balance (Mettler BB240, Mettler-Toledo Inc., Columbus, Ohio), and filled each dart to capacity with sterile water. In addition, we randomly selected 15 charges from each type of 0.22-caliber charge used in the study and weighed each charge to the nearest 0.01 g.

For each trial, the same person fired darts in groups of 5 replicates at a stationary target utilizing a shooting rest with approximately 30 seconds between subsequent shots. The trials were distinguished from each other by using unique combinations of charges, power settings, and target distances set in accordance with manufacturer's guidelines in each trial (Table 1). We brushed the projectors clean following each trial.

We recorded dart velocity, time, and distance from projector muzzle at approximately 8.5-millisecond intervals by Doppler radar chronograph (W-700 Doppler Radar System, Weibel Scientific, Allerød, Denmark). With the maximum shooting distance on the indoor testing range limited to 22 m, the number of paired velocity–distance recordings per dart ranged from 30 to 185 depending on dart velocity. We used simple linear regression analysis of velocity against distance values to develop velocity prediction equations for every dart fired as follows:

$$V_D = V_0 - (C_d \times D), \qquad (1)$$

where V_D is the velocity in meters/second at distance (D) in meters, V_0 is the velocity at the muzzle in meters/second, and C_d is the drag coefficient defined as the deceleration (m/sec/m) due to the drag of the dart (MacPherson 1994). We used these equations to predict dart velocities at manufacturer's recommended distances for distances exceeding 22 m and to estimate the impact velocity (V_{TD}) for each dart in which the target distance (TD) was set midway between the manufacturer's suggested minimum and maximum distance for the specific combination of dart volume, charge, power setting, and projector used. For example, the TD for a 3-ml light-mass, rapid-injection (LR) dart is 30.9 m when using a model 196 projector with a green charge and a power setting of 4 (manufacturer's suggested range is 27.4–34.3 m).

We estimated the precision at target as the maximum difference in drop between darts within a trial as follows:

$$\Delta P = (0.5 \times g \times t_{min}^2) - (0.5 \times g \times t_{max}^2), \qquad (2)$$

where ΔP is the estimated precision per trial in ±cm; g is the acceleration due to gravity, which is approximately 981 cm/second^2; and t_{min} and t_{max} are the times in seconds required for the fastest dart (minimum drop) and the slowest dart (maximum drop) to reach the target (Di Maio 1999).

To provide a frame of reference for the comparison of dart impact velocities (V_{TD}), we calculated the minimum impact velocity for the penetration of pigskin (overlying gelatin) by a 0.50-caliber dart body as:

$$V_{MP} = 158.5 \times S^{-0.3}, \qquad (3)$$

where V_{MP} is the minimum impact velocity in meters/second, 158.5 is a constant derived from the empirical determination of skin penetration threshold velocities for different handgun bullets fired into 1- to 3-mm-thick pigskin, and S is the dart sectional density (MacPherson 1994).

Wound Ballistics

We filled small- and large-volume darts (3- and 10-ml heavy-mass, rapid-injection [HR] and LR darts, and 3- and 6-ml light-mass, slow-injection [LS] darts) to capacity with a color dye solution and fired the darts at a 70-kg ordnance gelatin block that was covered tightly with a fresh elk hide (7 mm thick). We prepared the gelatin as 10% by weight (with 90% water) and maintained it at 4°C throughout testing (Fackler and Malinkowski 1988). We excluded the heavy-mass, slow-injection (HS) darts from testing in phase II because of difficulty maintaining pressure in the darts.

We classified the trials for phase II on the basis of the type of RDDS, the volume of dart, and the velocity of dart at impact (Table 2). We selected the charges and power settings for each trial to ensure that the V_{TD} of the "moderate-velocity" darts was similar to the velocity expected when following the manufacturer's recommendations and that the V_{TD} of the "high-velocity" darts was approximately 25% greater than that expected when following the manufacturer's recommendations.

For each trial, the same person fired darts in groups of 3 replicates at the gelatin block and fired a fourth dart into the thigh of a calf carcass to compare with the findings from the gelatin. We recorded impact of darts with the gelatin block and calf thigh using high-speed digital video (Phantom v5.0 camera system, Vision Research, Wayne, New Jersey) mounted on a tripod aligned perpendicular to the plane of impact. The recording rate was 1,000 frames/second with a resolution of 1,024 × 1,024 pixels.

Table 2. Description of trials[a] completed in phase II of a study conducted in Sep 2003 to evaluate the potential for different types of remote drug-delivery systems to cause injury.

Type[b]	Dart volume (ml)	Mean full mass (g)	Charge/power setting[c]	Mean impact velocity[d] (m/sec)
HR	3	19.6	green/na	63.6
	3	19.6	red/na	113.4
	10	33.3	green/na	50.3
	10	33.3	red/na	99.3
LR	3	11.0	green/3	57.5
	3	11.0	yellow/5	108.5
	10	23.1	green/4	47.7
	10	23.1	yellow/5	67.9
LS	3	12.8	red/20	48.4
	3	12.8	red/60	68.5
	6	18.7	red/20	43.4
	6	18.7	red/60	70.4

[a] Three replicates per trial.

