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REVIEW

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External transmitter attachment in snakes: a systematic review of methods, efficacy, and impacts

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Abstract

Background The advent of telemetry has revolutionized wildlife research in recent decades. For telemetry to be effective, transmitting devices must remain attached to study animals throughout a period of interest and without impacting pertinent behaviors. Surgical implantation remains the most common method used to attach transmitters to snakes, but concerns about the effects of transmitter implantation on snake health and behavior have motivated many researchers to opt for external transmitter attachments. Despite the increasing use and diversification of external transmitter attachment techniques in snake research, to date there have been no comprehensive reviews examining the methods, efficacies, and adverse impacts reported in the literature. We therefore conducted a systematic review of past research involving external attachment of transmitters on wild snakes. We extracted data from relevant studies to determine whether and how snake traits and transmitter attachment details correlated with efficacy and likelihood of adverse effects.

Results The 54 cases that met inclusion criteria covered 33 species and 3 families. External attachment was biased toward smaller-bodied snakes (median = 186 g), although larger snakes had longer retention durations. Adverse impacts were reported in 37% of studies ($n = 20$), and included altered behavior and movement, skin wounds at the attachment site, and death. Smaller snakes were more likely to exhibit adverse impacts from attached transmitters. Except for caudal attachments in rattlesnakes, attachment method did not have a significant effect on attachment duration. However, attachment method did influence the probability of causing adverse effects, with glue being the most likely to cause negative impacts.

Conclusions Externally attaching transmitters to snakes is an increasingly popular alternative to surgical implantation. To provide guidance to researchers considering this approach, we conclude our systematic review with recommendations for attaching external transmitters to snakes. Actions such as minimizing transmitter weight and protrusion, using shorter and stiffer antennas, and using flexible adhesives may help to avoid commonly reported problems. We encourage more consistency in reporting methodological details and results pertaining to efficacy and animal welfare.

Keywords Snake external transmitter, Radiotelemetry, Snake radio tracking, Radio transmitter, Subdermal stitch, Glue-on transmitter, Systematic review

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Introduction

Telemetry is a staple tool for wildlife research, providing the data for many analyses related to spatial ecology and habitat interactions [1, 3, 8]. It has been especially crucial in the study of cryptic organisms whose movements and behaviors may not be discoverable through other methods [17, 27]. To be effective, telemetry requires that a transmitter (i.e., radio or GPS be carried by an animal throughout a period of interest without substantially altering pertinent behaviors. This necessitates either internal placement (surgical implantation or forced ingestion [10, 22]) or external attachment (e.g., collars, backpacks, adhesives, etc. [18]) of radio transmitters.

Snakes possess simple, limbless bodies and regularly shed their skins, posing challenges to attachments that rely on external structures (e.g., limbs, fins, feathers, fur, etc.) or prominently regionalized bodies [25]. Consequently, most snake researchers have opted for surgical implantation [22, 23, 38] instead of external attachment. However, surgical implantation increases the risk of snake mortality due to anesthesia and possible postoperative infection [24]. In some cases, transmitter implantation has negatively affected growth and reproductive rates [33]. It has been pointed out that relying on movement and habitat data from snakes implanted with transmitters may be questionable because sick and convalescing individuals may not behave normally [23, 29].

Additionally, study constraints may make surgical implantation impractical. For instance, the small body size of a target species and ethical limits for transmitter package dimensions (typically expressed as a ratio of transmitter mass to body mass) may restrict researchers to using small and short-lived transmitters, requiring frequent surgeries to avoid losing study animals [7, 37]. Furthermore, certain research goals may only necessitate a brief monitoring period, making long-term tracking with surgically implanted transmitters unnecessary [36]. Finally, surgical procedures are expensive and require highly trained personnel [2]. For these reasons, researchers or regulatory bodies may deem surgical methods unjustified.

The drawbacks of surgical implantation make the use of temporary external transmitters an attractive alternative for gathering movement data, and researchers have devised numerous techniques to do so (e.g., [23, 37, 38]). External attachment can reduce handling time and stress and addresses concerns of surgery-induced sickness and convalescence behaviors [23]. Furthermore, because external attachment can be performed with minimal equipment, material cost is relatively low [38]. In many cases it can be performed in the field with little training and snakes can be released minutes after capture [23, 38]. Despite these advantages, external attachment has major shortcomings compared to surgical implantation. For example, external attachments typically fail much sooner than implanted transmitters, resulting in fewer data; adhesives can cause damage to skin and scales; and, crucially, external packages can become entangled in vegetation or other features of the snake's habitat, burdening, injuring, or even killing the snake [4, 19, 38].

