Tools and Technology Note

Terrestrial Passive Integrated Transponder Antennae for Tracking Small Animal Movements

NOAH D. CHARNEY,[1] *Organismic and Evolutionary Biology Program, Department of Biology, 319 Morrill Science Center, University of Massachusetts, Amherst, MA 01003, USA*

BENJAMIN H. LETCHER, *United States Geological Survey, Biological Research Division, S. O. Conte Anadromous Fish Laboratory, P.O. Box 796, One Migratory Way, Turners Falls, MA 01376, USA*

ALEX HARO, *United States Geological Survey, Biological Research Division, S. O. Conte Anadromous Fish Laboratory, P.O. Box 796, One Migratory Way, Turners Falls, MA 01376, USA*

PAIGE S. WARREN, *Department of Natural Resources Conservation, Holdsworth Natural Resources Center, University of Massachusetts, Amherst, MA 01003, USA*

ABSTRACT Measuring terrestrial movements of small animals poses a substantial technological challenge. We developed very long (up to 130 m) passive integrated transponder (PIT) detectors with which we tracked salamanders (Caudata) migrating from breeding ponds to their upland habitat >200 m away. In all 60 trials, salamanders were detected when released near the antennae. In a second test, we tracked 7 of 14 tagged marbled salamanders (*Ambystoma opacum*) migrating >65 m, well beyond the area protected by existing wetland buffer regulations in Massachusetts, USA. The mean rate of movement for these salamanders ($\bar{x}$ = 0.9 m/min; SE = 0.1 m/min) was substantially higher than rates of movement reported for related salamanders with radio-implants. These PIT antennae offer researchers a means to study small animal movements with less disruption of the animals' natural movement patterns than is caused by other available techniques. (JOURNAL OF WILDLIFE MANAGEMENT 73(7):1245–1250; 2009)

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The pond-breeding marbled salamander (*Ambystoma opacum*) is threatened in Massachusetts, USA, and protecting its upland habitat requires knowing how far salamanders travel from breeding ponds to their terrestrial home territories (Semlitsch 1998). Due to challenges associated with tracking these small salamanders, few estimates of their migration distances are available (Williams 1973, Douglas and Monroe 1981, Gamble et al. 2006).

Techniques appropriate for large, abundant organisms are inappropriate for small, rare animals. With larger salamanders, radio-implants are possible, although surgery may impact the health and behavior of the study individuals (Windmiller 1996). Transmitter cost and limited battery life also constrain experimental designs (Madison 1997, Madison and Farrand 1998, Montieth and Paton 2006, McDonough and Paton 2007). Techniques requiring recapture of animals (e.g., drift-fencing; Enge 1997) are labor-intensive, capture nontarget species, and interfere with regular movement patterns (Sheppe 1967). Radioactive tags have provided insight into movements of small salamanders, although health concerns and logistic constraints prevent the use of these techniques in many long-term studies (Semlitsch 1981, Ashton 1994). Harmonic oscillators have recently proven to be a safe way to track very small organisms; however, the tags can be detected only from a short distance and do not allow for individual identification (Pellet et al. 2006).

Passive integrated transponders (PIT) present a promising approach for estimating movement rates of small animals. Tiny PIT tags (8 mm × 1 mm) with unique identification codes can be implanted into animals, and, because they have no batteries, may last for the life of the animals (Gibbons and Andrews 2004). When recaptured using traditional techniques, PIT tags allow researchers to identify individuals when they are recaptured (Germano and Williams 1993, Ott and Scott 1999, Perret and Joly 2002). Detectors placed at fixed locations along streams facilitate detailed studies of fish movements (Prentice et al. 1990 *a*, *b*; Castro-Santos et al. 1996; Burns et al. 1997; Zydlewski et al. 2006). On land, antennae at culverts, around tree bases, and in small mammal burrows have been used to track movements of desert tortoises (Boarman et al. 1998), lizards (Gruber 2004), and rodents (Harper and Batzli 1996), respectively. Most of these techniques have thus far required that study organisms be funneled into small areas for detection or capture.

We examined a technique for tracking individuals carrying PIT tags across a 2-dimensional surface (e.g., the ground) that does not require funneling through confined areas. Our objective was to determine efficacy of using such antennae to track salamander movements.