[b] Remote drug-delivery systems are represented by heavy-mass, rapid-injection (HR); light-mass, rapid-injection (LR); and light-mass, slow-injection (LS) darts. Heavy-mass, slow injection darts were excluded from testing because of problems maintaining pressurization.

[c] na = not applicable.

[d] Distance to target ≤22 m.

Table 3. Physical dimensions of syringe darts and charges used in phase I of a study conducted in Sep 2003 to evaluate the potential for different types of remote drug-delivery systems to cause injury.

a) Syringe darts

RDDS[a]	Dart volume (ml)	Dart diameter (mm)	Needle length[b] (cm)	Total dart length (cm)	Average empty mass[c] (g)
HR	3	12.5	2.9	13.0	16.6 ± 0.07
	5	12.5	2.9	15.1	18.5 ± 0.15
	7	12.5	2.9	17.5	20.5 ± 0.26
	10	12.5	2.9	21.0	23.3 ± 0.13
HS	3	12.5	2.9	13.0	13.6 ± 0.05
	5	12.5	2.9	15.1	15.5 ± 0.17
LR	3	12.5	2.6	12.2	8.0 ± 0.04
	5	12.5	2.6	16.5	9.5 ± 0.07
	7	12.5	2.6	20.9	11.1 ± 0.03
	10	12.5	2.6	25.7	13.1 ± 0.09
LS	3	12.5	3.9	14.5	9.8 ± 0.05
	5	12.5	3.9	17.0	11.3 ± 0.05
	6	12.5	3.9	19.0	12.7 ± 0.04

b) Charges

RDDS[a]	Charge type	Average mass[c] (g)
HR and HS	Palmer—brown	0.73 ± 0.006
	Palmer—green	0.77 ± 0.008
	Palmer—yellow	0.81 ± 0.008
	Palmer—red	0.88 ± 0.008
	Palmer—internal (1–3 ml)	2.42 ± 0.010
	Palmer—internal (4–10 ml)	2.46 ± 0.008
LR	CCI—brown	0.74 ± 0.006
	CCI—green	0.76 ± 0.009
	CCI—yellow	0.82 ± 0.006
LS	Paxarms—red	1.12 ± 0.017

[a] Remote drug-delivery systems (RDDS) are represented by heavy-mass, rapid-injection (HR); heavy-mass, slow-injection (HS); light-mass, rapid-injection (LR), and light-mass, slow-injection (LS) darts.

[b] Needles for HR and LR darts were barbed and end-ported. Needles for HS and LS darts were side-ported and fitted with a needle seal.

[c] Mean ± SD for HR ($n = 20$), HS ($n = 20$), LR ($n = 60$), and LS ($n = 30$) darts.

Following each trial, we removed the darts from the gelatin and hide and examined the subcutaneous side of the hide for hair or skin pushed in around the area of impact. We excised color dye tracts caused by injection from the gelatin block and measured the total length and width of the permanent wound cavity (PWC; defined in the wound ballistics literature as the hollow path left by a projectile as it cuts through tissue or gelatin), as well as proportions of the PWC caused by needle penetration and dye ejection. We calculated depth of needle penetration by measuring the length of the widest portion of the PWC caused by the needle barb and added this to the distance between the barb and needle tip plus 7 mm for the average thickness of the elk hide. We then determined the amount of compression at impact by subtracting needle length from depth of needle penetration.

Statistical and Video Analyses

We used Pearson correlation analysis to measure associations between estimated precision and range in V_0 and C_d values per trial. We used one-way analysis of variance (ANOVA) to compare 1) estimated V_{TD} values among RDDS with distance to target as a covariate, 2) PWC depth between HR and LR darts with V_{TD} as a covariate, 3) PWC width among RDDS, and 4) compression depth among RDDS with dart mass and V_{TD} as covariates (Zar 1996). We compared depth of dye injection among RDDS by 2-way ANOVA with RDDS and dart volume as the factors and V_{TD} as a covariate (Zar 1996). Where required, we used Tukey's Honestly Significant Difference (HSD) test to make multiple comparisons among means (Zar 1996). We assigned statistical significance when the probability (*P*) of Type I error was ≤0.05. Unless stated otherwise, all results are reported as the mean ± SD.

We developed wound profiles for rapid- and slow-injection darts by combining the dye tract measurements and the analyses of high-speed digital video to construct scale drawings of test firings into the ordnance gelatin (Fackler 1988). We used Phantom® software (Phantom Camera Control Software version 603, Vision Research) to estimate V_{TD} and quantitatively describe the impact of darts with the gelatin and calf thigh.

Results

Mass, Precision, and Velocity

We measured a difference in mass of darts ranging from 37 to 100% between heavy and light darts depending on dart volume (Table 3a) and a difference in the mass of charges ranging from 2.7 to 4.4% depending on RDDS (Table 3b).

We found estimated precision (ΔP) was low (>10-cm drop between the fastest and slowest dart) for many of the trials using the heavy darts and for a few of the trials using the light darts (Fig. 1). The ΔP value was directly associated with the ranges in muzzle velocity (V_0) and drag coefficient (C_d) values among darts within trials (Pearson correlation analysis: ΔP vs. V_0, $r = 0.63$, $P \leq 0.001$, $n = 89$; ΔP vs. C_d, $r = 0.46$, $P \leq 0.001$, $n = 89$).