Radiotelemetric studies of snakes continue to proliferate, including those using external transmitters. Due to the myriad combinations of attachment techniques, species, environments, and data collection regimes, results pertaining to efficacy and safety of externally attached transmitters are highly variable. To date no comprehensive syntheses of these literature are available to researchers who must weigh the risks, benefits, costs, and limitations of various approaches when considering whether and how to externally tag the snakes they are studying. Furthermore, there is a high likelihood for increased use of external attachment techniques with the increasing availability of automated tracking systems (e.g., solar-powered GPS or ultra-high frequency transmitters) whose potential has yet to be fully realized in snakes. For these reasons, a synthesis of available literature is warranted.

We conducted a literature search and meta-analysis of past research involving external attachment of transmitters on snakes. We used data from relevant studies to determine whether and how study details such as snake traits, transmitter details, and attachment methods correlated with attachment longevity and the likelihood of snakes exhibiting adverse effects. By synthesizing the available information, we hoped to provide researchers with a basis for deciding whether external attachment is appropriate for their focal species, choosing among available attachment options, and anticipating likely health and efficacy outcomes.

Methods

We searched the published literature using key word searches in Google Scholar and Web of Science. The searches were conducted in January 2024. We used the Boolean search terms "(transmitter OR telemetry) AND (attach OR external) AND (snake)". We reviewed titles and abstracts for relevant works, in order, until we encountered 100 consecutive results that were not relevant to our search. Our initial list contained 58 candidate publications. We then reviewed candidate publications to determine whether they met the following inclusion criteria: (1) subjects must be free-ranging snakes; (2) attachments must be external radio or GPS transmitters; and (3) authors must have reported, at minimum, the species and the sample size studied.

We also reviewed reference lists within candidate publications for additional relevant works, which we added to the list of candidate publications if they met the inclusion criteria listed above. After eliminating candidate publications from the list that did not meet inclusion criteria, and after adding works from the references lists of candidate publications, 43 publications remained, which comprised our final list for analysis.

From each publication we extracted up to 14 variables related to the animals studied, the transmitter, the attachment method, its efficacy, and its effects (Table 1). Several studies compared multiple attachment techniques and/or multiple species. To maintain specificity of details to their respective techniques and species, we divided studies by species and attachment technique for all quantitative analyses. When studies did not include morphometric data (mass and snout-vent length [SVL]), we substituted the missing data with average adult mass and SVL from external sources, if available. Except when noted otherwise, all analyses related to mass and SVL used data from both focal studies and external sources.

To examine which factors influenced the probability of adverse effects, we used logistic regression to correlate pooled effects (behavioral, injury, and death) to covariates related to study details such as snake morphometrics (mass and SVL), transmitter dimensions (transmitter mass, transmitter-snake mass ratio [TSR]), and transmitter placement (body, tail). To relate covariates with the probability of adverse effects we used generalized linear models (GLMs) with logit link functions, treating adverse effects as a binomial response. To relate covariates with attachment duration, we used quasipoisson GLMs with log link functions to conform to properties of the data. For the categorical variables “attachment method” and “body placement” we grouped cases into the following categories: “tape-only”, “glue-only”, tape-and-glue”, and “subdermal stitch” for attachment method, and “body”, “tail”, and “rattle” for body placement. We excluded rattle attachments when using GLMs to determine the effect of attachment method on duration due to small sample size. When fitting GLMs involving categorical variables, we selected a reference group based on which had the lowest average response values and then calculated differences in effects with respect to the reference group.

All continuous covariates were z-score standardized. Coefficients were reported with their standard errors. Because most variables were not normally distributed, we used bootstrapping with 1000 replications to calculate their means and standard errors across cases. Unless otherwise noted, sample sizes are reported in number of publications. We used R computing software [21] packages dplyr [35] for data manipulation, boot [6] for bootstrapping means and standard errors, stats [21] for GLMs, and ggplot2 [34] for graphical presentation.