STUDY AREA

We tested half-duplex PIT systems at a seasonal pond surrounded by >1,000 ha of protected mixed-hardwood forest in the Holyoke Range in western Massachusetts. The closed-canopy forest was dominated by eastern hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*), oaks (*Quercus* spp.), birches (*Betula* spp.), maples (*Acer* spp.), and hickories (*Carya* spp.) and had a sparse understory layer. This pond and 13 other nearby ponds supported approximately 1,000–

[1] *E-mail: noah@alumni.amherst.edu*

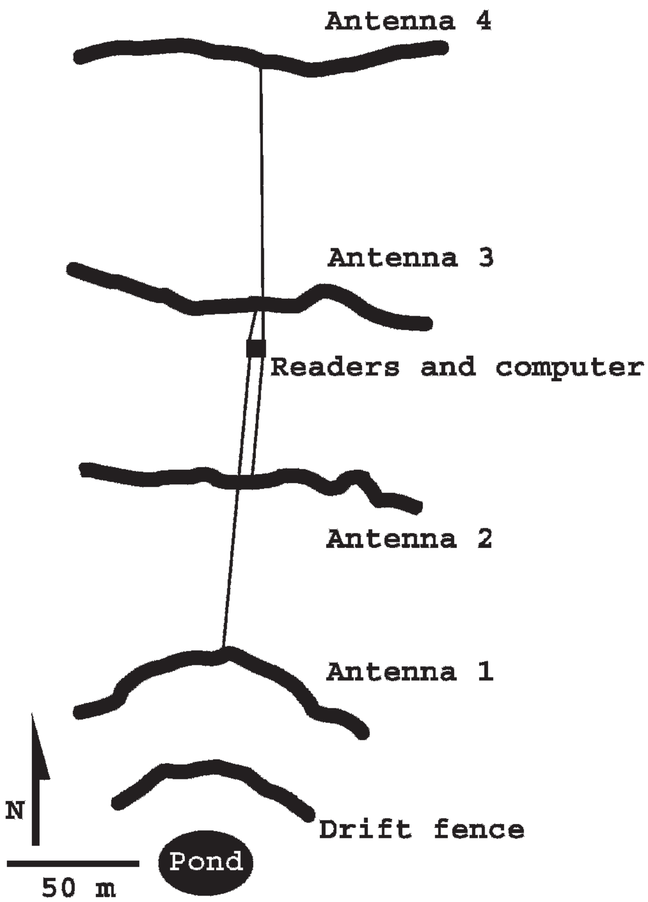

Figure 1. Diagram of the Holyoke Range field site and equipment used to track adult marbled salamanders during postbreeding migrations in Massachusetts, USA, September and October 2007.

1,500 adult marbled salamanders that were part of a long-term meta-population study (Gamble et al. 2006, 2007; Jenkins et al. 2006). Other species observed at the focal pond included spotted salamander (*Ambystoma maculatum*), red-spotted newt (*Notophthalmus viridescens*), four-toed salamander (*Hemidactylium scutatum*), and wood frog (*Rana sylvatica*). We placed antennae up to 300 m from the north of the pond (Fig. 1) because a large concentration of migrating adult marbled salamanders entered and exited the pond from that direction in previous years (Jenkins et al. 2006). The terrain sloped upwards heading away from the pond, averaging 5° for the first 100 m, 25° for the second 100 m, and 40° for the final 100 m.

We tested full-duplex PIT systems on the grounds of the S. O. Conte Anadromous Fish Research Center in Turners Falls, Massachusetts. We placed antennae within the interior of a mixed-hardwood forest approximately 200 m southeast of the Connecticut River and 100 m northeast of a cleared field. The closed-canopy forest was dominated by northern red oak (*Quercus rubra*), eastern hemlock, white pine, and birches and had a sparse understory layer. Terrain was level. Amphibian species observed at this site included eastern red-backed salamander (*Plethodon cinereus*), American toad (*Bufo americanus*), and Fowler's toad (*B. fowleri*).

METHODS

We adapted rectangular antennae used in streams (Zydlewski 2006) to lie across the ground and stretch >100 m. An antenna can detect a PIT tag crossing at any point over its length, though we cannot determine the precise crossing location along the antenna.

