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Lizards unplugged: a methodology study on radiotelemetry equipment for monitoring small–medium reptilian species

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Radiotelemetry has emerged as a crucial tool in wildlife biology, enabling researchers to monitor animal movements and behaviours in their natural habitats. While extensively used across various taxa, there remains a scarcity of studies dedicated to optimising radiotelemetry techniques for reptiles, especially small–medium lizard species (50–400 mm total length). In this study, the efficacy of two radio transmitters (Lotek PIP5 and Telemetrie-Service Dessau models) and different attachment methods on sand lizards inhabiting vineyard ecosystems were investigated. We evaluated three harness designs adopted over two years of fieldwork, the Adapted Rappole-Harness (ARH), Shoulder Harness (SH), and Axillary Harness (AH), considering methodological details, attachment longevity, signal range and strength, potential behavioural effects, threats to lizards' health and survival. Our results indicated that the ARH model was unsuitable, as lizards quickly removed it after few minutes. The SH remained attached for a maximum of 10 days, while the AH lasted up to 17 days, withstanding adverse environmental conditions and terrain abrasion. This study provides valuable insights into optimising radiotelemetry techniques for small–medium reptile species. By considering harness design, attachment location, materials and transmitter shape, researchers can enhance the welfare of tagged individuals and improve the efficiency of telemetry studies. Furthermore, this research underscores the need for standardised guidelines for transmitter attachment in reptiles, promoting animal welfare and advancing scientific understanding in this field. Sharing experiences and collaborating within the scientific community will foster progress in developing effective and ethical transmitter attachment protocols for small–medium reptiles.

Keywords: harness designs, radio-tag, sand lizards, telemetry, transmitters devices

INTRODUCTION

Radiotelemetry is a valuable and well-known technique adopted in wildlife biology and ecology to track movements and behaviour of various species in their natural habitats (Kenward, 2001). This technique involves attaching radio transmitters to animals and most commonly locating their positions from time to time or tracking their locations over a period of time. Studying species movement patterns (up to complete migration routes, e.g. Lamb et al., 2023); determine activity, home ranges and habitat utilisation on a smaller scale (e.g. Hansen et al., 2020), or assess effects of human activities and environmental changes on animal behaviour and survival (e.g. Thomas et al., 2018; Blais et al., 2023; Giuntini & Pedruzzi, 2023) are common areas of research. The number of papers reporting on tracking data collected increased considerably within the last 20 years (from below 500 in the time period 1959–2000 to nearly 2000 in 2001–2023; based on literature search in Scopus database using search terms radiotelemetry and radio-track). This continuous increase of published papers was a result of using and attaching every type of transmitter to nearly all kind of species within scientific working groups. Literature reports about radio tracking data from arthropods (Daniel Kissling et al., 2014; Cavigliasso et al., 2020; Růžičková & Elek, 2023) via fish (Panchan et al., 2022; Chevallier et al., 2023), to bats and other mammals, amphibians, birds, etc. (Frick et al., 2023; Lamb et al., 2023; Saha et al., 2023).

Regarding reptiles, although the number of papers reporting telemetry data is much lower than for other vertebrates (Millspaugh & Marzluff, 2001), a variety of techniques has been used to attach transmitters. These are surgical implants (Klingenböck et al., 2000; Guarino, 2002; Smith et al., 2010), direct adhesion to the skin (Sabo, 2003; Mathies & Martin, 2008), tail mounts (Germano, 2007; Barr, 2009), collars (Perez-Buitrago & Sabat, 2007) or harnesses (Flesch et al., 2009; Goodman et al., 2009; Clement et al., 2022). There are advantages and limitations of each of these techniques, and the choice of which approach to use depends on the morphology, size and behaviour of the species, the research questions under consideration, and the environment in which the studies are being conducted (Withey et al., 2001; Yet, 2014). Doody et al., (2009)

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for example, provide a detailed review of methods for securing radio transmitters to freshwater reptiles of varying shapes, sizes and adhesive surfaces, as well as potential difficulties and pitfalls. Goodman et al. (2009) reviewed case studies of internal implantation, ingestion and external attachment of transmitters to rock iguanas of the genus *Cyclura*.

Despite these specific reviews, very few publications address tracking device applications, their advantages and disadvantages, or the effects of tagging on reptiles in general. Indeed, the majority of the studies on radiotelemetry of reptiles simply describes the method applied, focusing mainly on the results about movements and their interpretation, and not necessarily reflecting the application method applied.

Among the various very high frequency (VHF) radio tracking devices adopted for terrestrial lizard taxa, backpack harnesses and a transmitter glued directly on the skin have shown to be the most common techniques (Warner et al., 2006; Price-Rees & Shine, 2011; Refsnider et al., 2015; Clement et al., 2022). Regardless of the species studied, there are general challenges that researchers must face while tagging lizards, such as the effect that a transmitter attachment can have on their behaviour. For example, habitats with dense vegetation or where lizards commonly enter small burrow entrances could be problematic with an external attachment (Warner et al., 2006). The other way around, habitat structures like jagged outcroppings or narrow cracks can affect the transmitter harness (van Winkel & Ji, 2014). Moreover, the transmitter and harness as extra weight could require higher energy cost (Knapp & Abarca, 2009) and/or slow down the animal, altering its behaviour and possibly affecting survival. Some studies have focused, for example, on whether lizards showed resistance to contact with ground surfaces, to tears on harness materials during locomotion (Warner et al., 2006) and that the application method avoids any possible rubbing or abrasive forces on the skin potentially caused by external transmitter harnesses (Goodman et al., 2009). Unfortunately, little effort has been placed on discussing the beneficial and/or adverse effects of these application options in terms of the study's objectives and animal welfare, gaining no knowledge in animal tagging (i.e. what should and should not be done). The lack of published data has hindered progress towards developing most effective and safe transmitter attachment protocols for small–medium reptiles, which are desired and helpful not only for animal welfare reasons, but also for supporting more scientific work using telemetry and devices by assisting permission approval procedures to apply such devices and gain most reliable data from tracking.

Our study aimed to investigate the efficiency of radio transmitter attachment methods on sand lizards *Lacerta agilis* Linnaeus, 1758, in vineyards in Germany. We discuss our results focusing on i) methodological details, ii) longevity of attachment, iii) signal range and strength, iv) potential effects on behaviour, threats to health and survival, and v) recommendations for transmitter use in lizard studies in farmland-like habitats.

