SHORT COMMUNICATION

DOPPLER RADAR: A NON-INVASIVE TECHNIQUE FOR MEASURING VENTILATION RATE IN RESTING BATS

By G. C. HAYS, P. I. WEBB, J. FRENCH and J. R. SPEAKMAN

Energetics Research Group, Department of Zoology, University of Aberdeen, Tillydrone Avenue, Aberdeen AB9 2TN, UK

Ventilation rate (fv) in bats has been measured using various techniques. These include: holding the bats and positioning a hot-wire anemometer close to one nostril (Roberts, 1972); attaching a face mask incorporating a flow probe (Suthers *et al.* 1972; Thomas and Suthers, 1972; Suthers and Fattu, 1973; Thomas, 1981; Thomas *et al.* 1984; Carpenter, 1985, 1986); using a body plethysmograph (Suthers and Fattu, 1973; Fattu and Suthers, 1981); inserting electrodes into the chest coupled to an impedance pneumograph (Studier and O'Farrell, 1972, 1976); and attaching a microphone to the abdomen (Kulzer, 1965; Schnitzler, 1968). These techniques are all invasive, raising the possibility that the values of fv recorded may deviate from those of unhindered animals. Here we describe the use of low-power Doppler radar to measure fv non-invasively in the pipistrelle bat *Pipistrellus pipistrellus* Schreber (Microchiroptera, Vespertilionidae).

The Doppler radar (model 22, Mariner Radar Ltd, Lowestoft, England) produced a continuous emission of linearly polarised microwaves (wavelength 32 mm, frequency 9.41 GHz) radiated *via* a horn antenna (length 13 cm). The maximum level of exposure caused by the radar was $0.01 \, \text{mW cm}^{-2}$, which is an order of magnitude below the minimum levels at which any microwave-induced effects have been demonstrated in mammals (Léonard *et al.* 1983). The model 22 modulated output was displayed on a storage oscilloscope (Gould 1425) and plotted on a Gould Colorwriter 6120.

When the bats (5–7 g) were at rest, small (approximately 1 mm deep) rapid (several Hz) vibrations of the body surface were visible with the naked eye. Fig. 1 shows the modulated output when the antenna was directed at a resting bat's dorsal surface. For movements of greater than one-quarter of a wavelength ($32/4=8$ mm) the frequency of the oscillations in the modulated voltage output from the model 22 was proportional to the radial speed of the target. However, for movements of less than 8 mm the output indicated changes in the radar–target range by virtue of the phase change between outgoing and return signals. The signal shown in Fig. 1 is therefore a direct measure of the linear displacement of the bat's surface. To establish whether these were breathing movements, a hot-
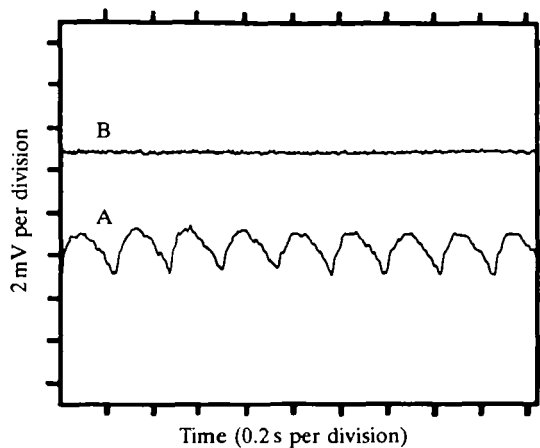
Fig. 1. (A) Body movements of a free-hanging *P. pipistrellus* detected by the radar. Frequency=261 min^{-1}. (B) Signal obtained when the bat was removed from the radar beam.

wire anemometer was constructed from a 2.7 V torch bulb, with the glass cover removed, connected in series with a 10 Ω resistor, and operated off a 4 V power supply. The torch bulb was mounted on a micromanipulator. If the bulb filament was positioned within a few millimetres of a bat's nostrils, each time the bat exhaled the temperature of the filament would drop, producing a change in voltage across the hot wire which was displayed on a second channel of the oscilloscope. Using this technique it was relatively easy to record fv when a bat was held, but we found it extremely difficult to position the filament close enough to the nostrils to record fv in free-hanging bats, as they were usually disturbed and became restless. However, after several attempts we successfully used the hot-wire anemometer to monitor fv in a free-hanging *P. pipistrellus* while the body movements were simultaneously recorded using the radar (Fig. 2). The close correlation between the two results demonstrated that the radar was indeed detecting breathing movements. The phase of the hot-wire anemometer signal lagged about 20–40 ms behind the radar signal. We estimated the thermal response time of the hot wire by expelling air over it from a Pasteur pipette. We recorded when the voltage across the hot wire changed in relation to the onset and cessation of the expulsion of air from the pipette bulb. The mean response time was 4.85 ms (S.E.=0.59 ms). However, this was a maximum estimate since it assumed no compression of the air within the pipette bulb and also ignored any delay between the expelled air passing from the mouth of the pipette to the hot wire (approximately 1 mm). Clearly most of the lag between the radar and hot-wire anemometer signals (Fig. 2) represented a real time delay between the breathing movements and the air flows over the hot wire.