We designed antennae for 2 types of PIT transceivers: a Digital Angel (St. Paul, MN) FS1001A full duplex transceiver (FD) and a set of Texas Instruments (Dallas, TX) Series 2000 half duplex transceivers (HD). We powered both with 12-V batteries. The PIT transceivers, batteries, switching circuits, and tuning boxes were all housed in separate weather-resistant plastic containers.

We used fundamental electrodynamics principles to develop the working rules we followed in designing our antennae (Griffiths 1999). In short, inductance (which depends upon antenna geometry) and capacitance (which depends in part on fixed capacitors) must yield a natural resonant frequency that matches the output frequency of the PIT transceiver. Interested parties can contact the corresponding author for technical specifications.

In large antennae, capacitive coupling between the wire and the earth's surface may cause the antennae to de-tune during rain events, especially when low capacitance values are needed to tune the circuit. To avoid complications of weather-dependent tuning, the wire may be wrapped with a cylindrical insulator of sufficient diameter to make the external capacitance insignificant.

To construct the FD antennae, we placed a pair of 76-m plastic-coated lamp wires parallel to each other 0.2 m apart (Fig. 2a) and wrapped them in closed-cell polyethylene foam cylinders (outer diam = 0.03 m). The HD antennae consisted of a pair of lamp wires approximately 0.05 m apart and 130 m long (Fig. 2b). The HD system did not require foam insulation because its internal capacitance was much greater than the capacitance between the wire and the earth's surface. One side of the antenna loop lay on the ground and we propped up the other side on guide sticks. We left an additional 10 m at the ends of the HD antennae so that we could fine-tune the inductance.

For coarse tuning in the FD antenna, we attached a set of fixed capacitors in series with the transceiver. We used a tuning box built into the FD transceiver for fine tuning (Texas Instruments sells separate tuning boxes for tuning the HD antenna). To tune, we first set inductance of the antenna by adjusting the length of the wire, then adjusted capacitance to maximize the read-range.

For both the FD and HD antennae, we raked leaf litter from a 0.5-m buffer on either side of the wires. We then gathered small sticks locally and laid them perpendicular to the wire every 0.15 m, giving the appearance of miniature railroad tracks (Fig. 2). The sticks guided salamanders so that the PIT tags they carried were optimally oriented for detection. Although the travel direction of a salamander was altered for a few centimeters, we did not funnel salamanders from a large space to a smaller space. The sticks also provided sufficient space for salamanders to pass freely under the HD foam insulation.