MATERIALS & METHODS

Species choice and study area

The sand lizard is a small to medium sized diurnal ground-dwelling lizard (total length of about 250 mm, snout-vent length 110 mm). It has one of the largest geographical ranges among reptile species, occupying much of Central and Eastern Europe to Mongolia in the East (Gasc et al., 2004; Blanke & Fearnley, 2015). Throughout much of its range, sand lizards inhabit a variety of habitat types including farmland, and particularly agricultural margins, grassland, steppe and hedgerows (Gasc et al., 2004), offering a remarkable example of ecological plasticity in lizards. In Germany, adult sand lizards have an annual activity period from spring (mid-March–early April) to summer (around August). Their daily activity peaks can be unimodal or bimodal (depending on the temperature), with an increase of the activity in late spring–early summer months (Hafner & Zimmermann, 2007). Sand lizard movements are generally gender-specific: males have been reported as having home ranges of up to a few hundred square metres (which overlap inter-individually), while those of females are generally smaller (Nicholson & Spellerberg, 1989; Wieczorek et al., 2020). The overall morphological,

Figure 1. Study area - **a)** Typical patchwork vineyards area in northern Baden-Württemberg, Germany; **b)** examples of suitable habitats for lizards in vineyards.

ecological, biological and distribution characteristics make the species an appropriate model for studying telemetry and tracking methods within small–medium lizards (50–400 mm total length).

Fieldwork was carried out in July–early August 2018 and June–early August in 2021 in four agricultural sites in northern Baden-Württemberg, Germany, in an area typically characterised by a patchwork of vineyards (see Fig. 1a). Vineyards provide suitable habitats for sand lizards, including vegetated ground cover between and under the vine rows, walls, common woodpiles and sandy ground, encompassing a mosaic of basking and egg-laying spots, shelter and dietary resources (Fig. 1b).

Radio transmitters and attachments used

Two different transmitter types were used (Table 1): Lotek model PIP5 and a Telemetrie-Service Dessau model. Both transmitters featured a compact, lightweight design, making them well-suited to minimise impact on small animals such as lizards. Specifically, the Lotek transmitter had a flat, elongated shape, while the Dessau model was slightly smaller and more rounded. Both operated within a similar frequency range and emitted pulses at specific intervals, ensuring reliable tracking.

In a preliminary trial conducted before the start of this study, the radio transmitters were attached directly to the animals' backs using only glue. However, they remained attached for only a few days (personal observations). Therefore, in the present study, radio transmitters were attached to lizards using three backpack harness designs. The first type (from now on referred in the text as Adapted Rappole-Harness, ARH) was modified from the 'Rappole-Harness' method commonly used for smaller bird species (Rappole & Tipton, 1991). The harness consisted of two rubber loops branching from a central paper pad where the transmitter (Lotek model) was glued on with a tissue glue (SURGIBOND). The harness was positioned between lizard's shoulders (Fig. 2a), passing the two rubber rings through the lizard's head and crossing them over the chest; it weighed in total approx. 0.46 g (0.41 g PIP5 transmitter weight + 0.05 g patch weight and glue). Any glue was directly placed on the lizards for this backpack model.

The second harness type (from now on referred in the text as Shoulder Harness, SH) consisted of a transparent, water-resistant sticky patch (OPSITE™ Flexifix tape) with a circle opening on the left (approx. 5 mm wide) and two straps on the right. The dimensions of the patch and the straps were adapted to the size of the lizard. The attachment on the lizard was firstly made by inserting the left limb through the left circular opening of the patch. The patch was then passed over and adhered to the radio transmitter (Lotek model), which was placed between the shoulders and directly in contact with the lizard's skin dorsal surface. It was then extended over the animal's belly in its median portion where the two straps were secured (Fig. 2b). This type weighed in total approx. 0.54 g (0.46 g PIP5 transmitter weight + 0.08 g patch weight). These first two harnesses were initially used in a small pilot study with few animals conducted in 2018, which subsequently led to the development of the third harness in 2021.

The same patch material of SH was used in 2021 to build the third harness, from now on referred in the text as Axillary Harness (AH). For this model, the patch was modified and simplified compared to the SH; a rectangle shape with no circular opening and straps. The radio transmitter (Lotek and Dessau models) was glued to the back of the lizard, behind the shoulders, with a drop of SURGIBOND glue and then fixed with the patch, which was stuck along the animal´s flanks and then joined at the vent (Fig. 2c). The backpack weighed in total approx. 0.51 g (0.46 g Lotek/Dessau transmitter weight + 0.05 g patch weight and glue).

The backpack harnesses were fitted neatly but did not constrict the chest and interfere with breathing. Following literature works, all types of harnesses accounted for less than 5% of the individual's body

Table 1. Transmitter details and harness designs: ARH = Adapted Rappole Harness; SH = Shoulder Harness; AH = Axillary Harness.

Manufacturer	Lotek	Telemetrie-Service Dessau
WEBLINK	https://www.lotek.com/ (last accessed 20 October 2023)	https://www.telemetrie-service.de/ (last accessed 20 October 2023)
Model	PIP5 Ag 379	Telemetriesender V4
Weight (g)	0.41 (2018) 0.46 (2021)	0.46 (2021)
Sizes (L x W x H mm)	14.4 x 6.3 x 2.6	10.8 x 6.4 x 4.5
Antenna length (mm)	151.6	104.2
Pulse length (ms)	14	20
Pulse frequency (bpm)	35 (2018) 43 (2021)	30 (2021)
Transmitter frequency range (MHz)	148.450–151.856	150.113–150.965
Estimated lifespan (weeks)	6	2
Harness adopted / N lizards males, females	ARH / 2,1 (2018) SH / 3,1 (2018) AH / 9,6 (2021)	AH / 3,5 (2021)