We found large variation in the range of V_0 and C_d values within trials for some dart types (Table 4). This was most apparent in the trials using heavy darts (Table 4a,b). Variation tended to be smaller and more consistent in the trials using LR darts, but the

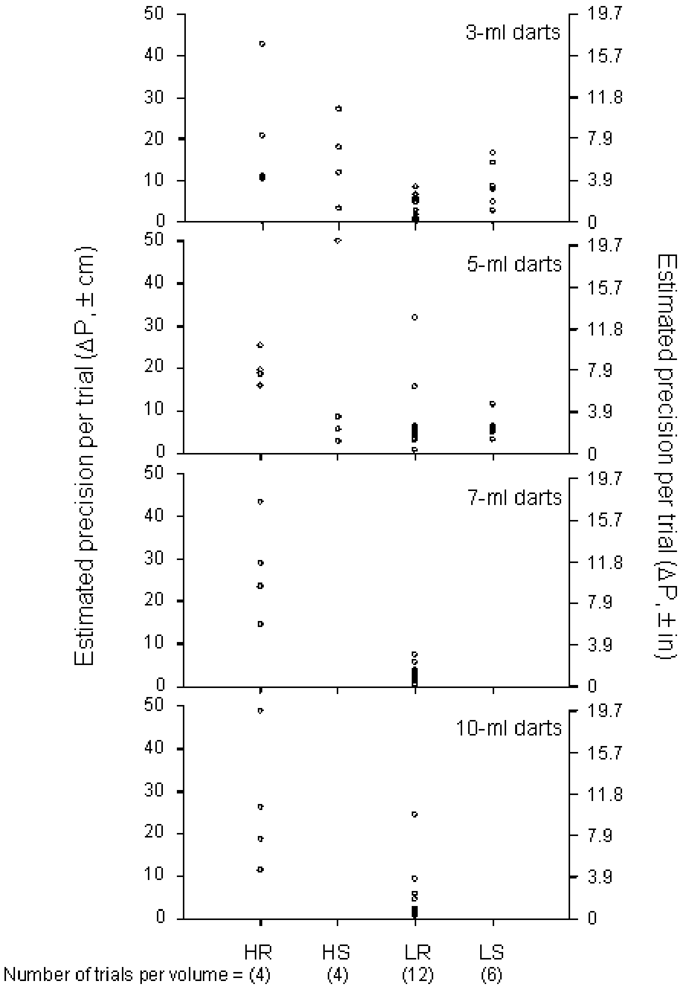

Figure 1. The precision at target (ΔP) of different-sized darts representative of various remote drug-delivery systems (RDDS). ΔP was estimated as the maximum difference in drop between darts within a trial ($n = 5$ replicates per trial). The RDDS are represented by heavy-mass, rapid-injection (HR); heavy-mass, slow-injection (HS); light-mass, rapid-injection (LR), and light-mass, slow-injection (LS) darts.

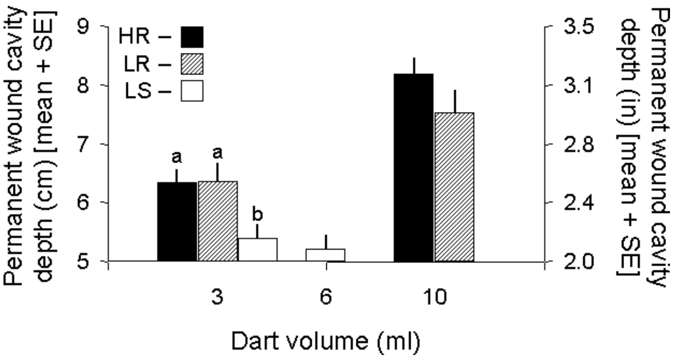

Figure 2. The permanent wound cavity (PWC) depth caused by different-sized darts representative of various remote drug-delivery systems. The mean PWC depths are adjusted for an impact velocity of 72.4 m/second and a needle length of 32 mm.

magnitude of difference between minimum and maximum values was large in a few trials (Table 4c,d). We found variation to be smallest and most consistent in the trials using LS darts (Table 4e).

We found large variation in the range of impact velocity (V_{TD}) values both within and among RDDS. Mean V_{TD} values ranged 32–91 m/second for HR darts ($n = 16$ trials), 48–94 m/second for HS darts ($n = 8$ trials), 20–87 m/second for LR darts ($n = 48$ trials), and 35–58 m/second for LS darts ($n = 18$ trials). When controlling for dart volume, V_{TD} was lowest for LS darts among the 3- and 5-ml darts (3 ml, $F_{3,129} = 45.4$, $P \leq 0.001$; 5 ml, $F_{3,129} = 31.3$, $P \leq 0.001$; Tukey's HSD, $P \leq 0.05$), and highest for LR darts among the 7- and 10-ml darts (7 ml, $F_{1,79} = 26.2$, $P \leq 0.001$; 10 ml, $F_{1,79} = 4.5$, $P = 0.036$). We compared the mean V_{TD} value for each trial to the calculated minimum impact velocity for the penetration of 1–3-mm-thick pigskin overlying gelatin (V_{MP}) by a dart of equivalent mass and diameter (Table 4). We considered the potential for penetration by the dart body to be high for many of the trials using HR and HS darts (16 out of 24 trials) and for a few of the trials using LR darts (7 out of 48 trials). We considered skin penetration to be unlikely to occur with the LS darts.