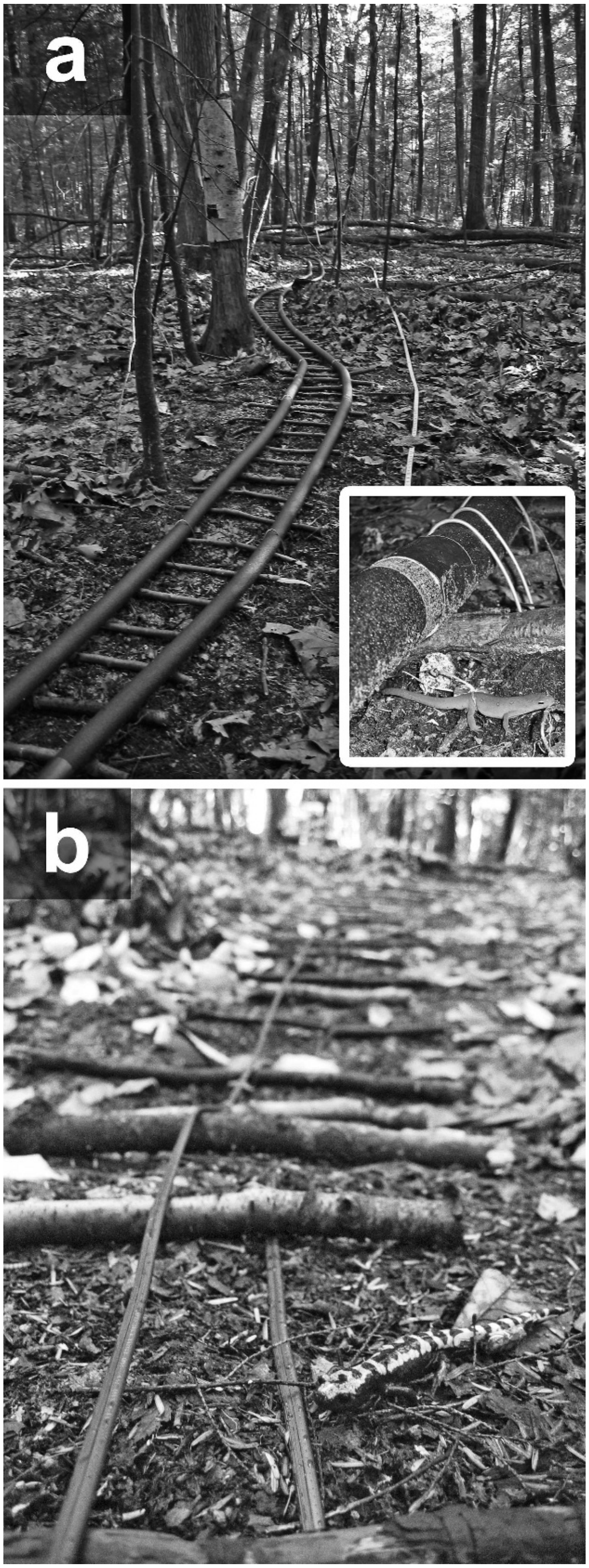

Figure 2. Examples of passive integrated transponder (PIT) antennae in the field. A tagged juvenile red-spotted newt crosses under the full duplex (FD) antenna at the S. O. Conte Anadromous Fish Research Center in Turners Falls, Massachusetts, USA (a). A tagged adult marbled salamander approaches a half duplex (HD) antenna in the Holyoke Range in Massachusetts (b).

We tested detection rate for both the HD and FD systems and we separately tested the utility of the design for the HD system by tracking migrating marbled salamanders. To assess detection rate under varied weather conditions, we placed salamanders at randomly selected points adjacent to the antenna and allowed them to walk across. For the FD system, we used 12-mm × 1-mm PIT tags tied with dental floss to the backs of juvenile eastern spotted newts with snout–vent lengths from 3.5 cm to 3.8 cm. We set newts at 12 random points during a nighttime rainstorm. Without retuning the antennae, we then repeated this procedure at 18 random points during a sunny day. To measure detection rate of the HD array, we allowed marbled salamanders to cross at 30 locations during a clear day. We affixed a 12-mm wedge transponder to the tail of each marbled salamander using Krazy Glue® cyanoacrylate (Elmer's Products, Inc., Columbus, OH). Before application, we wrapped tags with strips of paper made from cotton and linen to aid in glue adhesion.

We tested the utility of antenna arrays for measuring length of postbreeding migrations of marbled salamanders. Using the HD system, we estimated the distance that marbled salamanders migrated from their breeding pools to their upland territories. We placed antennae at 66 m, 130 m, 200 m, and 300 m from the high-water mark of one vernal pool (Fig. 1). These antennae bisected the path of any animal walking north from the pond. Twinaxial shielded cables connected each antenna to one central box containing a computer and transceivers that controlled the antennae.

At 13 m from the pond high-water mark, a drift-fence with pitfall traps caught migrating salamanders. We affixed tags (either HD 12-mm wedge transponder or HD 23.1-mm glass transponder) to the tail of each salamander with glue as described above. We held 2 marbled salamanders and one spotted salamander overnight to demonstrate that tags stayed affixed for the sampling period. After tagging, we released salamanders on the upland side of the drift-fence near where we captured them. To conserve battery power, we only turned on the antennae during nights that we released tagged salamanders (27 Sep, 9 Oct, 11 Oct, and 19 Oct 2007).

We used detection events and time stamps recorded by the computer to estimate distribution of distances between breeding pond and salamander home territories as well as salamanders' rates of travel. Because we focused on breeding adults, we expected $>$96% of salamanders to be migrating to upland habitat, not dispersing to another pond (Gamble et al. 2007). In this analysis, we included only 14 tagged salamanders released from 2 central pitfall traps on rainy nights when antennae were operating. We excluded salamanders released from peripheral traps ($n = 2$), released on nights when the forest floor remained dry ($n = 6$), or released towards nonoperational antennae ($n = 1$). Our methods were approved by the University of Massachusetts Institutional Animal Care and Use Committee (protocol no. 25-02-01).