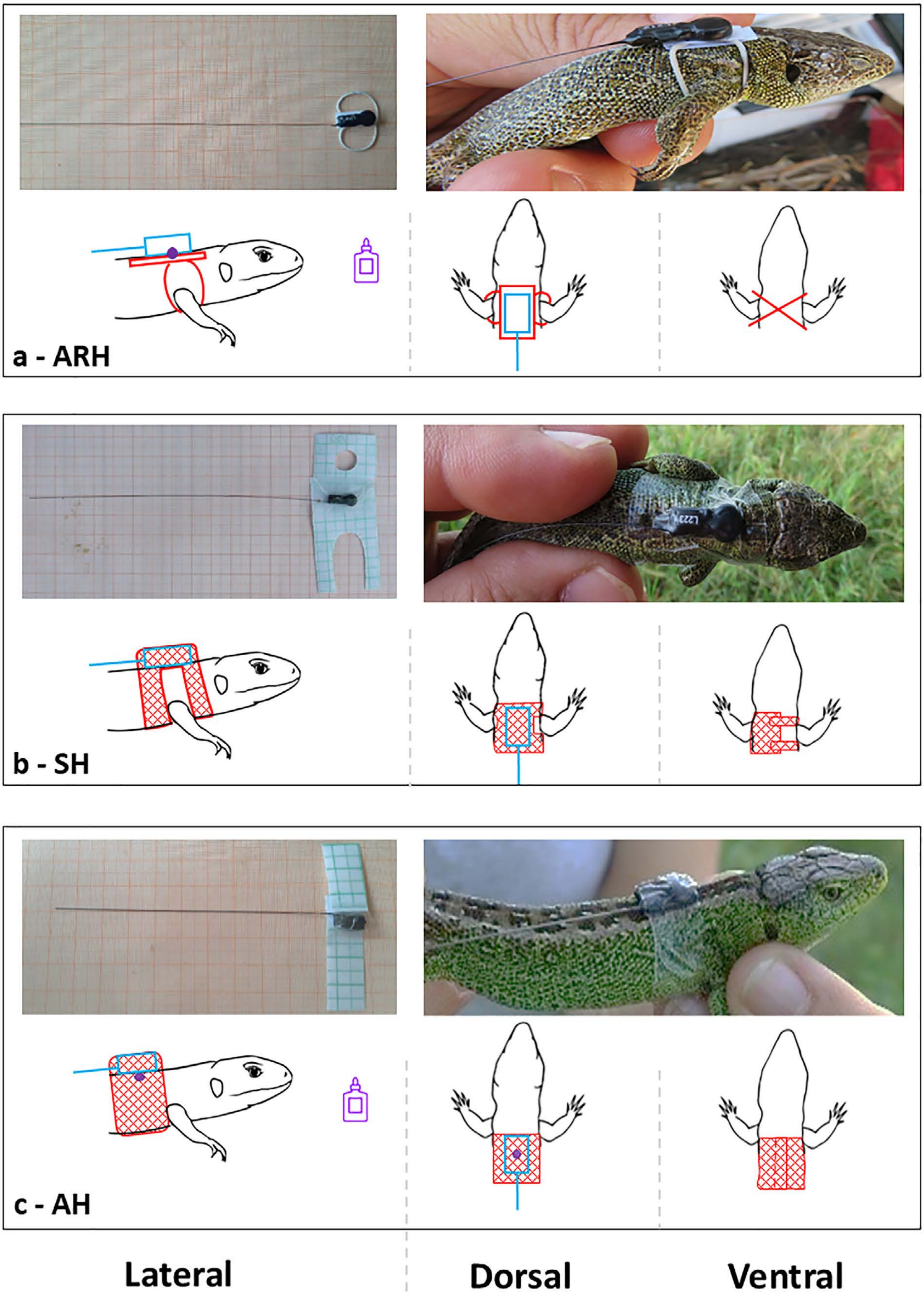

Figure 2. **a.** Adapted Rappole-Harness - ARH; **b.** Shoulder Harness - SH; **c.** Axillary Harness - AH. All sections a, b and c show in the top pictures the radio-transmitter and lizards wearing the respective backpacks, and below the attachment procedure. Purple spots mark glue drop positions, red areas and blue rectangle represent the harness and radio transmitter, respectively.

Figure 3. Cap placed on trapped and tagged sand lizard, *Lacerta agilis*.

weight. Small individuals were not used (< 9 g). The backpacks were voluntarily designed for ethical and animal welfare reasons by selecting shapes and materials that would guarantee an autonomous detachment of the backpack in the event of losing contact with the animal (and possible non-recapture), for example, due to an early depletion of the transmitter battery.

Field activity

Adult sand lizards were captured by noosing or by hand, sexed using sexual secondary characters (Arnold & Ovenden, 2002), measured (snout to vent (SVL) with a calliper (precision 0.01 mm), and weighted (digital scale, KERN EMB 200-2, precision 0.01 g). To minimise measurement bias, all data were collected by the same operator.

Since this work was part of a long-term study about detailed activity ranges, lizards were marked with internal tags. Then, each captured specimen was scanned to verify any potential recapture event. In case of first capture, the animal was marked by subcutaneous insertion of a passive integrated transponder (PIT; Uno Pico transponder, 0.02 g) at shoulder height, closing the entry point with some drops of SURGIBOND glue. A dark cap placed on the lizard's head was used to calm the lizards during the injection of the PIT and the transmitter attachment procedure (Fig. 3). Each animal was kept 24 h inside a terrarium, filled with branches and vegetation to test the backpack stability and to observe any signs of rejection, discomfort or decreased mobility of the lizard caused by backpack transmitters. After that, specimens were released in the same spots they were captured. Panasonic R1000 receiver combined with YAGI antennas were used to locate the lizards after release in the vineyards. After the first location of the animal, the observer maintained a distance of approx. 5 m to track animals activity status (active/inactive) during either continuous (07:00–20:00 h) or morning (07:00–01:00 h) or afternoon (01:00–20:00 h) telemetry sessions. Lizards were repeatedly observed with binoculars to assess possible entanglements of the harness and/or the transmitter in the vegetation, and any predation event. Additionally, specific behaviours were recorded, including: i) basking, ii) foraging, and iii) courtship. For some visual impression of trapping, tagging and tracking of sand lizards please see (https://www.youtube.com/watch?v=ke5QdXeeHkI ; last access October 2023). If the backpack was lost, the transmitter was found and a new harness was set on recaptured lizard (when possible) or on a new and suitable individual.

Literature overview

Since the lack of methodological information about tag use, tagging and tracking experience on small–medium lizards with harness, a systematic literature search was conducted in Scopus, Google Scholar and Web of Science database using the following combinations of keywords: radio telemetry + lizard* OR reptile*; radio-track + lizard* OR reptile*; backpack + lizard*. Since our work focused on small–medium size lizards, we took into consideration only papers on small to medium sized lizards up to a SVL of 142 mm. Moreover, we restricted our search to methodological studies, excluding those focused solely on telemetry results, such as home range estimations or movement patterns.

