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Anechoic aquarium for ultrasonic neural telemetry

Allen F. Mensinger^{1,3*} and Max Deffenbaugh^{2,3}

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An acoustic neural telemetry tag has been developed for recording from free-swimming aquatic animals. Microwire electrodes were implanted into the VIIIth nerve of the toadfish, *Opsanus tau*, and interfaced to An acoustic neural telemetry tag has been developed for recording from free-swimming aquatic animals.
Microwire electrodes were implanted into the VIIIth nerve of the toadfish, *Opsanus tau*, and interfaced to
the subderma Microwire electrodes were implanted into the VIIIth nerve of the toadfish, *Opsanus tau*, and interfaced to the subdermally implanted tag. The telemetry tag frequency modulates the neural signal, converting it into a varyi the subdermally implanted tag. The telemetry tag frequency modulates the neural signal, converting it
into a varying frequency, which is amplified and transmitted acoustically (centre frequency of 90 kHz and
a 20 kHz bandw into a varying frequency, which is amplified and transmitted acoustically (centre frequency of 90 kHz and a 20 kHz bandwidth). This acoustic signal is detected by a receiver hydrophone, and the receiver reconstructs the fu a 20 kHz bandwidth). This acoustic signal is detected by a receiver hydrophone, and the receiver reconstructs the full neural waveform from the acoustic signal. However, due to the multipath environment in the experimental constructs the full neural waveform from the acoustic signal. However, due to the multipath environment
in the experimental aquarium, the acoustic signal is quickly degraded as the hydrophone is moved away
from the source. in the experimental aquarium, the acoustic signal is quickly degraded as the hydrophone is moved away
from the source. In order to receive the signal independent of fish position, an anechoic aquarium was
designed. Streams from the source. In order to receive the signal independent of fish position, an anechoic aquarium was designed. Streams of microbubbles $(ca. 70 \mu m$ diameter) were generated to produce a curtain of sound-absorptive materia designed. Streams of microbubbles (*ca.* 70 μ m diameter) were generated to produce a curtain of sound-
absorptive material along the walls and water surface of the aquarium. Microbubble generation signifi-
cantly reduc absorptive material along the walls and water surface of the aquarium. Microbubble generation significantly reduced the multipath artefacts, and allowed signal discrimination independent of fish and hydrophone position. Th cantly reduced the multipath artefacts, and allowed signal discrimination independent of fish and
hydrophone position. The anechoic aquarium will allow the recording of neural activity from free-
swimming fishes in quasi-n hydrophone position. The anechoic aquarium will allow the recording of neural activity from free-
swimming fishes in quasi-natural habitats, thus allowing better understanding of the neural mechanisms
of behaviour.

Keywords: telemetry; anechoic; acoustical

1. INTRODUCTION

It has long been a goal of neuroethologists to continuously record neural activity from unrestrained, naturally
hehaving animals Recent studies have produced stable It has long been a goal of neuroethologists to continuously
record neural activity from unrestrained, naturally
behaving animals. Recent studies have produced stable
neural recordings in free-swimming toadfish (Obsanus tau neural activity from unrestrained, naturally
behaving animals. Recent studies have produced stable
neural recordings in free-swimming toadfish (*Opsanus tau*)
from sieve microelectrodes chronically implanted into the behaving animals. Recent studies have produced stable
neural recordings in free-swimming toadfish (*Opsanus tau*)
from sieve microelectrodes chronically implanted into the neural recordings in free-swimming toadfish (*Opsanus tau*)
from sieve microelectrodes chronically implanted into the
regenerated VIIIth nerve (Mensinger & Highstein 1999;
Mensinger et al. 2000). An acoustic transmitter ta from sieve microelectrodes chronically implanted into the regenerated VIIIth nerve (Mensinger & Highstein 1999; Mensinger *et al.* 2000). An acoustic transmitter tag has been developed to interface with the sieve electrode regenerated VIIIth nerve (Mensinger & Highstein 1999;
Mensinger *et al.* 2000). An acoustic transmitter tag has
been developed to interface with the sieve electrode to
allow acoustic telemetry of neural signals from a free Mensinger *et al.* 2000). An acoustic transmitter tag has been developed to interface with the sieve electrode to allow acoustic telemetry of neural signals from a free-swimming animal in a quasi-natural environment been developed to interface with the sieve electrode to allow acoustic telemetry of neural signals from a free-
swimming animal in a quasi-natural environment (Mensinger & Deffenbaugh 1998) allow acoustic telemetry of neural
swimming animal in a quasi-
(Mensinger & Deffenbaugh 1998).
In contrast to the situation with In the situation and in a quasi-natural environment
In contrast to the situation with terrestrial animals,
cording from mobile aquatic animals presents a