Wound Ballistics

We confirmed the mean V_{TD} values for the different trials described in Table 2 by analysis of the high-speed digital video segments recording the impact of darts with the gelatin block. We excluded from the statistical analyses the results of 2 HR and 3 LR darts because of partial penetration of the dart body through the elk hide and into the gelatin. The V_{TD} of each of these 5 darts was approximately 25% greater than that expected when following the manufacturer's guidelines.

We consistently found hair, and sometimes skin, on the subcutaneous surface of the elk hide beneath the area of impact for the rapid-injection darts. Hair and skin also were found within the PWC for 7 of the 19 rapid-injection darts tested. We did not find hair or skin left beneath the skin or in the PWC with any of the slow-injection darts. However, we found that needle seals used on the slow-injection darts consistently penetrated the skin, either partially or completely.

We found that the length of the PWC was affected by the dart mass, the V_{TD}, and the mechanism of drug injection (Fig. 2). The PWC length increased with dart mass (HR vs. LR darts: $F_{3,18} = 10.0$, $P \leq 0.001$) when V_{TD} was held constant at 72.4 m/second and needle length was corrected to 32 mm (1.25 inches). However, the PWC length also was directly related to the V_{TD} ($F_{1,19} = 6.5$, $P = 0.021$). We also found that rapid-injection darts formed a longer PWC than did the slow-injection darts (3-ml darts only: $F_{2,16} = 3.9$, $P = 0.048$) and confirmed this finding by dissecting and measuring the PWC formed in the thighs of calf carcasses.

We found that the width of the PWC was affected most by the needle barb length and was consequently wider for rapid-injection darts (HR = 2.0 ± 0.50 mm and LR = 2.2 ± 0.57 mm) than for slow-injection darts (LS = 0.9 ± 0.38 mm; $F_{2,29} = 23.4$, $P \leq 0.001$; Tukey's HSD, $P \leq 0.05$).