RESULTS

In our study, overall, 30 adult sand lizards (2018: 5 males – mass rage: 10.25–19.64 g; 2 female – mass rage: 14.23–16 g. 2021: 12 males – mass rage: 9.50–15.97 g; and 11 females – mass rage: 12.05–17.88 g) were captured and tagged.

In the small pilot study of 2018, the ARH model was equipped on 3 lizards (Table 1). However, since this model was not directly attached to the animals with glue as the other two prototypes, lizards were able to slip off the backpack partly within a few minutes while moving among the twigs inside the terrarium. Thus, the ARH model was discarded during the study. Although the small sample size of the present study, we would not recommend AHR model for working with sand lizards or similar species.

A total of 4 lizards wore the SH model (Table 1), which remained attached for a minimum of 6 days up to a maximum of 10 days consecutively (average 8.75 ± 1.89 days).

On the 15 individuals fitted with the AH and Lotek transmitter (Table 1), the model lasted for a minimum of 2 days up to a maximum of 17 days (average 7 ± 3.75 days). Similarly, the model fitted on 8 individual with AH and Dessau transmitter lasted for a minimum of 3 days up to a maximum of 17 days (average 8.1 ± 3.5 days). Lizards wearing either of SH or AH did not

Figure 4. Pictures of lizards equipped with backpacks naturally basking and squeezing through tight vegetation: Shoulder Harness (left); Axillary Harness (right).

exhibit negative impacts on their movements or habitat utilisation. They were regularly observed engaging in natural behaviours such as basking, interacting with conspecifics, manoeuvring through dense vegetation and entering holes in the soil (Fig. 4). Both harness models withstood rainfall events (up to 0.90 mm per day, max 25.7 mm in 2018; 3.04 mm per day, max 31.2 mm in 2021), variations in temperatures (10–37 °C in 2018; 8–35 °C in 2021) and varying degrees of potential abrasion from rough tree-bark, soil and rock surfaces. No entanglements in vegetation were recorded. Finally, all radio transmitters, with the exception of two (due to predatory event and/or battery failure), were successfully recovered, and no evidence of abrasion and injuries were found in the recovered animals after removal of the harnesses on the body and particularly skin of the tagged lizards.

Both transmitter models gave excellent results in terms of strength, intensity and quality of the signal. The tagged lizard signals were received up to the double of the distance (300 m maximum) of their suggested range.

From 300 articles returned from the literature search, our exclusion criteria produced a final sample of 31 methodological studies which have trialed a variety of harness designs on small to medium sized lizards (up to a body length of 250 mm) since the first harness prototypes (Fihser & Muth, 1995; Richmond, 1998; Ussher, 1999) (Table 2). Compared to these other studies, the transmitter models experimented in this work appeared to perform quite well in terms of weight (among the lightest adopted until now), and attachment longevity, considering and balancing the few negative effects on the animals (Table 2).

Table 2. Summary of harness designs on small to medium sized lizards from literature review and present study. Asterisk symbol (*)= more info in the manuscript text; U=unreported.

Reference	Species	Fastening materials	Radio tag models	Harness position	Backpack weight (g)	Attach-ment longevity	Battery life	Sample size	Injury	Other problems
Dent, 1986	*L. agilis*	Elastoplast and superglue	Biotrack (Huntingdon, Cambs.)	Pelvic girdle (dorsally)	1.8	7 days	3 weeks	17	Small damage to the scale beneath the transmitter	Considerable weight of the transmitter
Fihser & Muth, 1995	*P. mcallii*	Polypropylene mesh and clear polyurethane elastic (Stretchrite 114)	SMI transmitter (AVM Instrument Co.)	Neck	< 4	U	2–4 months	45	U	In 33% of the case, the transmitters fell off in a couple of days
Richmond, 1998	*P. coronatum*	Bicycle inner tube and glue	PD-2 (Holohil Systems Ltd.)	Between shoulders	4.5	As long as transmitter battery life	4.5–6 months	28	U	Few individuals slipped out of their harnesses
Warrick et al., 1998	*G. sila*	Nylon cable tie secured with copper wire	Advanced Telemetry Systems, Inc.	Neck	4	U	± 15 days	16	U	In three cases the backpack was shed when the straps failed

Reference	Species	Fastening materials	Radio tag models	Harness position	Backpack weight (g)	Attachment longevity	Battery life	Sample size	Injury	Other problems
Burrow, 2001	*P. coronatum*	Beige cotton muslin with elastic straps and cyanoacrylate gel adhesive	L and L Electronics, Mahomet	Neck	3	U	U	89	U	Few detachments
Schneyer, 2001	*N. gemmeus*	Leukostrip ® wound closure strips and Hansaplast ® self-adhesive dressing	BD-2 (Holohil System Ltd.)	Between shoulders	< 0.9	12–29 days	35 days	11	No	U
Reaney & Whiting, 2003	*A. a. atricollis*	Bicycle inner tube and glue	Heli-Trace	Between shoulders	6.4–7.8		U	4	U	U
Sabo, 2003	*S. occidentalis*	Epoxy adhesive	Hohohil, Carp, ON)	Pelvic girdle (dorsally)	1.3	U	U	17	U	Antenna length disturbed animal movements
Knapp & Ownes, 2005	*L. c. coryi*	Monofilament lines and ethylcyanoacrylate glue gel	BD-2 and PD-2 (Holohil Systems Ltd.)	Pelvic girdle (dorsally)	1.3–5.13	U	12–16 weeks	80	Abrasions developed after 2weeks	2 geckos prematurely sloughed their skin
Neilson et al., 2006	*O. homalonotum*	0	BD-2 (Holohil System Ltd.)	Base of tail (dorsally)	1	18–30 days	U	8	U	2 geckos lost harness and transmitters
Warner et al., 2006	*A. muricatus*	Black nylon mesh and superglue (UHU Australia)	BD-2 (Holohil System Ltd.)	Between shoulders	2.14	18 days	5 months	53	No	8 lizards entangled in vegetation 4 lizards predated
Germano, 2007	*O. otagense*	LeucoporeH® bandage tape	BD-2 (Holohil System Ltd.)	Base of tail (laterally)	1	U	6 weeks	13	U	4 lizards predated
Hare et al., 2007	*N. manukanus*	U	BD-2 (Holohil System Ltd.)	U	1	U	U	5	U	U
Hoare et al., 2007	*H. duvaucelii*	Easifix® polyamide & cellulose contour bandage + Mefix® hypoallergenic self-adhesive fabric strips	Sirtrack	Between shoulders	0.9	U	U	10	U	Lost transmitter, geckos escaping the harness and battery failures
Barr et al., 2009	*O. homalonotum*	Leucopor® surgical tape	BD-2 (Holohil System Ltd.)	Base of tail (laterally)	0.92	2–25 days	30 days	9	No	1 lost transmitter 3 backpack early shed
Gebauer, 2012	*O. grande*	Sensitive skin Leucopore® bandage tape	BD-2 and LB-2, (Holohil Systems Ltd.)	Base of tail (laterally)	0.6–0.9	U	4–5 weeks	57	U	U
Hoare et al., 2013	*Mokopirirakau* ”southern forest”	Micropore self-adhesive tape	BD-2 (Holohil System Ltd.)	U	≥ 9.3	U	U	2	U	U
Romijn et al., 2014	*Mokopirirakau* ”southern North Island”	Nexcare flexible clear tape	BD-2 (Holohil System Ltd.)	Base of tail (dorsally) or shoulder	1.08	U	U	8	U	Too heavy backpack Peeled off tape causing altered behaviour