Results

Our literature search resulted in 43 publications that met inclusion criteria (See Supplementary Table 1). These included 30 scientific articles, 12 unpublished theses, and 2 technical reports. Subdividing publications that tested multiple species or transmitter attachment methods resulted in 54 cases (hereafter “studies”) with which to perform statistical analyses.

Table 1 Variables collected from cases included in our systematic review

Variable	Notes
Species	Species studied
Morphometrics	Average mass and snout-vent length (SVL) across study animals. If data were unreported, we substituted mean mass and SVL data from external sources (Table S2, Appendix 2)
Sample size	Number of study animals
Transmitter mass	Transmitter package mass, inclusive of attachment device/material (when reported)
Transmitter-snake mass ratio (TSR)	Transmitter mass / snake mass
Transmitter type	Radio or GPS
Mean duration	Average number of days individuals were tracked before transmitters died or were removed
Mean number fixes	Average number of fixes per study animal. If data were unreported, used mean duration (assumes animals were tracked daily)
Attachment	Noted materials and attachment methods (e.g., tape, glue, thread, subdermal stitch, or combinations thereof)
Longitudinal attachment position	Anterior body, posterior body, tail, or rattle (*Crotalus*, *Sistrurus*)
Transverse attachment position	Dorsal or ventral
Effect specification	Whether authors evaluated health and/or behavioral effects of transmitters
Effect presence/absence	Whether authors observed any health and/or behavioral effects of transmitters
Type of effect(s)	What types of health/behavioral effects were observed (abrasions, tail injuries, restricted movement, etc.)

The studies included 32 species of snakes belonging to 22 genera and 3 families. Since the earliest publication in 1990, use of external transmitter attachment has steadily increased, with half of all publications published since 2018 (Fig. 1).

Studies varied in the details that were either reported or derivable from reported data (Table 2). Snake mass and SVL were reported in 37% and 28% of studies, respectively. References for substituted mass and SVL can be found in Supplementary Table 2. The full dataset extracted from the included studies can be found in Supplementary Table 3. External transmitter attachment was biased toward small-bodied snakes (median = 186 g). The ratio of transmitter mass to snake mass (TSR) ranged from 0.3 to 9.4% for studies that reported snake mass. However, TSR was as high as 12% ($\bar{x} = 2.2 \pm 0.4\%$, range = 0.2–12%) when data were supplemented with mass data from external sources. TSR was highest among small snakes and dropped exponentially with increasing snake mass (Fig. 2). Transmitter attachment sites were distributed longitudinally on the snake as follows: anterior third 2% ($n = 1$ study); posterior third 55% ($n = 29$ studies); tail 40% ($n = 21$ studies); and rattle 4% ($n = 2$ studies).

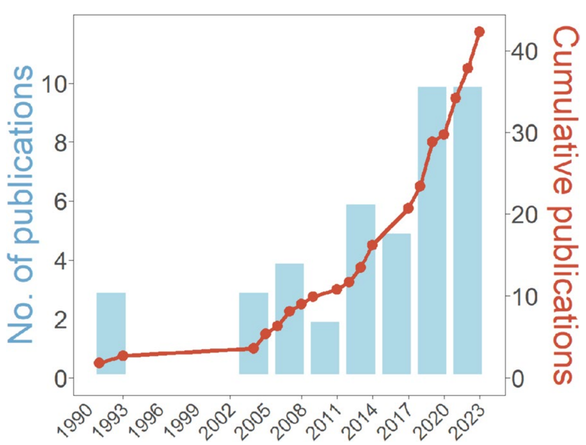

Fig. 1 Number of publications using external transmitter attachment on snakes from 1991 through 2023

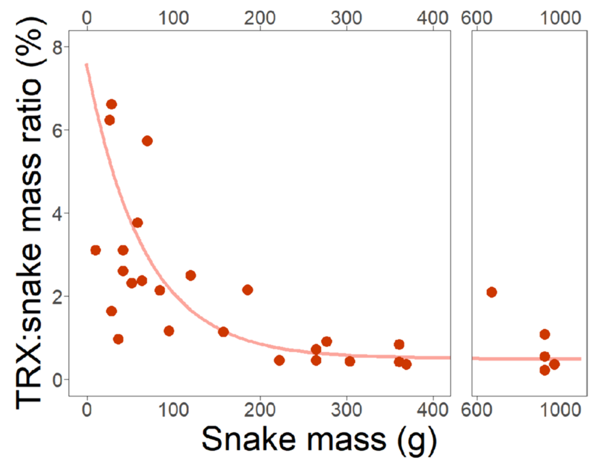

Fig. 2 Relationship between snake mass and the transmitter (TRX):snake mass ratio expressed as a percentage of snake mass

Transversely, placements were either ventral 8% ($n = 4$ studies) or dorsal 92% ($n = 49$ studies).