The orientation and distance of the radar with respect to the bat had a pronounced effect on the signal-to-noise ratio. This was partly due to the variation
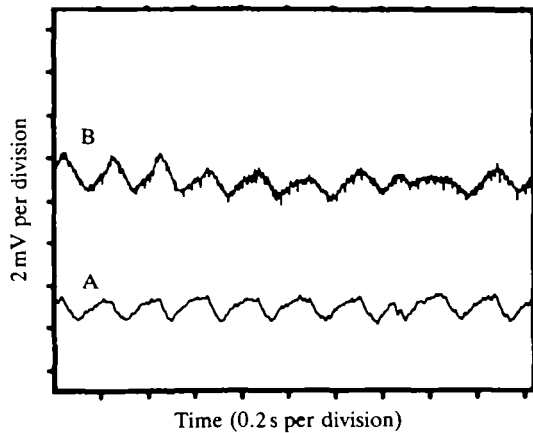
Fig. 2. Simultaneous radar (A) and hot-wire anemometer (B) measurements of ventilation rate ($294 min^{-1}$) in a free-hanging *P. pipistrellus*.

in power density at different ranges and partly due to the localised nature of the breathing movements influencing the magnitude and polarisation of the returned signal. However, by making small adjustments until a strong signal was obtained, fv could always be monitored when the antenna pointed at a bat's dorsal surface. The maximum distance between the mouth of the antenna and the bat at which fv could be monitored was about 70 cm.

The effect of handling on fv was examined by recording fv in five free-hanging *P. pipistrellus* using the radar, and then holding these bats and immediately recording fv using the hot-wire anemometer. Handling had a marked but inconsistent effect, causing fv to increase significantly (Student's t-test, $P<0.001$) in four of the five bats (Fig. 3).

Ventilation rate in bats has been recorded by visually counting the breathing movements (Bartholomew *et al.* 1964; Carpenter and Graham, 1967; Leitner and Nelson, 1967; Carpenter, 1985). However, when we attempted to record fv visually in a free-hanging *P. pipistrellus* using five 10 s samples, our estimate of 269 breaths min^{-1} (s.e.=11) was significantly different (Student's t-test, $P<0.001$) from the true fv of 389 breaths min^{-1} (s.e.=10.5) determined by the radar. In addition to inaccuracy at such high rates of breathing, visual estimates are very difficult to make for sustained periods, while the radar technique lends itself to automation.

Since the radar detected movement, it could only be used to monitor fv when a bat was at rest. However, in addition it revealed any activity as an erratically changing high-amplitude signal, easily distinguishable from the much smaller and regular fv signal. Doppler radar has previously been used to detect activity in studies on insects (Buchan and Sattelle, 1979) and humans (Buruma *et al.* 1982), and in the latter it has also been used as an arterial pulse-sensing technique (Lee and Lin, 1985; Papp *et al.* 1987).
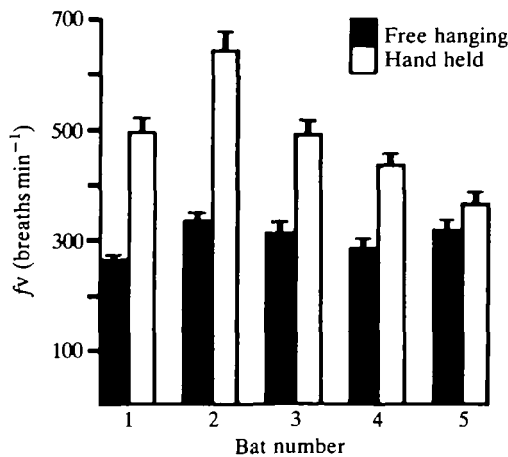
Fig. 3. Comparison of the ventilation rates for five *P. pipistrellus* when free hanging (radar measurements) and when hand held (hot-wire anemometer measurements). Values are means calculated from 5–10 sampling periods lasting 1.5–2 s. Vertical lines are 1 s.e. In bats 1–4 the increase in fv when hand held is statistically significant ($P<0.001$).