Reference	Species	Fastening materials	Radio tag models	Harness position	Backpack weight (g)	Attach-ment longevity	Battery life	Sample size	Injury	Other problems
van Winkel & Ji, 2014	*H. duvaucelii*	1-Black rubber (bicycle inner tubing); 2-Co-Flex® stretching and self-adhering material	"small single-stage"	Between shoulders	3.5	1. 43 days 2. 12.4 days	80 days	20	Abrasion with rubber harness	U
Refsnider et al., 2015	*S. cowlesi*	Silurgical glue	Unknown	Anterior limb girdle (dorsally)	0.35	U	2–3 weeks	22	U	2 lizards predated
Germano & Rathbun, 2016	*G. sila*	Thin brass wire and epoxy glue	BD-2 (Holohil System Ltd.)	Neck	2.2	U	16–18 weeks	65	No	20 lizards predated
Mundo Hernandez, 2017	*Aspidoscelis* sp.	Black latex band (SYRVET® syrflex)	Telenax® TCX-007BR	Between shoulders	3.12	28 days	4 weeks	4	No	1 backpack lost
Brazeau & Hecnar, 2018	*P. fasciatus*	Surgical tape and 3M Tegaderm Film	BD-2 (Holohil System Ltd.)	Base of tail (laterally)	0.4	16 days	21 days	31	U	8 tail drop; 8 shed 6 batteries died 3 skinks predated 2 transmitters snagged on objects (too long antenna, and due to the tape) 2 transmitters prematurely removed 2 unknown fate
Westphal et al., 2018	*G. sila*	Jewelry wire and epoxy	BD-2 (Holohil System Ltd.)	Neck	1.6–2.2	U	8–16 weeks	28	U	U
Miller et al., 2019	*P. cornutum*	Nontoxic eyelash glue, monofilament fishing line and rubber tubing	BD-2 (Holohil System Ltd.)	Neck	1.4	U	8–16 weeks	57	Unreported	40 lizards predated
Hansen et al., 2020	*G. versicolor*	Silurgical glue	Model PIP3 AD337, Sirtrack Pty Ltd	U	0.38	6 days	6 days	48	U	U
Wieczorek et al., 2020	*L. agilis*	Silurgical glue	1. BD-2 (Holohil System Ltd.) 2. Own design	Dorsum	1. 0.7–0.9 2. 0.6–1.1	U	5-8 weeks	44	U	18 lizards lost 7 lizards died on the roads 3 lizards predated
Hibbitts et al., 2021	1. *H. lacerata* 2. *H. subcaudalis*	Cyanoacrylate glue	R1614, Advanced Telemetry Systems, Isanti, MN	Dorsum	0.3	U	U	1. 15 2. 21	U	4 lizards predated 2 road killed
Vesy et al., 2021	*P. cornutum*	100% non-toxic silicone adhesive and braided elastic band	1. BD-2 (Holohil System Ltd.) 2. RECCO Rescue Systems, Lidingo, Sweden	Dorsum	0.8–1.8	U	4–14 weeks	150	No	88 lizards unknown fate, probably predated

Reference	Species	Fastening materials	Radio tag models	Harness position	Backpack weight (g)	Attach-ment longevity	Battery life	Sample size	Injury	Other problems
Clement et al., 2022	*L. agilis*	Nylon mesh	Dessau V1	Between shoulders	0.35	10.5 days	30 days	15	U	1 animal lost 1 animal entangled in the backpack 6 lost the transmitter
Zuliani et al., 2022	*G.sila*	Small beaded chain, jewellery wire, and epoxy	BD-2 (Holohil System Ltd.)	Neck	1.6–2.2	U	8-16 weeks	62	U	U
Present study	*L. agilis*	1.ARH* 2.SH* 3.AH*	See Table 1	1-2. Between shoulders 3. Dorsum	1. 0.46 2. 0.54 3. 0.51	1. Discarded 2. 10 days 3. 17 days	See Table 1	30	No	2 animals lost: predatory event and/or battery failure

DISCUSSION

In general, radiotelemetry is a very useful technique for monitoring reptile movements and behaviour, which has been and will continue to be a dominant and essential tool in wildlife research. Most often, radiotelemetry provides the best way to determine how elusive and secretive animals move, choose resources and define their populations. An essential assumption in any radiotelemetry study is that the attachment techniques and transmitter devices are reliable and safe, without measurable effect on the subject animal. Nevertheless, the impact of radio-marking animals has often been dismissed as irrelevant. Our study investigated backpack harness designs for attaching radio transmitters to small–medium size lacertid lizards, confirming it as a practical and effective technique for continuous telemetry studies. While alternative tracking methods exist (i.e. marking lizards with colour-coded dots and recording their locations using high-precision GNSS), these approaches rely on resighting probability. In contrast, radiotelemetry enables continuous tracking, even in dense vegetation, providing more precise movement data and reducing observer bias.