We found that differences in compression depth among the

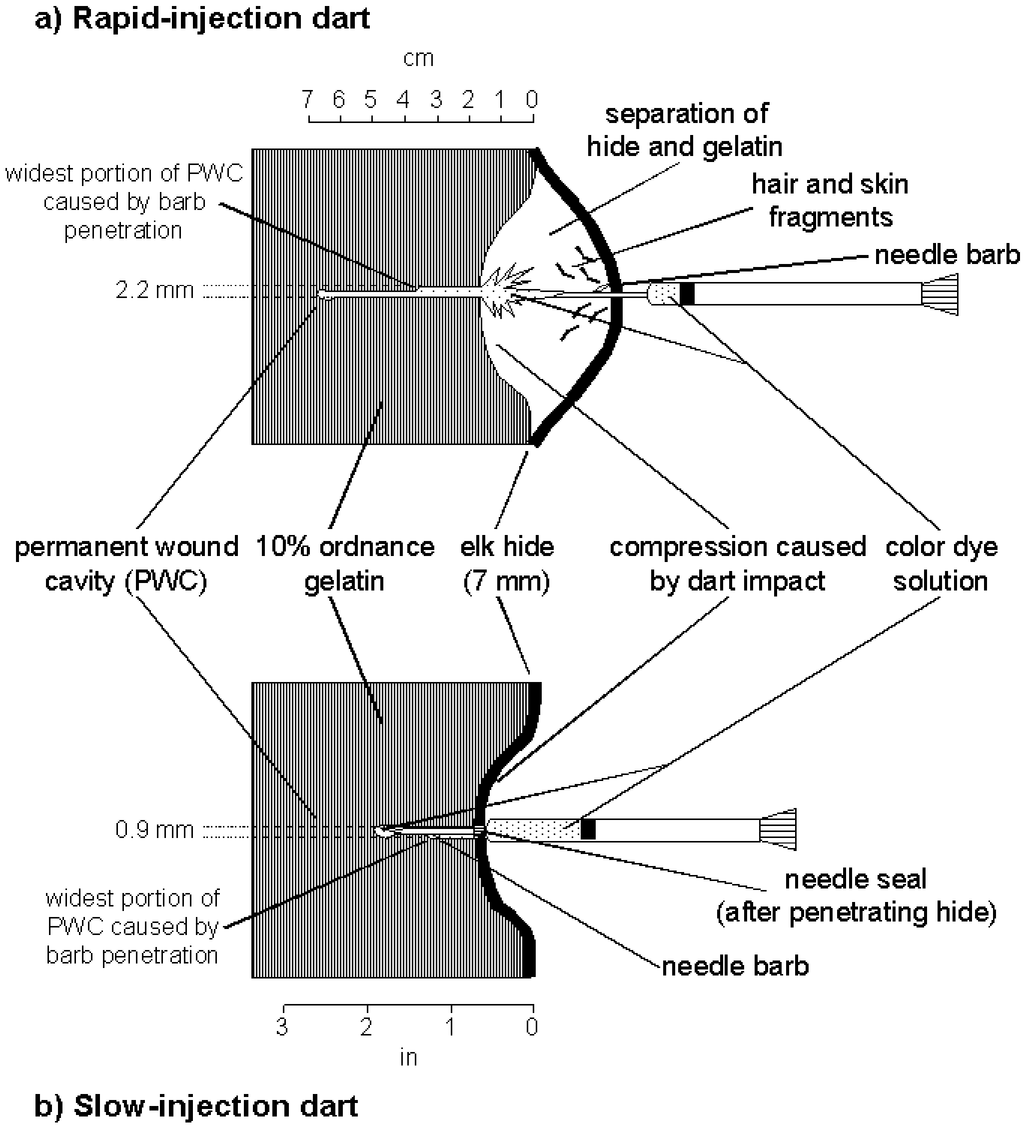

Figure 3. Comparison of wound profiles for 3-ml light-mass darts with rapid- and slow-injection mechanisms. Wound cavity measurements correspond with values obtained for light-mass, rapid-injection and light-mass, slow-injection darts fitted with 32-mm needles and fired in accordance with manufacturer's recommendations for distance to target, charge strength, and power setting.

RDDS were not statistically significant (HR = 8.0 ± 2.22 mm, LR = 11.4 ± 2.21 mm, LS = 9.4 ± 2.82 mm; $F_{2,29} = 3.2$, $P = 0.058$). However, the compression depth increased with dart mass ($F_{1,29} = 8.6$, $P = 0.007$) and V_{TD} ($F_{1,29} = 5.5$, $P = 0.027$).

We found that the injection depth was approximately 4 times greater with rapid-injection darts than with slow-injection darts ($F_{2,29} = 22.5$, $P \leq 0.001$; Tukey's HSD, $P \leq 0.005$), and was not affected by dart volume ($F_{2,29} = 1.7$, $P = 0.198$) or V_{TD} ($F_{1,29} = 2.9$, $P = 0.103$).

In reviewing the video segments in slow motion, we found that rapid-injection darts consistently pulled the elk hide away from the gelatin following detonation of the internal powder charge (Fig. 3). This resulted in the dart needle retracting completely from the PWC and the partial ejection of color dye into the space created between the hide and gelatin. We also observed this effect in the video segments showing the impact of darts with the thigh of a calf carcass. Further, when we dissected the calf thigh at the point of impact, we consistently found a dye-filled cavity in the subcutis when using rapid-injection darts but not when using slow-injection darts. The full retraction of rapid-injection darts from the elk hide or calf skin was prevented by the needle barb catching against the subcutaneous surface of the skin.

Discussion

Using methodology employed to study wound ballistics in humans (Fackler 1988, MacPherson 1994, Haag and Haag 2002), we identified characteristics of RDDS that can contribute to injury in animals. Some findings suggest the potential for significant tissue injury with specific types of RDDS, and that continued improvement in design is required to further reduce morbidity and mortality. We identified low precision, high-impact velocity, the penetration of skin by needle seals, wound contamination by hair

Table 4. Muzzle velocity (V_0) and drag coefficient (C_d) values[a] for trials using different remote drug-delivery systems (RDDS) in phase I of a study conducted in Sep 2003 to evaluate the potential for different types of RDDS to cause injury.