We recorded two variables related to attachment efficacy: number of fixes and attachment duration. The single study incorporating GPS had a higher number of fixes per individual (180 fixes, $n = 1$) than studies using radio transmitters ($\bar{x} = 13.9 \pm 8.8$ fixes, $n = 52$). However, the tracking duration using GPS (19 days, $n = 1$) did not exceed that of the radio-tracking studies ($\bar{x} = 29 \pm 10.2$ days, $n = 52$). Snake family had a significant effect on attachment duration, with viperids ($\bar{x} = 38.8 \pm 9.7$ days) retaining transmitters longer than colubrids ($\bar{x} = 18.9 \pm 2.8$ days; $\beta = 0.72 \pm 0.33$, $p = 0.03$). We did not include elapids in this comparison due to the small sample size ($n = 2$ studies). Snake mass was a significant predictor of attachment duration, with larger snakes retaining transmitters for longer ($\beta = 0.33 \pm 0.13$, $p = 0.01$).

There were no significant differences in attachment duration whether researchers used glue, tape, glue and tape, or subdermal stitch. Because attachment method was categorical, we calculated the effect of each attachment method on duration with respect to a reference group. We used glue-only as the reference group

Table 2 Reporting frequencies, means, and standard errors for variables extracted from publications

Variable	Sample size	Snake mass (g)	Snake SVL (cm)	TRX mass (g)	TSR (%)	Attachment details	Effects specified	Attachment duration (d)	*n* loc. fixes
Median	9	186	80.5	1.8	2.1	–	–	19.3	11.5
Mean ± SE	14.7 ± 2.4	293 ± 78	79 ± 6.6	2.7 ± 0.4	2.7 ± 0.6	–	–	28 ± 5	22 ± 8
Range	1–84	9.6–1333	31–123	0.3–14	0.3–9.4	–	–	1–189	1–180
n publications	43	13	15	31	18	42	30	30	16

since it had the shortest average attachment duration. While not significant, mean durations for subdermal stitch (35.0 ± 11.2, $n=4$) and tape-only ($\bar{x}=31.7 \pm 4.9$, $n=14$) were longer than for glue-only, (16.3 ± 4.8 days, $n=7$), and these differences approached significance ($p=0.09$ and $p=0.08$, respectively). As for the body positioning of the transmitter, rattle attachments had the longest mean attachment duration (100.5 ± 62.7 days, $n=2$) followed by body attachments (25.8 ± 4.8 days, $n=28$) and tail attachments (22.3 ± 4.9 days, $n=12$). However, excluding subdermal stitch to consider only adhesive attachments reduced mean tail attachment duration considerably (15.9 ± 2.7 days, $n=8$).

Negative effects of transmitters, as broadly defined, included altered behavior, injuries, and death, and were reported in 37% of studies ($n=20$). Behavioral effects were mainly caused by transmitters or antennas becoming entangled in vegetation or lodged in rocks (25% of studies, $n=13$). Only one study reported the transmitter preventing normal shedding. Injuries occurred at the attachment site and included abrasion wounds, bleeding, scarring, and removal of scales (22% of studies, $n=12$). Entrapment of the transmitter package or antennas in vegetation and rock was the sole cause of transmitter-related mortality (6% of studies, $n=3$). Smaller-bodied snakes were more likely to exhibit negative impacts from attached transmitters: the probability of adverse effects was significantly higher among snakes with shorter SVL ($\beta=-0.7 \pm 0.4$, $p=0.04$; Fig. 3a) and lower mass ($\beta=-1.3 \pm 0.6$, $p=0.04$; Fig. 3b). Though not significant, adverse effects may have been more likely with higher TSR ($\beta=0.3 \pm 0.2$, $p=0.17$; Fig. 3c). Transmitter mass alone was not a good predictor of adverse effects ($\beta=-0.06 \pm 0.1$, $p=0.6$; Fig. 3d). Snakes that died due to external transmitters becoming entrapped in vegetation or rock had the lowest mean mass ($\bar{x}=38 \pm 13$ g), followed by those that exhibited adverse effects of any kind ($\bar{x}=161 \pm 40$ g; Fig. 4).