Focusing on backpack designs, one of the first aspect to be considered is the location of harness attachment. Many lizards are characterised by a slender and elongated body, which allows an excellent performance in running, climbing and entering shelters often through narrow spaces. A harness must guarantee these performances. Generally, four lizards' body parts are used to fix transmitters:

i) dorsal part at the height of the shoulders (Richmond, 1998; Mundo Hernandez et al., 2017; Clement et al., 2022)
ii) dorsum, just behind the shoulders (Price-Rees & Shine, 2011; Mundo Hernandez et al., 2017; Wieczorek et al., 2020)
iii) base of the tail both dorsally and laterally (Neilson et al., 2006; Germano, 2007; Barr, 2009; Hagen & Bull, 2011; Gebauer, 2012; Brazeau & Hecnar, 2018)
iv) limb girdle anterior (Refsnider et al., 2015) and posterior (Knapp & Owens, 2005).

In our study, we tested two positions: between the shoulder (ARH and SH models) and dorsum (AH model). All harnesses, especially AH, could be set up easily with only one operator, resulting in less stress for the animal. Although the SH model exhibited a greater stability than AH, and no unnatural movements or entanglements in vegetation were observed, if not precisely positioned and fixed, it could move and hinder the movement of the lizard's head and neck (Yet, 2014). Due to our limited sample size, further testing would be necessary to confirm its reliability on a broader scale. In literature, the main reported transmitter attachment positions are between the shoulders (adopted in different lizards' species) and at the base of the tail (utilised mainly on skinks; Table 2). Despite several problems reported for these two attachment positions (e.g. entanglement in vegetation, loss of the harness, premature shedding or loss of tails), due to a lack of new information and data in recent years, they remain the primary transmitter attachment positions for small–medium lizards.

Choosing the right materials and design for a harness to tag lizards is also key, taking into account animals' physical and behavioural habits as well as any limitations caused by its environment. The harness materials adopted in our study did not appear to cause irritation to the skin; however, we observed variations in the length of attachment time depending on the type of material used to construct the harness. The rubber component for the ARH model remained attached to lizards for a few minutes only, compared to the OPSITE™ Flexifix tape used for SH and AH. This tape is breathable and showed to be highly elastic, guaranteeing a very good fit and compatibleness to the lizard's body, limiting the alteration of the lizard phenotypic colouration as much as possible. Different radiotelemetry studies adopted similar medical adhesive tapes, especially on geckos, allowing the harness to remain attached for up to four weeks (Schneyer, 2002; van Winkel & Ji, 2014). Although we did not observe in our study any problems, it has been suggested that adhesion to scales may hamper with the sloughing process (Schneyer, 2002), and that medical tapes could be particularly prone to weathering, losing their adhesive properties under different weather and habitat conditions (Romijn et al., 2014) and over time (van Winkel & Ji, 2014). These latter authors demonstrated how the reduced length of attachment in medical tape harnesses could be attributed also to behavioural habits, such as moving over rough surfaces during foraging, and seeking tight crevices as retreat sites. Consequently, the use of adhesive tapes in natural field conditions, and particularly moist environments, may shows limitations especially for telemetry studies intended to run for longer periods. Moreover, it must be considered that partial detachment of the tape in wet conditions could increase the risks associated with entanglement in vegetation, as well as accumulation of soil debris between the skin and the tape, potentially leading to injuries or inflammations. Paying attention to the condition of the adhesive harnesses on lizards on track, and replacing them, although it would require another trapping event for the individual, may be necessary during long-term field studies (Yet, 2014).

Finally, while transmitter shape could also theoretically influence the amount of time an attachment procedure last, our results suggest that other factors—such as adhesive properties, material flexibility or individual lizard behaviour—may play a more significant role. In our study, the AH model with the Lotek transmitter, featuring a flat shape, was easier to place on the lizard's back and thus it was expected to provide better contact with the lizards' body, potentially reducing premature detachment. However, the Dessau transmitter capsule, despite its slightly rounded shape, remained attached for a slightly longer duration on average. Currently, to the best of our knowledge, no studies have specifically investigated the influence of transmitter shape on attachment duration in small reptiles, highlighting the need for further research on this parameter.

The availability of positive and negative experience by using different harness designs and transmitters models is essential to develop best fit and most efficient attachment methods. Based on our outcomes, considering small sample size in some cases, and pondering all pros and cons, the most effective transmitter models should be those with a balance of lightweight design, minimal injury and reasonable attachment longevity. Despite the fact that in Europe lacertid lizards are the prevalent group of reptiles (Arnold & Ovenden, 2002; Carretero, 2004), often studied and adopted as model species in a broad range of biological disciplines, information about methods and effects of telemetry transmitters attachment on this reptile family are mainly old and scattered (Table 2). Missing or unrecognised effects of radio transmitters on animals can introduce bias into the conclusions drawn from radiotelemetry studies. A simple example is when transmitters increase mortality, leading to biased survivorship estimates derived from radio tagged animals. Another source of bias can occur if observations from different study sites are combined, but individuals from one site are more affected by the transmitters than those from other sites. Radiotelemetry studies should therefore include an understanding of transmitter effects and their magnitude. Our study can be seen as a basis for further discussion and guidance for future studies on (i) what should be considered when attaching radiotelemetry transmitters in small–medium lizard species, (ii) on determining the most adequate and applicable parameters in order to achieve the highest welfare standards possible and most reliable data about the tagged lizards monitored; and (iii) motivate to share experience about transmitter attachment in reptiles within the scientific community. Our results emphasise the need to define specific guidelines for transmitters application on lizards, and in accordance with Withey et al. (2001), radio-tagging studies should consider the following: a) be aware of animal morphology, shape, growth and seasonal changes in body size and condition when choosing a transmitter type, in order to adjust the attachment technique accordingly and avoiding too heavy harnesses that could badly influence animals' behaviours; b) consider the times in which transmitters will be shed; c) carefully consider harnesses design and fit to minimise effects: too tight harnesses might limit movements, but too loose ones can be easily slipped off and/or entangle the animal, inducing potential injuries; d) avoid placing transmitters on animals during times of stress (e.g. poor resource years, reproductive seasons); e) allow a period of several days to test harnesses attachment and to acclimate the animals with it, before collecting data. f) Test the effect of harnesses with a priory trial between control and tagged animals; and g) describe any results concerning the effects of transmitters, both positive and negative.

We hope that this work is a stimulus to publish further data on experiences in order to further and continuously optimise the attachment of transmitters to lizards, accompanied by a continuous reduction in the size of the transmitters.

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Author contributions

The authors confirm contribution to the paper as follows: study conception and design: GM, JDL, TG; data collection: GM, GS; analysis and interpretation of results:

GM, GS, JDL, TG; draft manuscript preparation: GS, GM, JDL, TG. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

Arnold, E.N. & Ovenden, D.N. (2002). *Field Guide: Reptiles & Amphibian in Europe & Great Britain*. Collins & Co., London.