Volume (ml)	**Charge**	**Power setting**	***n*[b]**	**V_0 (m/sec)[c]**	**C_d (m/sec/m)**
a) Heavy-mass rapid-injection darts					
3	brown	na	4	49 ± 7.7 (39–58)	−0.20 ± 0.107 (−0.35 to −0.09)
	green	na	5	72 ± 5.6 (66–78)*	−0.34 ± 0.027 (−0.38 to −0.31)
	yellow	na	4	96 ± 2.4 (93–99)*	−0.50 ± 0.150 (−0.77 to −0.40)
	red	na	5	126 ± 2.7 (124–130)*	−0.60 ± 0.062 (−0.68 to −0.54)
5	brown	na	5	42 ± 3.7 (37–47)	−0.15 ± 0.030 (−0.18 to −0.10)
	green	na	5	65 ± 3.7 (59–69)*	−0.28 ± 0.027 (−0.30 to −0.23)
	yellow	na	5	87 ± 3.5 (82–90)*	−0.38 ± 0.040 (−0.44 to −0.35)
	red	na	5	118 ± 3.5 (113–123)*	−0.76 ± 0.557 (−1.75 to −0.46)
7	brown	na	5	36 ± 4.9 (30–43)	−0.09 ± 0.033 (−0.14 to −0.06)
	green	na	5	56 ± 3.6 (50–60)	−0.22 ± 0.013 (−0.23 to −0.21)
	yellow	na	5	78 ± 3.6 (74–81)*	−0.30 ± 0.020 (−0.31 to −0.27)
	red	na	4	103 ± 5.2 (99–109)*	−0.38 ± 0.032 (−0.41 to −0.35)
10	brown	na	5	33 ± 3.2 (28–36)	−0.13 ± 0.137 (−0.38 to −0.05)
	green	na	4	53 ± 4.6 (49–59)	−0.20 ± 0.009 (−0.21 to −0.19)
	yellow	na	4	70 ± 1.5 (68–71)*	−0.23 ± 0.007 (−0.24 to −0.22)
	red	na	5	91 ± 1.4 (90–93)*	−0.27 ± 0.042 (−0.33 to −0.23)
b) Heavy-mass slow-injection darts					
3	brown	na	5	61 ± 7.0 (50–68)	−0.48 ± 0.039 (−0.53 to −0.44)
	green	na	5	91 ± 5.9 (87–101)*	−0.68 ± 0.018 (−0.70 to −0.66)
	yellow	na	5	113 ± 2.1 (112–116)*	−0.77 ± 0.069 (−0.85 to −0.71)
	red	na	3	148 ± 7.3 (143–161)*	−0.97 ± 0.120 (−1.16 to −0.86)
5	brown	na	5	51 ± 9.3 (36–61)	−0.31 ± 0.147 (−0.39 to −0.05)
	green	na	4	79 ± 3.4 (75–83)*	−0.40 ± 0.241 (−0.53 to −0.04)
	yellow	na	4	104 ± 2.5 (101–107)*	−0.59 ± 0.050 (−0.65 to −0.54)
	red	na	5	129 ± 1.4 (127–130)*	−0.71 ± 0.031 (−0.74 to −0.67)
c) Light-mass rapid-injection darts, 3 and 5 ml					
3	brown	2	1	28 (28)	−0.154 (−0.154)
		3	4	36 ± 0.9 (35–37)	−0.22 ± 0.020 (−0.24 to −0.20)
		4	5	56 ± 1.3 (55–58)	−0.31 ± 0.014 (−0.33 to −0.29)
		5	5	74 ± 2.9 (72–78)	−0.38 ± 0.023 (−0.41 to −0.36)
	green	2	4	63 ± 1.8 (61–65)	−0.34 ± 0.009 (−0.35 to −0.33)
		3	5	64 ± 1.1 (64–66)	−0.34 ± 0.012 (−0.36 to −0.33)
		4	4	83 ± 2.0 (81–85)	−0.42 ± 0.019 (−0.45 to −0.41)
		5	5	103 ± 0.5 (103–104)*	−0.52 ± 0.018 (−0.54 to −0.49)
	yellow	2	4	79 ± 1.2 (77–80)	−0.41 ± 0.020 (−0.43 to −0.39)
		3	4	86 ± 1.1 (84–87)	−0.44 ± 0.022 (−0.46 to −0.41)
		4	5	104 ± 1.1 (102–105)*	−0.53 ± 0.011 (−0.55 to −0.52)
		5	5	126 ± 0.9 (125–127)*	−0.74 ± 0.057 (−0.82 to −0.68)
5	brown	2	2	20 ± 0.4 (19–20)	−0.52 ± 0.197 (−0.66 to −0.38)
		3	3	33 ± 1.9 (31–34)	−0.12 ± 0.018 (−0.14 to −0.11)
		4	5	46 ± 0.9 (45–47)	−0.20 ± 0.010 (−0.21 to −0.18)
		5	3	60 ± 2.6 (58–63)	−0.25 ± 0.023 (−0.27 to −0.23)
	green	2	4	52 ± 3.7 (47–56)	−0.23 ± 0.021 (−0.26 to −0.21)
		3	5	54 ± 1.8 (51–56)	−0.23 ± 0.022 (−0.25 to −0.19)
		4	4	69 ± 2.1 (66–71)	−0.28 ± 0.016 (−0.30 to −0.26)
		5	5	87 ± 1.5 (85–89)*	−0.39 ± 0.058 (−0.46 to −0.32)
	yellow	2	5	67 ± 1.1 (66–69)	−0.26 ± 0.008 (−0.28 to −0.26)
		3	4	72 ± 1.0 (71–74)	−0.31 ± 0.025 (−0.33 to −0.28)
		4	4	85 ± 0.9 (84–86)*	−0.33 ± 0.021 (−0.35 to −0.31)
		5	5	100 ± 1.8 (97–102)*	−0.47 ± 0.036 (−0.50 to −0.42)
d) Light-mass rapid-injection darts, 7 and 10 ml					
7	brown	2	3	27 ± 1.0 (26–28)	−1.08 ± 1.053 (−2.25 to −0.20)
		3	2	31 ± 0.02 (31–31)	−0.63 ± 0.598 (−1.06 to −0.21)
		4	3	39 ± 1.4 (38–40)	−0.25 ± 0.020 (−0.27 to −0.24)
		5	5	51 ± 0.7 (50–52)	−0.34 ± 0.024 (−0.37 to −0.31)
	green	2	5	46 ± 2.2 (44–49)	−0.30 ± 0.014 (−0.32 to −0.29)
		3	5	49 ± 0.9 (47–50)	−0.31 ± 0.008 (−0.32 to −0.30)
		4	5	59 ± 1.3 (57–61)	−0.38 ± 0.015 (−0.40 to −0.36)
		5	5	70 ± 0.9 (69–72)	−0.48 ± 0.020 (−0.50 to −0.45)
	yellow	2	4	57 ± 0.9 (56–58)	−0.38 ± 0.005 (−0.39 to −0.37)
		3	5	61 ± 1.9 (59–64)	−0.41 ± 0.025 (−0.44 to −0.37)
		4	4	72 ± 1.1 (71–74)	−0.49 ± 0.004 (−0.50 to −0.49)
		5	5	83 ± 1.4 (81–85)*	−0.58 ± 0.023 (−0.60 to −0.49)

Table 4. continued.