The risk of adverse effects depended partly on attachment method. Because attachment method was a categorical variable, test statistics were calculated with respect to a reference group. We chose tape-only as the reference group since this had the lowest incidence of adverse effects (24%, $n=13$ studies). Glue-only resulted in adverse effects in 70% of studies ($n=10$) and was the only method whose effect size was significantly different than tape-only ($\beta=1.8 \pm 0.9$, $p=0.04$), implying a higher probability of adverse effects when using glue-only. Glue-only also appeared to have a higher probability of causing adverse effects when compared to subdermal stitch, but the difference was barely not significant ($\beta=1.9 \pm 1.1$, $p=0.07$). Attachment position (i.e., body, tail, or rattle) did not appear to influence the probability of adverse effects ($\beta=0.29 \pm 0.59$, $p=0.62$).

Discussion

Prior to the present review there have been few attempts to compare external transmitter attachment methods for snakes. Exceptions include Újvári and Korsós [32], who compared the external attachments of Ciofi and Chelazzi [7] and Gent and Spellerberg [11] in their review of snake telemetry practices,and several authors who made within-study comparisons of multiple attachment methods or multiple species (e.g., [14, 19, 23]).

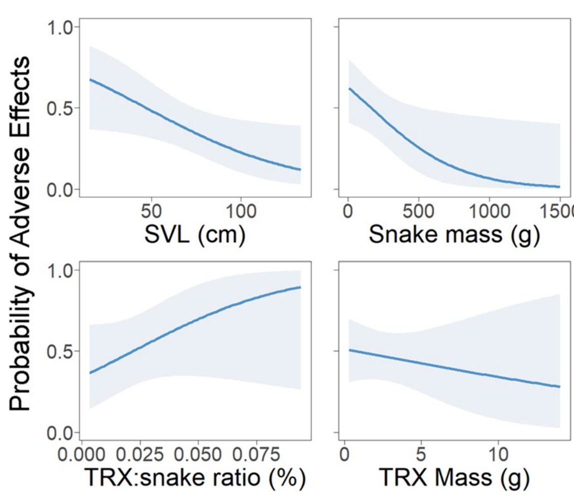

Fig. 3 Effects and 95% confidence intervals of different snake and transmitter dimensions on the probability of adverse effects. *SVL* snout-vent length, *TRX* transmitter

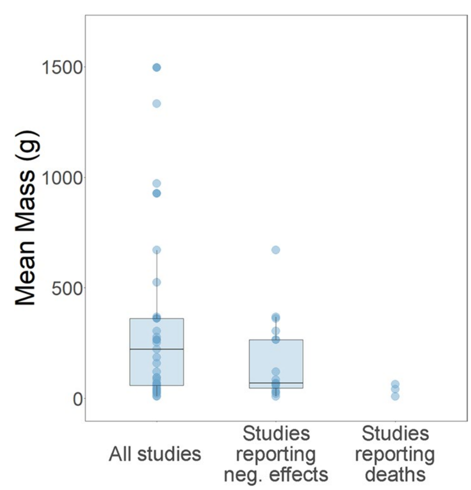

Fig. 4 Distributions of snake body mass within three study categories: all reviewed studies, studies that reported negative effects of any kind, and studies that reported deaths. Each circle represents one study

Due to the typically short attachment durations, external transmitters were most often used to address short-term behaviors, for example, short-term habitat use and selection; behavioral and physiological responses to specific events, such as translocation; daily travel distances; or movements to critical habitats such as nests, gestation sites, and hibernacula. One common reason stated by authors for using external transmitters was that surgical implantation was not justifiable due to snake body size constraints. Accordingly, external attachment methods were biased toward small-bodied snakes (median = 186 g).