(Mensinger & Deffenbaugh 1998).
In contrast to the situation with terrestrial animals,
recording from mobile aquatic animals presents a
different array of problems. The increased drag of the In contrast to the situation with terrestrial animals,
recording from mobile aquatic animals presents a
different array of problems. The increased drag of the
aqueous medium dictates that telemetry devices must be recording from mobile aquatic animals presents a
different array of problems. The increased drag of the
aqueous medium dictates that telemetry devices must be
small and streamlined or implanted subcutaneously different array of problems. The increased drag of the
aqueous medium dictates that telemetry devices must be
small and streamlined or implanted subcutaneously.
Implantation greatly reduces the risk of infection or aqueous medium dictates that telemetry devices must be
small and streamlined or implanted subcutaneously.
Implantation greatly reduces the risk of infection or
damage to the device but is offset either by limited small and streamlined or implanted subcutaneously.
Implantation greatly reduces the risk of infection or
damage to the device, but is offset either by limited
battery life or by the need for invasive battery changes Implantation greatly reduces the risk of infection or damage to the device, but is offset either by limited battery life or by the need for invasive battery changes. Additionally, the conductivity of seawater precludes the battery life or by the need for invasive battery changes.
Additionally, the conductivity of seawater precludes the
use of radio-telemetry for practical bio-monitoring
frequencies except at ranges less than $\text{Im } (\text{Simon } et al)$ Additionally, the conductivity of seawater precludes the use of radio-telemetry for practical bio-monitoring frequencies except at ranges less than 1m (Simon *et al.*) 1994). In contrast, acquisitive telemetry offers suffi use of radio-telemetry for practical bio-monitoring
frequencies except at ranges less than 1 m (Simon *et al.*
1994). In contrast, acoustic telemetry offers sufficient 1994). In contrast, acoustic telemetry offers sufficient *Author and address for correspondence: Biology Department,

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MN 55812-2496, USA (amensing@d.umn.edu).

range, but can be limited by echoes (multipath) in range, but can be limited by echo
enclosed environments such as tanks.
We have previously reported the enclosed environments such as tanks.
We have previously reported the development of an

enclosed environments such as tanks.
We have previously reported the development of an
implantable, inductively powered telemetry tag that
addresses the problems of size and power (Mensinger & We have previously reported the development of an
implantable, inductively powered telemetry tag that
addresses the problems of size and power (Mensinger &
Deffenbaugh 1998) In this paper we report the developimplantable, inductively powered telemetry tag that
addresses the problems of size and power (Mensinger &
Deffenbaugh 1998). In this paper, we report the develop-
ment of an ancoboic aquarium that eliminates multinath addresses the problems of size and power (Mensinger &
Deffenbaugh 1998). In this paper, we report the develop-
ment of an anechoic aquarium that eliminates multipath
artefacts and allows acoustic telemetry of full neural Deffenbaugh 1998). In this paper, we report the development of an anechoic aquarium that eliminates multipath artefacts, and allows acoustic telemetry of full neural waveforms from free-swimming fishes ment of an anechoic aquarium that elir
artefacts, and allows acoustic telemeti
waveforms from free-swimming fishes.