Volume (ml)	Charge	Power setting	*n*[b]	V_0 (m/sec)[c]	C_d (m/sec/m)
10	brown	2	5	20 ± 7.1 (8–25)	−0.14 ± 1.621 (−1.26 to +2.73)
		3	5	27 ± 0.6 (26–27)	−0.40 ± 0.416 (−0.94 to −0.03)
		4	5	34 ± 1.1 (33–35)	−0.16 ± 0.028 (−0.19 to −0.11)
		5	5	43 ± 1.1 (42–45)	−0.24 ± 0.016 (−0.26 to −0.22)
	green	2	5	39 ± 1.7 (38–41)	−0.21 ± 0.028 (−0.25 to −0.17)
		3	5	41 ± 0.7 (41–42)	−0.22 ± 0.017 (−0.25 to −0.21)
		4	4	51 ± 1.1 (49–52)	−0.30 ± 0.006 (−0.31 to −0.30)
		5	3	60 ± 0.9 (59–61)	−0.35 ± 0.012 (−0.37 to −0.34)
	yellow	2	5	50 ± 0.6 (49–51)	−0.29 ± 0.019 (−0.30 to −0.25)
		3	4	53 ± 0.8 (53–54)	−0.31 ± 0.028 (−0.35 to −0.29)
		4	5	67 ± 11.7 (60–88)	−0.43 ± 0.173 (−0.74 to −0.31)
		5	5	74 ± 5.3 (70–83)	−0.75 ± 0.715 (−2.03 to −0.39)
e) Light-mass slow-injection darts					
3	red	10	3	49 ± 3.4 (46–53)	−0.37 ± 0.030 (−0.41 to −0.35)
		20	5	57 ± 2.0 (54–59)	−0.42 ± 0.023 (−0.44 to −0.38)
		30	5	71 ± 0.7 (70–72)	−0.52 ± 0.023 (−0.55 to −0.49)
		40	3	78 ± 2.5 (75–80)	−0.57 ± 0.004 (−0.58 to −0.57)
		50	5	89 ± 0.7 (88–90)	−0.65 ± 0.010 (−0.66 to −0.64)
		60	5	96 ± 1.3 (94–97)	−0.67 ± 0.093 (−0.76 to −0.53)
5	red	10	4	39 ± 2.2 (36–42)	−0.24 ± 0.011 (−0.25 to −0.22)
		20	3	54 ± 0.5 (53–54)	−0.34 ± 0.016 (−0.35 to −0.32)
		30	5	65 ± 0.7 (65–66)	−0.39 ± 0.011 (−0.41 to −0.38)
		40	5	73 ± 0.6 (72–74)	−0.44 ± 0.009 (−0.45 to −0.42)
		50	5	81 ± 0.7 (80–82)	−0.49 ± 0.019 (−0.51 to −0.46)
		60	4	88 ± 0.7 (88–89)	−0.51 ± 0.037 (−0.55 to −0.48)
6	red	10	4	37 ± 1.0 (36–38)	−0.22 ± 0.013 (−0.24 to −0.20)
		20	4	49 ± 0.6 (48–49)	−0.27 ± 0.010 (−0.28 to −0.26)
		30	5	61 ± 0.6 (60–61)	−0.31 ± 0.013 (−0.34 to −0.30)
		40	5	69 ± 0.5 (68–69)	−0.35 ± 0.004 (−0.36 to −0.35)
		50	4	78 ± 2.5 (76–82)	−0.39 ± 0.016 (−0.41 to −0.38)
		60	5	82 ± 0.8 (81–83)	−0.43 ± 0.016 (−0.45 to −0.41)

[a] Muzzle velocity (V_0) and drag coefficient (C_d) values are presented as mean ± SD with the min. and max. values in round brackets. The velocity at a given distance from the muzzle is calculated by $V_D = V_0 - (C_d \times D)$ where V_D is the velocity in m/sec at distance (D) in m.

[b] Technical problems were encountered in trails where the number of replicates is <5.

[c] The potential for skin penetration by the dart body was considered high (*) when the mean impact velocity per trial (V_{TD}) ≥ the minimum impact velocity for the penetration of 1–3-mm-thick pigskin overlying gelatin (V_{MP}) by a dart of equivalent mass and diameter.

and skin, and the use of a rapid-injection mechanism as the primary factors causing injury. Heavy darts and long needle barbs also may contribute to injury.

We found precision to be lowest in trials using heavy darts. The low precision was caused primarily by large variation within trials in muzzle velocity (V_0), drag coefficient (C_d), or a combination of these factors. Precision also was affected by the amplification of moderate differences in V_0 or C_d over long target distances, i.e., >30 m. We suggest that large differences in V_0 can be explained by inconsistencies in charge loads and variable gas leakage around the dart as it traveled down the barrel. We noted that the sound of charges detonating was quite variable within trails using heavy and LR darts, and dart velocity appeared to correlate closely with the quality of sound. Fast darts tended to be accompanied by clear, sharp reports whereas slower darts were preceded by dull, muffled reports. We suggest that variation in C_d was caused by differences within trials in the rotational stability of darts. We detected dart flight instability (yaw) as marked deviations in the Doppler radar velocity recordings and by reviewing video segments in slow motion.