Barr, B.P. (2009). Spatial ecology, habitat use, and the impacts of rats on chevron skinks (*Oligosoma homalonotum*) on Great Barrier Island: A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Conservation Biology, Massey University, Auckland, New Zealand [Thesis, Massey University]. https://mro.massey.ac.nz/handle/10179/1210.

Blais, B.R., Johnson, S.L. & Koprowski, J.L. (2023). Effects of disturbances and environmental changes on an arid land riparian generalist. *PeerJ* 11, e15563. https://doi.org/10.7717/peerj.15563.

Blanke, I. & Fearnley, H. (2015). *The sand lizard: Between light and shadow*. Laurenti-Verlag.

Brazeau, D.J, & Hecnar, S.J. (2018). Summer movements of the common five-lined skink (*Plestiodon fasciatus*) in the northern portion of its range. *Herpetological Conservation and Biology* 13(3), 743–752.

Carretero, M.A. (2004). From set menu to a la carte. Linking issues in trophic ecology of Mediterranean lacertids. *Italian Journal of Zoology* 71(sup2), 121–133. https://doi.org/10.1080/11250000409356621.

Cavigliasso, P., Phifer, C.C., Adams, E.M., Flaspohler, D., Gennari, G.P., Licata, J.A. & Chacoff, N.P. (2020). Spatio-temporal dynamics of landscape use by the bumblebee *Bombus pauloensis* (Hymenoptera: Apidae) and its relationship with pollen provisioning. *PloS ONE* 15(7), e0216190.

Chevallier, E., Denys, G.P., Marlot, R., Duntze, M., Mierral, A., Fasquel, A., Dhainaut, M. & Boucault, J. (2023). Behaviour of two predator fishes *Esox lucius* Linnaeus, 1758 and *Silurus glanis* Linnaeus, 1758 during two successive floods in the French Aisne River. *Cybium: Revue Internationale d'Ichtyologie* 47(1), 79–99.

Clement, V., Schluckebier, R. & Rödder, D. (2022). About lizards and unmanned aerial vehicles: assessing home range and habitat selection in *Lacerta agilis*. *Salamandra* 58, 24–42.

Daniel Kissling, W., Pattemore, D.E. & Hagen, M. (2014). Challenges and prospects in the telemetry of insects. *Biological Reviews* 89(3), 511–530.

Doody, J.S., Roe, J., Mayes, P. & Ishiyama, L. (2009). Telemetry tagging methods for some freshwater reptiles. *Marine and Freshwater Research* 60(4), 293–298. https://doi.org/10.1071/MF08158.

Fihser, M. & Muth, A. (1995). A backpack method for mounting radio transmitters to small lizards. *Herpetological Review* 26(3), 139–139.

Flesch, J.S., Duncan, M.G., Pascoe, J.H. & Mulley, R.C. (2009). A simple method of attaching GPS tracking devices to free-ranging lace monitors (*Varanus varius*). *Herpetological Conservation and Biology* 4(3), 411–414.

Frick, C.H., Hole, D., Sandow, D., Olds, L.G., Ostendorf, B., Taggart, D. & Roshier, D. (2023). The utility of coded very high frequency telemetry for monitoring reintroduced mammal populations. *Ecology and Evolution* 13(6), e10193.

Gasc, J.-P., Cabela, A., Crnobrnja-Isailovic, J., Dolmen, D., Grossenbacher, K., Haffner, P., Lescure, J., Martens, H., Martinez Rica, J.P. & Maurin, H. (2004). *Atlas of amphibians and reptiles in Europe*. Muséum National d'Histoire Naturelle Paris.

Gebauer, K. (2012). Grand skink (*Oligosoma grande*, Gray 1945) metapopulations in indigenous tussock grasslands and exotic pasture grasslands in Southern New Zealand. (Doctoral dissertation, University of Otago).

Germano, J.M. (2007). Movements, home ranges, and capture effect of the Endangered Otago skink (*Oligosoma Otagense*). *Journal of Herpetology* 41(2), 179–186. https://doi.org/10.1670/0022-1511(2007)41[179:MHRACE]2.0.CO;2.

Giuntini, S. & Pedruzzi, L. (2023). Sex and the patch: The influence of habitat fragmentation on terrestrial vertebrates' mating strategies. *Ethology Ecology & Evolution* 35(3), 269–298.

Goodman, R., Knapp, C., Bradley, K., Gerber, G. & Alberts, A. (2009). Review of radio transmitter attachment methods for West Indian rock iguanas (genus *Cyclura*). *Applied Herpetology* 6(2), 151–170. https://doi.org/10.1163/157075408X386169.

Guarino, F. (2002). Spatial ecology of a large carnivorous lizard, *Varanus varius* (Squamata: Varanidae). *Journal of Zoology* 258(4), 449–457. https://doi.org/10.1017/S0952836902001607.

Hafner, A. & Zimmermann, P. (2007). *Zauneidechse Lacerta agilis* (Linnaeus, 1758). *Die Amphibien Und Reptilien Baden-Württembergs*, 543–558.

Hagen, I.J. & Bull, C.M. (2011). Home ranges in the trees: Radiotelemetry of the prehensile tailed skink, *Corucia zebrata*. *Journal of Herpetology* 45(1), 36–39.

Hansen, N.A., Driscoll, D.A., Michael, D.R. & Lindenmayer, D.B. (2020). Movement patterns of an arboreal gecko in fragmented agricultural landscapes reveal matrix avoidance. *Animal Conservation* 23(1), 48–59. https://doi.org/10.1111/acv.12505.

Kenward, R.E. (2001). A manual for wildlife radio tagging: behaviour and home ranges. *A Manual for Wildlife Radio Tagging*, 201–232. Academic press.

Klingenböck, A., Osterwalder, K. & Shine, R. (2000). Habitat use and thermal biology of the "Land Mullet" *Egernia major*, a large scincid lizard from remnant Rain Forest in southeastern Australia. *Copeia* 2000(4), 931–939. https://doi.org/10.1643/0045-8511(2000)000[0931:HUATBO]2.0.CO;2.

Knapp, C.R. & Abarca, J.G. (2009). Effects of radio transmitter burdening on locomotor ability and survival of iguana hatchlings. *Herpetologica* 65(4), 363–372.