2. MATERIAL AND METHODS (a) *Terial AND* **METHOI**
(a) *Telemetry tag*
is a flat orlinder (2.00

(a) **Telemetry tag**
The transmitter tag is a flat cylinder (2 cm diameter \times 1 cm high). Contained within the tag are miniature 0.2 F ultra-high-The transmitter tag is a flat cylinder $(2 \text{ cm} \text{ diameter} \times 1 \text{ cm})$
high). Contained within the tag are miniature 0.2 F ultra-high-
capacity energy storage capacitors, which provide power to the
tag electronics, a circular ind high). Contained within the tag are miniature 0.2 F ultra-high-
capacity energy storage capacitors, which provide power to the
tag electronics, a circular inductive coil used to recharge the
tag e piezeelectric transducer capacity energy storage capacitors, which provide power to the
tag electronics, a circular inductive coil used to recharge the
tag, a piezoelectric transducer for transmitting data acoustically,
and alectronic simulture. T tag electronics, a circular inductive coil used to recharge the
tag, a piezoelectric transducer for transmitting data acoustically,
and electronic circuitry. The circuitry includes two input
electrodes which are connected tag, a piezoelectric transducer for transmitting data acoustically,
and electronic circuitry. The circuitry includes two input
electrodes, which are connected to a differential amplifier. A
veltage controlled essillator co and electronic circuitry. The circuitry includes two input
electrodes, which are connected to a differential amplifier. A
voltage-controlled oscillator converts the electrode voltage into a
varying frequency which is empli electrodes, which are connected to a differential amplifier. A
voltage-controlled oscillator converts the electrode voltage into a
varying frequency, which is amplified and transmitted acoustic-
ally by the niggradatrie tr voltage-controlled oscillator converts the electrode voltage into a
varying frequency, which is amplified and transmitted acoustic-
ally by the piezoelectric transducer. This acoustic frequency
modulated signal, has a sent ally by the piezoelectric transducer. This acoustic frequency modulated signal has a centre frequency of 90 kHz and a ally by the piezoelectric transducer. This acoustic frequency
modulated signal has a centre frequency of 90 kHz and a
 20 kHz bandwidth. The tag is powered by magnetic induction
sither has a subscript from all before modulated signal has a centre frequency of 90kHz and a
20kHz bandwidth. The tag is powered by magnetic induction
either by a recharging 'wand' before submersion or underwater
by a magnetic field gapeneted by a gracially de either by a recharging 'wand' before submersion or underwater
by a magnetic field generated by a specially designed recharging habitat.

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(b) *Receiver system*

The acoustic signal from the tag is detected by a receiver (b) **Receiver system**
The acoustic signal from the tag is detected by a receiver
hydrophone. The received signal is filtered and demodulated to
reconstruct the full neural waveform. The demodulator emits a The acoustic signal from the tag is detected by a receiver
hydrophone. The received signal is filtered and demodulated to
reconstruct the full neural waveform. The demodulator emits a
constant duration pulse at each zero c reconstruct the full neural waveform. The demodulator emits a
constant duration pulse at each zero-crossing of the received reconstruct the full neural waveform. The demodulator emits a
constant duration pulse at each zero-crossing of the received
signal, to convert the frequency modulated signal into a pulse
position modulated (PPM) waveform. constant duration pulse at each zero-crossing of the received
signal, to convert the frequency modulated signal into a pulse
position modulated (PPM) waveform. The PPM waveform is
then filtered by an eight pole ellintic lo position modulated (PPM) waveform. The PPM waveform is
then filtered by an eight-pole elliptic low-pass filter, recon-
structing the neural waveform. then filtered by an eight-pole elliptic low-pass filter, recon-