Accuracy is a function of bias and precision. Low bias is achieved largely through experience and regular practice, an important point that has been emphasized by many (Kock 1987, Bush 1992, Nielson 1999, Kreeger et al. 2002). When bias is low, precision becomes largely a function of equipment. Unfortunately, the precision of RDDS has received little attention in the published literature. Valkenburg et al. (1999) tested the velocity and consistency of select HR darts and reported large variation in dart velocity when using powder charges and discussed the implication of variation in dart velocity for accuracy in a later article (Valkenburg and Tobey 2001). Variation in the drop of repeated shots was >10 cm in >30% of the trials conducted in this laboratory study, and the proportion would likely be greater under field conditions. The potential for this low precision to cause significant injury is largely dependent on the size of the target area, which is determined mostly by the size of the target animal.

We measured high-impact velocities ($V_{TD} > 50$ m/sec) in many of the trials using heavy darts and in a few trials using LR darts. In many cases, the V_{TD} values exceeded empirical skin-penetration threshold velocities (V_{MP}) for different handgun bullets fired into 1–3-mm-thick pigskin (MacPherson 1994) and sometimes were high enough to result in partial penetration of the ordnance gelatin and elk hide (7 mm thick), or the calf carcass, by the dart body. Partial or complete penetration of target animals by whole darts has been described in the published literature (Thomas and Marburger 1964, Valkenburg et al. 1983, Bates et al. 1985, Spurlock and Spurlock 1988), as has the high velocity of HR darts when using powder charges (Jessup 1988, Valkenburg et al. 1999). The profile and diameter of the projectile and the resistance of the animal's skin to stress are important determinants of penetration in addition to dart mass and velocity (MacPherson 1994). The effect of projectile diameter was illustrated clearly when we observed that the needle seals of LS darts consistently penetrated the elk and calf hides. We calculated the V_{MP} for the needle seals of LS darts to be 33–36 m/second depending on dart volume, which was well below the range of V_{TD} values (50–53 m/sec) measured for LS darts. The dart body profile also is important; one with a tapered (or pointed) profile is more likely to penetrate than one with a blunter profile (Haag and Haag 2002).

We consistently found hair and skin forced beneath the elk hide and sometimes into the PWC following impact with rapid-injection darts. We suggest this was caused by the large-diameter (12–14-gauge), end-ported needles used on these darts and not the rapid-injection mechanism per se. The contamination of a dart wound in a living animal is likely to result in localized infection and the formation of an abscess but could lead to a more generalized illness. Although the contamination of dart wounds has not been well documented, routine prophylactic treatment by instillation of oil-based antibiotic preparations deep into dart wounds and by systemic antibiotic therapy is widely recommended (Nielson 1999, Jessup 2001, Kreeger et al. 2002). Nevertheless, the efficacy of these treatment procedures for wildlife is not known (Pietsch et al. 1999).

One of our more significant findings was that the PWC length can be as much as 3× the needle length, depending on the dart characteristics. The HR darts that impact at high velocity will cause the deepest wounds in a living animal, and, although tissue compression will increase marginally with heavier and faster darts, it is the injection mechanism that affects the wound depth most. The forceful expulsion of drug from rapid-injection darts essentially forms a hydraulic needle that advances the crushing of tissue well beyond the tip of the needle.

Another major finding in our study was that the rapid-injection mechanism formed a cavity beneath the skin as a result of the forceful repulsion of the dart during injection (see Fig. 3). We observed in the video segments at slow motion that, even as the gelatin (or calf muscle) was compressed by the dart impact, the dart was moving rapidly in a reverse direction away from the impact site. The consequences were twofold; the hide was pulled away from the gelatin block (or muscle) and the needle was pulled free of the PWC before the ejection of dye was completed. In a living animal, the tearing of subcutaneous tissue will result in hemorrhage and the formation of a cavity in the subcutis permitting accumulation of blood and drug and, potentially, pus. In addition, if the needle retracts from the muscle before the ejection of drug is complete, the animal may be under-dosed and the induction of immobilization prolonged. Kreeger (2002) compared induction times between rapid- and slow-injection darts in a controlled, crossover design study, but found no differences. However, the drug volumes used in this study were presumably small ($\leq$2 ml), and possibly too small to affect the injection of drug into muscle. Undoubtedly, the needle barb was a factor contributing to the formation of a cavity beneath the elk hide or calf skin used in our study. However, observations that rapid-injection darts without needle barbs are repelled from living animals without any significant amount of drug injection have been well documented (Bush 1992) and reinforce the need for some type of anchoring device (e.g., barb, collar) on rapid-injection darts fitted with end-ported needles.

Management Implications

Remote drug-delivery systems are an essential tool of wildlife management required for the capture of free-ranging wildlife for the purposes of management, research, and conservation. Despite their extensive use, the potential for RDDS to cause significant injury has received little attention. We found that some types of RDDS are likely to cause serious injury that may affect target animals for a prolonged period following capture (e.g., days, weeks, and possibly months). Further, such injuries are not likely to be apparent at capture because they are well concealed by skin and fur. To reduce morbidity and mortality associated with RDDS, we recommend that 1) field personnel use darts with slow-injection mechanisms in preference to those using rapid-injection mechanisms, 2) field personnel rigorously test their equipment under both controlled and field conditions and communicate their findings to the manufacturers, and 3) manufacturers design their products and develop recommendations for use based on empirical evidence.

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