We categorized attachment techniques based on the materials used and the position of the transmitter on the snake's body. These categories were necessarily broad to allow meaningful statistical analyses, and it is important to recognize that there was considerable variation within categories. For example, tape-only attachments included various materials (e.g., gaffer tape, duct tape, medical tape, etc.), and wrapping methods (from partially to fully encircling the body). Likewise, transmitters were variously placed ventrally, dorsally, anteriorly, posteriorly, or on the tail. While some variations within categories were likely safer or more effective than others, sample size constraints prevented us from making more detailed within-group comparisons.

In addition to sample size constraints, lack of detail and reporting consistency prevented a more thorough analysis of negative impacts. For instance, only half of studies (51%) reported whether adverse effects (e.g., altered behavior, injury, or death) were observed, and those that did mostly presented effects in the form of presence or absence rather than frequency. This limited us to addressing study-level rather than individual-level probability of adverse effects. We chose to treat studies that did not mention adverse effects as negatives, but it is possible adverse effects occurred in some of those studies but were not mentioned. Similar limitations prevented us from statistically accounting for within-study distributions of attachment duration, snake mass, snake SVL, and transmitter-snake mass ratio (TSR).

For the external attachments that relied on adhesives (e.g., tape, glue, or combinations thereof), attachment durations were often limited by the timing of ecdysis. To increase attachment durations, several authors held snakes in captivity and attached transmitters immediately post-ecdysis. Only two attachment methods circumvented the issue of ecdysis altogether: the subdermal stitch (e.g., [23]) and attachment to rattles in *Crotalus* (e.g., [15]). In addition to circumventing the problem of ecdysis, these attachments allowed for relatively straightforward replacement of transmitters that were approaching the end of their battery life. Therefore, we expected rattle and subdermal stitch attachments would have the longest reported attachment durations. However, this only seems to have been the case for rattle attachments, which remained for much longer (101 days, $n = 2$) than subdermal suture (35.0 ± 11.2 days, $n = 4$) or transmitters attached to the skin using adhesives (24.4 ± 3.0 days, $n = 34$). Rattle-attached transmitters were lost when they became entangled in vegetation, breaking off the rattles [15]. Interestingly, despite the seemingly more secure and permanent attachment offered by the subdermal stitch, the mean attachment duration was comparable to that of tape-only (Fig. 3) and was not significantly longer than any of the attachment methods used.

In addition to lower average frequencies of ecdysis, several other biological traits may be responsible for the longer attachment durations seen in vipers (e.g., *Crotalus, Sistrurus*) versus colubrids (e.g., *Elaphe, Thamnophis*). For example, vipers exhibit more stationary foraging strategies (i.e., ambush hunting) than colubrids [28], and longer periods of motionlessness may reduce wear-and-tear on transmitter attachments. Second, the keeled scales and relatively stout bodies of vipers may provide superior adhesion surfaces for glue or tape attachments [31]. Third, the viperids in the studies analyzed were larger-bodied (381 ± 192 g) than the colubrids (216 ± 39 g), and we found that mass positively predicted attachment duration. Third, their stout bodies result in the posterior abdomen and tail being much narrower than the midbody. Transmitters attached to these regions may be less protrusive and less likely to repeatedly catch and rub against objects. Regardless of family, body size in general correlated with longer attachment durations, possibly due to greater attachment surface areas, decreased shed frequencies, or allometries between size and movement behaviors [5].

Only one study that met our inclusion criteria used externally mounted GPS units [12]. This study had the advantage of a greater number of location fixes and reduced manual tracking effort relative to those using radio transmitters alone. However, ecdysis still constrained the attachment duration of the GPS transmitters, which was shorter (19 days) than the average for all transmitters (29 days). Because GPS units are more expensive, use of GPS is often reserved for long-term tracking studies in other wildlife [16, 30]. Furthermore, the tendency of reptiles to remain stationary for long periods of time results in highly autocorrelated data, which may only be overcome by longer tracking periods. Therefore, methods that allow tracking devices to remain attached during shedding, such as the subdermal stitch method or internal transmitters with protruding antennas ([26], not reviewed), may be the most practical for many GPS applications. However, those attachments are more invasive than ones using adhesives alone.