RESULTS

The FD and HD transceivers detected salamanders in all 30 trials, which suggests that the system is likely to detect $>$95% of tagged salamanders that occur under similar conditions.

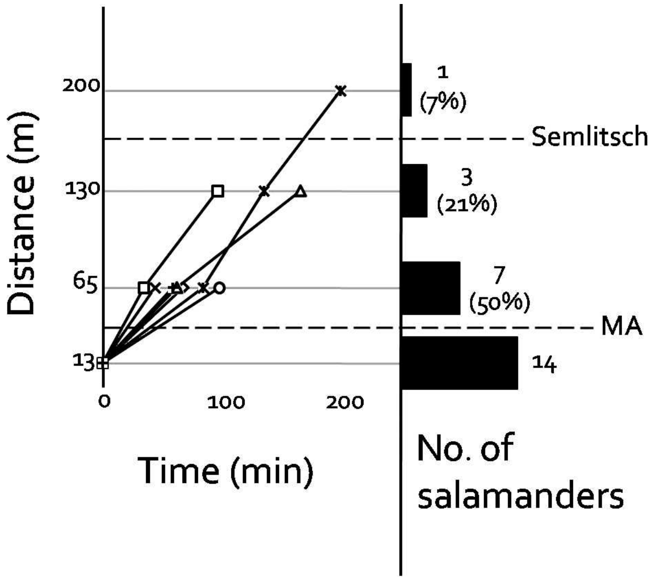

Figure 3. Movements of 14 adult marbled salamanders away from a pond during postbreeding migrations on 4 nights (27 Sep, 9 Oct, 11 Oct, and 19 Oct 2007) in the Holyoke Range in Massachusetts, USA. At least half of the salamanders went farther than the Massachusetts 30-m buffer zone (MA), whereas we detected only one salamander (7% of sample) beyond Semlitsch's (1998) proposed 164-m buffer zone (see text).

Both the HD and FD antennae remained tuned despite changes in ambient temperature, humidity, and precipitation.

Of the 14 migrating marbled salamanders released on rainy nights from the central pitfall traps towards functioning antennae, we detected 7 at the 66-m antenna, 3 at the 130-m antenna, one at the 200-m antenna, and none at the 300-m antenna. Salamanders detected at the 130-m antenna were a subset of those detected at the 66-m antenna and included the salamander detected at the 200-m antenna (Fig. 3). Mean rate of movement for the 7 salamanders was 0.9 m/minute (SD = 0.2; range = 0.5–1.2 m/min).

DISCUSSION

We demonstrated that long PIT tag antennae may be used to estimate movement rates and extents for small animals. Movement rates of migrating marbled salamanders we documented are similar to movement rates of untagged spotted salamanders observed by Windmiller (1996). By contrast, a study of migrating spotted salamanders using radiotag implants reported much slower rates of movements (max. $<$0.3 m/min; Madison 1997). It is possible that behavior of salamanders may be affected by implantation of radiotransmitters, a phenomenon well-documented in other taxa (Withey et al. 2001). Less invasive techniques like the one we developed may be necessary to obtain unbiased estimates of the movement ecology of small animals.

The 2 major advantages of these arrays over traditional drift-fences are that animals can move freely across each antenna and that nontarget species are not caught. With traditional drift-fences, animal movements are stopped until a researcher releases them. Distance moved in a night may reflect frequency at which traps are checked more than it reflects natural movement patterns of study animals. Furthermore, drift-fences deflect animals from their natural movement trajectory and force them to walk until they reach a trap.

We estimated minimal distances that salamanders traveled to upland territories, yet even these low estimates place the home territories of half of our study animals more than twice as far from their breeding pool as the distance protected by current wetland buffer regulations (Fig. 3; Griffin 1989). Improving detection rate would yield higher estimates of salamander travel distances. Modified study designs could include extending antennae to detect salamanders that would have walked around the edges during this pilot study, tracking salamanders for several consecutive nights of their migration, and permanently implanting tags to avoid loss.