(c) *Anechoic aquarium*

A 1m diameter ¢breglass tank (Rowland Fiberglass, Inc., (c) *Anechoic aquarium*

A 1m diameter fibreglass tank (Rowland Fiberglass, Inc.,

Ingleside, TX, USA) served as the experimental aquarium

(ferure 1) The experimental activity 2001 of filtered sequenter A 1m diameter fibreglass tank (Kowland Fiberglass, Inc.,
Ingleside, TX, USA) served as the experimental aquarium
(figure 1). The aquarium was filled with 3201 of filtered seawater
to a denth of 45 cm. Water was recirculate (figure 1). The aquarium was filled with 3201 of filtered seawater to a depth of 45 cm . Water was recirculated through the aquarium via an external water pump (Flotec, Delavan, WI, to a depth of 45cm. Water was recirculated through the
aquarium via an external water pump (Flotec, Delavan, WI,
USA). Water was drawn through a submerged intake in the
centre of the tank 5cm beneath the surface. Air was m aquarium via an external water pump (Flotec, Delavan, WI,
USA). Water was drawn through a submerged intake in the
centre of the tank, 5 cm beneath the surface. Air was mixed into
the return flow via an aerator positioned a centre of the tank, 5 cm beneath the surface. Air was mixed into
the return flow via an aerator positioned above the water
surface. The macrobubbles in the water return were then cleaved the return flow via an aerator positioned above the water the return flow via an aerator positioned above the water
surface. The macrobubbles in the water return were then cleaved
into microbubbles by the impeller of the water pump. This
microbubble laden water was equally distri surface. The macrobubbles in the water return were then cleaved
into microbubbles by the impeller of the water pump. This
microbubble-laden water was equally distributed around the
inside walls of the tank by a 2.5 cm diam microbubble-laden water was equally distributed around the inside walls of the tank by a 2.5 cm diameter outflow ring (polymicrobubble-laden water was equally distributed around the
inside walls of the tank by a 2.5 cm diameter outflow ring (poly-
ethylene tube), which was positioned on the bottom of the tank
in contact with the wall. The wate in contact wills of the tank by a 2.5 cm diameter outflow ring (poly-
ethylene tube), which was positioned on the bottom of the tank
in contact with the wall. The water containing the microbubbles
was forced out of 1.5 pm ethylene tube), which was positioned on the bottom of the tank
in contact with the wall. The water containing the microbubbles
was forced out of 1.5 mm pores in the outflow ring equally
graced at 2.5 cm intervals. The micr in contact with the wall. The water containing the microbubbles
was forced out of 1.5 mm pores in the outflow ring equally
spaced at 2.5 cm intervals. The microbubbles rose to the surface
along the sides of the topk, and w was forced out of 1.5 mm pores in the outflow ring equally
spaced at 2.5 cm intervals. The microbubbles rose to the surface
along the sides of the tank, and were prevented from mixing
with the control water column by a cir spaced at 2.5 cm intervals. The microbubbles rose to the surface
along the sides of the tank, and were prevented from mixing
with the central water column by a circular plastic partition
(2 mm thick) positioned 5 cm from t with the central water column by a circular plastic partition (2 mm thick) , positioned 5 cm from the tank wall. The partition terminated *ca.* 8 cm below the water surface, allowing microbub-(2 mm thick), positioned 5 cm from the tank wall. The partition
terminated ca .8 cm below the water surface, allowing microbub-
bles to be drawn just below the water surface of the tank by the
centrally positioned water, terminated *ca*. 8 cm below the water surface, allowing microbub-
bles to be drawn just below the water surface of the tank by the
centrally positioned water intake. This system generated a
continuous flow of bubbles alon centrally positioned water intake. This system generated a continuous flow of bubbles along the aquarium walls and water surface.

(d) *Electrode implantation*

Toadfish were anaesthetized with 0.001% MS-222 (Sigma (d) *Electrode implantation* via