We have shown that Doppler radar enables the accurate determination of ventilation rate in unhindered free-hanging *P. pipistrellus* in the laboratory. In addition, the technique could have applications in certain free-living situations such as bat roosts and hibernacula where fv has never been recorded before, and may also be suitable for measuring fv in other resting animals.

References

Bartholomew, G. A., Leitner, P. and Nelson, J. E. (1964). Body temperature, oxygen consumption, and heart rate in three species of Australian flying foxes. *Physiol. Zool.* **37**, 179–198.

Buchan, P. B. and Sattelle, D. B. (1979). A radar-Doppler autocorrelation analysis of insect activity. *Physiol. Entomol.* **4**, 103–109.

Buruma, O. J. S., Kemp, B., Roos, R. A. C., Franzen, J. M. and Van Der Velde, E. A. (1982). Quantification of choreatic movements by Doppler radar. *Acta neurol. scand.* **66**, 363–368.

Carpenter, R. E. (1985). Flight physiology of flying foxes, *Pteropus poliocephalus*. *J. exp. Biol.* **114**, 619–647.

Carpenter, R. E. (1986). Flight physiology of intermediate-sized fruit bats (Pteropodidae). *J. exp. Biol.* **120**, 79–103.

Carpenter, R. E. and Graham, J. B. (1967). Physiological responses to temperature in the long-nosed bat, *Leptonycteris sanborni*. *Comp. Biochem. Physiol.* **22**, 709–722.

Fattu, J. M. and Suthers, R. A. (1981). Subglottic pressure and the control of phonation by the echolocating bat, *Eptesicus*. *J. comp. Physiol.* **143**, 465–475.

KULZER, E. (1965). Temperaturregulation bei Fledermausen (Chiroptera) aus verschiedenen Klimazonen. *Z. vergl. Physiol.* **50**, 1–34.

LEE, J. Y. AND LIN, J. C. (1985). A microprocessor-based noninvasive arterial pulse wave analyzer. *IEEE Trans. biomed. Eng.* **32**, 451–455.

LEITNER, P. AND NELSON, J. E. (1967). Body temperature, oxygen consumption and heart rate in the Australian false vampire bat, *Macroderma gigas*. *Comp. Biochem. Physiol.* **21**, 65–74.

LÉONARD, A., BERTEAUD, A. J. AND BRUYÈRE, A. (1983). An evaluation of the mutagenic, carcinogenic and teratogenic potential of microwaves. *Mutation Research* **123**, 31–46.

PAPP, M. A., HUGHES, C., LIN, J. C. AND POUGET, J. M. (1987). Doppler microwave a clinical assessment of its efficacy as an arterial pulse sensing technique. *Invest. Radiol.* **22**, 569–573.

ROBERTS, L. H. (1972). Correlation of respiration and ultrasound production in rodents and bats. *J. Zool., Lond.* **168**, 439–449.

SCHNITZLER, H.-U. (1968). Die Ultraschall-Ortungslaute der Hufeisen-Fledermause (Chiroptera–Rhinolophidae). *Z. vergl. Physiol.* **57**, 376–408.

STUDIER, E. H. AND O'FARRELL, M. J. (1972). Biology of *Myotis thysanodes* and *M. lucifugus* (Chiroptera: Vespertilionidae). I. Thermoregulation. *Comp. Biochem. Physiol.* **41A**, 567–595.

STUDIER, E. H. AND O'FARRELL, M. J. (1976). Biology of *Myotis thysanodes* and *M. lucifugus* (Chiroptera: Vespertilionidae). III. Metabolism, heart rate, breathing rate, evaporative water loss and general energetics. *Comp. Biochem. Physiol.* **54A**, 423–432.

SUTHERS, R. A. AND FATTU, J. M. (1973). Mechanisms of sound production by echolocating bats. *Am. Zool.* **13**, 1215–1226.

SUTHERS, R. A., THOMAS, S. P. AND SUTHERS, B. J. (1972). Respiration, wing-beat and ultrasonic pulse emission in an echo-locating bat. *J. exp. Biol.* **56**, 37–48.

THOMAS, S. P. (1981). Ventilation and oxygen extraction in the bat *Pteropus gouldii* during rest and steady flight. *J. exp. Biol.* **94**, 231–250.

THOMAS, S. P., LUST, M. R. AND VAN RIPPER, H. J. (1984). Ventilation and oxygen extraction in the bat *Phyllostomus hastatus* during rest and steady flight. *Physiol. Zool.* **57**, 237–250.

THOMAS, S. P. AND SUTHERS, R. A. (1972). The physiology and energetics of bat flight. *J. exp. Biol.* **57**, 317–335.