Knapp, C.R. & Owens, A.K. (2005). An effective new radio transmitter attachment technique for lizards. *Herpetological Review* 36(3), 264–265.

Lamb, J.S., Loring, P.H. & Paton, P.W.C. (2023). Distributing transmitters to maximize population-level representativeness in automated radio telemetry studies of animal movement. *Movement Ecology* 11(1), 1. https://doi.org/10.1186/s40462-022-00363-0.

Mathies, T. & Martin, D.J. (2008). Overwintering site selection by short-horned lizards (*Phrynosoma Hernandesi*) in northeastern Colorado. *Journal of Herpetology* 42(1), 163–171. https://doi.org/10.1670/06-260R1.1.

Millspaugh, J.J. & Marzluff, J.M. (2001). Chapter 15 - Radio-Tracking and Animal Populations: Past Trends and Future Needs. In: *Radio Tracking and Animal Populations.* Millspaugh, J.J. & Marzluff, J.M. (Eds.). Academic Press. 383–393 pp. https://doi.org/10.1016/B978-012497781-5/50016-5.

Mundo Hernandez, V., Martinez Haro, M.D.C., Balderas Plata, M.A., Antonio Nemiga, X. & Manjarrez Silva, F.J. (2017). Use of backpack radio-transmitters on lizards of the genus *Aspidocelis* (Squamata: Teiidae). *Mesoamerican Herpetology.* http://ri.uaemex.mx/handle/20.500.11799/68438.

Neilson, K., Curran, J.M., Towns, D.R. & Jamieson, H. (2006). Habitat use by chevron skinks (*Oligosoma homalonotum*) (Sauria: Scincidae) on Great Barrier Island, New Zealand. *New Zealand Journal of Ecology* 345–356.

Nicholson, A.M. & Spellerberg, I.F. (1989). Activity and home range of the lizard *Lacerta agilis* L. *The Herpetological Journal* 1(8), 362–365.

Panchan, R., Pinter, K., Schmutz, S. & Unfer, G. (2022). Seasonal migration and habitat use of adult barbel (*Barbus barbus*) and nase (*Chondrostoma nasus*) along a river stretch of the Austrian Danube River. *Environmental Biology of Fishes* 105(11), 1601–1616.

Perez-Buitrago, N. & Sabat, A. (2007). Natal dispersal, home range and habitat use of hatchlings of the Mona Island iguana (*Cyclura cornuta stejnegeri*). *Applied Herpetology* 4, 365–376. https://doi.org/10.1163/157075407782424557.

Price-Rees, S.J. & Shine, R. (2011). A backpack method for attaching GPS transmitters to bluetongue lizards (*Tiliqua*, scincidae). *Herpetological Conservation and Biology*.

Rappole, J.H. & Tipton, A.R. (1991). New harness design for attachment of radio transmitters to small passerines (Nuevo diseño de arnés para atar transmisores a passeriformes pequeños). *Journal of Field Ornithology* 62(3), 335–337.

Refsnider, J.M., Des Roches, S. & Rosenblum, E.B. (2015). Evidence for ecological release over a fine spatial scale in a lizard from the White Sands formation. *Oikos* 124(12), 1624–1631. https://doi.org/10.1111/oik.02406.

Richmond, J.Q. (1998). Backpacks for lizards: A method for attaching radio transmitters. *Herpetological Review* 29(4), 220.

Romijn, R., Nelson, N. & Monks, J. (2014). Forest geckos (*Mokopirirakau* 'Southern North Island') display diurno-nocturnal activity and are not reliant on retreats. *New Zealand Journal of Zoology* 41(2), 103–113. https://doi.org/10.1080/03014223.2013.860041.

Růžičková, J. & Elek, Z. (2023). Beetles on the move: not-just-a-technical review of beetles' radio-tracking. *Entomologia Experimentalis et Applicata* 171(2), 82–93. https://doi.org/10.1111/eea.13260.

Sabo, J.L. (2003). Hot rocks or no hot rocks: overnight retreat availability and selection by a diurnal lizard. *Oecologia* 136(3), 329–335. https://doi.org/10.1007/s00442-003-1292-6.

Saha, K., Prakash, H., Mohapatra, P.P. & Balakrishnan, R. (2023). Is flying riskier for female katydids than for males? *Behavioral Ecology and Sociobiology* 77(2), 27.

Schneyer, N. (2002). Effects of avian predation and habitat degradation on the population dynamics of the jewelled gecko (*Naultinus gemmeus*) from the Every Scientific Reserve, Otago Peninsula, New Zealand. University of Otago.

Smith, J.G., Griffiths, A.D. & Brook, B.W. (2010). Survival estimation in a long-lived monitor lizard: radio-tracking of *Varanus mertensi*. *Population Ecology* 52(1), 243–247. https://doi.org/10.1007/s10144-009-0166-0.

Thomas, L.S., Teich, E., Dausmann, K.H., Reher, S. & Turner, J.M. (2018). Degree of urbanisation affects eurasian red squirrel activity patterns. *Hystrix* 29(2), 175–180. https://doi.org/10.4404/hystrix-00065-2018.

Ussher, G.T. (1999). Method for attaching radio transmitters to medium-sized reptiles: Trials on tuatara (*Sphenodon punctatus*). *Herpetological Review* 30(3), 151.

van Winkel, D. & Ji, W. (2014). Attaching radio-transmitters to geckos: trials and tribulations. *Herpetological Review* 45, 13–17.

Warner, D.A., Thomas, J. & Shine, R. (2006). A simple and reliable method for attaching radio-transmitters to lizards. *Herpetological Conservation and Biology* 1(2), 129–131.

Wieczorek, M., Rektor, R., Najbar, B. & Morelli, F. (2020). Tick parasitism is associated with home range area in the sand lizard, *Lacerta agilis*. *Amphibia-Reptilia* 41(4), 479–488. https://doi.org/10.1163/15685381-bja10018.

Withey, J.C., Bloxton, T.D. & Marzluff, J.M. (2001). Chapter 3—Effects of Tagging and Location Error in Wildlife Radiotelemetry Studies. In: *Radio Tracking and Animal Populations.* Millspaugh, J.J. & Marzluff, J.M. (Eds.). Academic Press. 43–75 pp. https://doi.org/10.1016/B978-012497781-5/50004-9.

Yet, S. (2014). Radio-tracking lizards: Standard Operating Procedure. University of Otago, New Zealand.

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