The cost of a multi-year study of upland salamander movements using the HD system is comparable to the cost of using aluminum drift-fencing (Table 1). The cost of using drift-fencing increases substantially as traps are checked more frequently and study duration increases. Once installed, PIT arrays allow continuous long-term monitoring with little added costs. The most labor-intensive part of the PIT antenna array was laying the cross-sticks to guide salamanders, which took approximately 4 person-hours/100 m, much less than the 15–20 person-hours needed to install 100 m of drift-fence (Windmiller 1996). In future trials, we plan to preform antennae with guide sticks in the lab to expedite installation and removal at the field site. The PIT readers can be reused for many other experiments, whereas the costs of drift-fence installation and monitoring are almost entirely nonrecoverable. We borrowed the readers we used from ongoing fish research at no cost. Multiplexing systems under development (W. Leach, Oregon RFID, personal communication) may soon eliminate the need for separate transceivers, which will substantially reduce equipment costs further.

High detection rates likely depend upon good antenna maintenance and require that animals cross the antenna on the soil surface. Our detections of salamanders during heavy rain in the FD trials and during heavy rain in the postbreeding migrations across the HD antennae demonstrated that antennae function during inclement weather.

Table 1. Estimated cost (in US$) for a hypothetical study of salamander movements during breeding migrations using a half duplex (HD) passive integrated transponder (PIT) antennae system or a traditional drift-fence based on data collected in the Holyoke Range, Massachusetts, USA, October and September 2007. Detection rings (HD antennae or drift-fence) would be placed at 60 m and 110 m from the centers of 10 ponds. Ponds would be monitored 20 nights per year for 3 years.

Technique	Equipment	PIT tags	Setup labor	Monitoring labor	Total
HD system	110,000	2,000	6,000	10,000	130,000
Drift-fence	20,000		30,000	70,000	120,000

The FD antenna remained installed for a month without requiring retuning and functioned well during nighttime and daytime trials. However, leaves piling on the antennae, snow accumulation, or rodents chewing on the wires could make them ineffective. The PIT tags need to be oriented parallel to the magnetic field lines produced by the antennae (generally circles centered on each wire) and within about 5 cm of one of the wires to be detected. Marbled salamanders can be tracked effectively during migration (a critical portion of their life cycle; Semlitsch 1998) because they walk on the surface. As with most available techniques, long PIT antennae are not likely to detect salamanders during other parts of the year when they are underground. A tagged animal remaining stationary at an antenna could inhibit detection of other animals passing the same antenna, because PIT transceivers cannot detect >1 tag simultaneously at the same section of an antenna. However, in our field experiment with marbled salamanders, none of the 11 detection events lasted more than a few seconds, indicating that animals move quickly past antennae and are unlikely to interfere with other salamander detections. Removing leaf litter and other potential cover may deter animals from resting at the antennae and increase antenna effectiveness.

Maintaining a power supply at the field site is another consideration for employing PIT antenna arrays. We carried a lead acid battery to the site and only operated the antennae during narrow time windows. In locations where systems can be connected to fixed electrical lines, generators, or solar panels, these power sources may facilitate long-term studies that require continuous monitoring (Boarman et al. 1998, Achord et al. 2004, Meynecke et al. 2008). Although solar power can be a reliable source of energy in remote locations, it requires an area with direct sunlight and could add a few thousand dollars to the initial cost.

Future arrays might be configured as grids of antennae to allow measurement of animal locations along 2 coordinate axes. Tagged animals residing within the area covered by the grid would be detected as they crossed antennae. Each detection could be treated as a recapture in a mark–recapture analysis. Researchers who are already using implanted PIT tags for long-term identification of individuals could address questions about within-territory movements and dispersal of their study animals by incorporating the system we described.

Management Implications

Most of the life cycle of most pond-breeding amphibians is spent in upland habitat, yet protecting this habitat has proven difficult in part due to lack of knowledge of their migration distances (Semlitsch 1998). Our study suggests that, at our focal pond, the Massachusetts 30-m wetland buffer zone (Massachusetts Wetlands Protection Act. MGL c.131 s.40) would not provide effective protection of marbled salamander habitat (Fig. 3). Using PIT antennae with multiple taxa at many ponds, researchers might determine whether such regulations are adequate to conserve upland habitat. During spring migrations, researchers can deploy this system across a range of sites to estimate what percentage of animals move beyond proposed pond-buffer distances.

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