It is important to note that we defined negative effects broadly to include impediments to movement or shedding, injuries to the attachment site, or death as a result of transmitter entrapment in rock or vegetation. The detection or nondetection of adverse transmitter effects on snakes was explicitly addressed in only 51% ($n=30$) of studies. Among studies that did explicitly address whether transmitters affected snakes, 2/3 ($n=20$) reported negative effects. Smaller snakes appear more susceptible to these effects. For example, the snakes in studies that reported behavioral effects, injuries, or death due to transmitter attachments were smaller than the snakes in studies that did not report any adverse effects (see Fig. 4). Among studies whose average snake mass was within the lower 50th percentile, 54% reported adverse effects. We suspect the less durable skin and scales of smaller snakes may increase the risk of abrasion wounds; their relatively lower mass and strength may limit their ability to break loose of vegetation or rock entrapments; and relatively thin tails may be more prone to injury when tail attachments are used.

Conclusion

The often-cryptic appearance and behavior of snakes make extended observation of wild individuals difficult. External transmitter placement can allow additional opportunities for gathering movement data when other methods are not feasible. The use of external transmitter attachment is increasing, and to date no syntheses of the available literature have been published. We hope our review will provide a more comprehensive basis for researchers to (1) choose among available attachment options; (2) anticipate likely efficacy and health outcomes; and (3) consider whether external attachment is appropriate for their research needs and study species. Based on this review we make the following recommendations to researchers considering external transmitter placements on snakes.

Minimize transmitter-snake mass ratio (TSR) Smaller snakes had higher TSR and experienced higher rates of adverse effects. While not statistically significant, our model predicted a positive correlation between TSR and the probability of adverse effects, which surpassed 50% when TSR exceeded 3%. Reducing TSR will likely decrease the probability of negative impacts.

Use stiffer, shorter antennas The most common cause of adverse effects was transmitter entrapment in vegetation or rock. Two transmitter antenna modifications may help reduce this risk: (1) stiffer antenna material; and (2) shortened transmitter antennas. This latter modification may reduce transmission strength, which in turn may impact tracking of highly vagile snakes.

Minimize package protrusion Risks of entrapment and impediments to movement can be further reduced by minimizing transmitter size and by attaching it to a relatively narrow part of the body, ideally such that the combined diameter of the transmitter package and the snake's body at the attachment site does not exceed the snake's maximum diameter. This latter option may only be available for stout-bodied snakes. Another solution introduced by Wylie et al. [37] was to place transmitters ventrally and use tape to compress the transmitter against the venter, reducing the package protrusion.

Use attachments that permit flexion and expansion Glue and tape attachments that interfere with body flexion can impact movement or cause skin injury [9, 20], and attachments with large surface areas can interfere with expansion during ingestion of large prey ([13], not reviewed). Minimizing attachment surface area and using flexible adhesive materials should reduce these risks.

Avoid glue on skin Glue-only skin attachments had the highest rate of adverse effects (70%). Furthermore, glue-only was associated with the shortest average attachment duration of the methods compared. This may be due to the inability of glue to flex when the snake moves and bends (see above). We recommend avoiding glue when attaching transmitters to skin.

Report efficacy and effects details Consistent and detailed reporting of methodological details (e.g., sample size, transmitter dimensions, snake body dimensions, and attachment methods) and results related to efficacy and animal welfare (attachment durations, occurrence of adverse effects, and details of those effects) would be beneficial for guiding researchers as well as facilitating future comparisons among techniques. Individual-level results allow for the most interpretability, but at minimum, summary statistics (e.g., mean, SD, and range for quantitative variables, frequencies for categorical variables) should be provided. Researchers should consider including these details among the supporting information of their publications.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-024-00371-4.

Supplementary Material 1: Table 1 Reference list of studies that were included in our systematic review

Supplementary Material 2: Table 2 Reference list of studies used for morphometric data when those data were not reported in reviewed studies

Supplementary Material 3: Table 3Data extracted from reviewed studies and used for analyses

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Author contributions
TC designed the review inclusion criteria and data collection, performed the majority of the literature review, all statistical analysis, and the majority of the writing. FC assisted with literature review, compiled additional sources for morphometric data, and was a major contributor to the writing. Both authors read and approved the final manuscript.

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Availability of data and materials
The datasets supporting the conclusions of this article are available in the GitHub repository, https://github.com/tyler-christensen/ext_trx_review

Declarations

Ethics approval and consent to participate
Not Applicable.

Consent for publication
Not Applicable.

Competing interests
The authors declare that they have no competing interests.

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