Toadfish were anaesthetized with 0.001% MS-222 (Sigma Ac

Chemical Co., St Louis, MO, USA) and injected with 0.1ml 1% of Ioadfish were anaesthetized with 0.001% MS-222 (Sigma
Chemical Co., St Louis, MO, USA) and injected with 0.1 ml 1%
pancuronium bromide. A small craniotomy was made directly
gues the anterior ramue of the VIIIth nerve Tuin Chemical Co., St Louis, MO, USA) and injected with 0.1 ml 1%
pancuronium bromide. A small craniotomy was made directly
over the anterior ramus of the VIIIth nerve. Twin microwire
electrodes of insulated 20.0m dismater plat pancuronium bromide. A small craniotomy was made directly
over the anterior ramus of the VIIIth nerve. Twin microwire
electrodes of insulated 20 µm diameter platinum–iridium wire
(Sigmund Cohn Composition Mt Vannan NV USA) electrodes of insulated 20 µm diameter platinum-iridium wire
(Sigmund Cohn Corporation, Mt Vernon, NY, USA) were electrodes of insulated 20 µm diameter platinum-iridium wire
(Sigmund Cohn Corporation, Mt Vernon, NY, USA) were
connected with conductive epoxy to 50 gauge multistranded
reald wires 6.0m in length, which terminated into a (Sigmund Cohn Corporation, Mt Vernon, NY, USA) were
connected with conductive epoxy to 50 gauge multistranded
gold wires, 6 cm in length, which terminated into a multipin
connector. The nost migrousine esceptibly was appea connected with conductive epoxy to 50 gauge multistranded
gold wires, 6 cm in length, which terminated into a multipin
connector. The post-microwire assembly was encased in silastic
(PL Madisel, Portland, OB, USA) to ensum gold wires, 6 cm in length, which terminated into a multipin
connector. The post-microwire assembly was encased in silastic
(PI Medical, Portland, OR, USA) to ensure water tightness.
The electrodes was inserted provingly t connector. The post-microwire assembly was encased in silastic
(PI Medical, Portland, OR, USA) to ensure water tightness.
The electrodes were inserted proximal to the anterior ramus of
the VIIIth name. Nouvel estimity was (PI Medical, Portland, OR, USA) to ensure water tightness.
The electrodes were inserted proximal to the anterior ramus of
the VIIIth nerve. Neural activity was confirmed by recording
differentially from the two migrovines The electrodes were inserted proximal to the anterior ramus of
the VIIIth nerve. Neural activity was confirmed by recording
differentially from the two microwires with an A-M Systems
1900 differential applifor (A M Systems the VIIIth nerve. Neural activity was confirmed by recording
differentially from the two microwires with an A-M Systems
1800 differential amplifier (A-M Systems, Inc., Carlsborg, WA,
USA) The algotrade was affixed with sup differentially from the two microwires with an A-M Systems
1800 differential amplifier (A-M Systems, Inc., Carlsborg, WA,
USA). The electrode was affixed with cyanoacrylate to the edge of
the erenisteny and the remaining o 1800 differential amplifier (A-M Systems, Inc., Carlsborg, WA,
USA). The electrode was affixed with cyanoacrylate to the edge of
the craniotomy and the remaining opening sealed with cyanoa-
smilets sel, the wound sutured a the craniotomy and the remaining opening sealed with cyanoa-
crylate gel, the wound sutured and the fish allowed to recover
overnight. The microwire connector was then inserted into the crylate gel, the wound sutured and the fish allowed to recover telemetry tag mounted on the fish's head. All animal care proceovernight. The microwire connector was then inserted i
telemetry tag mounted on the fish's head. All animal care
dures conformed to institutional animal care guidelines. **(e)** *Experimental design*

(e) **Experimental design**
To demonstrate the anechoic qualities of the aquarium, the (e) *Experimental design*
To demonstrate the anechoic qualities of the aquarium, the
telemetry tag was initially hardwired to a function generator
that sexual sees model fish that produced waveforms approvi-To demonstrate the anechoic qualities of the aquarium, the
telemetry tag was initially hardwired to a function generator
that served as a model fish that produced waveforms approxi-
mating the fragmany and applitude of nam that served as a model fish that produced waveforms approximating the frequency and amplitude of normal VIIIth nerve

Figure 1. Diagrammatic representation of the anechoic aquarium, (*a*) cross-section and (*b*) top view. An external water pump recirculates the water through the tank. Water aquarium, (a) cross-section and (b) top view. An external
water pump recirculates the water through the tank. Water
is drawn through a centrally positioned, subsurface intake.
The water flow draws macrobubbles into the water pump recirculates the water through the tank. Water
is drawn through a centrally positioned, subsurface intake.
The water flow draws macrobubbles into the return flow
through the gerator. The impeller of the water pu is drawn through a centrally positioned, subsurface intake.
The water flow draws macrobubbles into the return flow
through the aerator. The impeller of the water pump turns
the macrobubbles into microbubbles some of which The water flow draws macrobubbles into the return flow
through the aerator. The impeller of the water pump turns
the macrobubbles into microbubbles, some of which have through the aerator. The impeller of the water pump turns
the macrobubbles into microbubbles, some of which have
the desired $70 \mu m$ diameter. The microbubbles are returned
to the tank via an outflow ring. A plastic parti the macrobubbles into microbubbles, some of which have
the desired $70 \mu m$ diameter. The microbubbles are returned
to the tank via an outflow ring. A plastic partition restricts
the microbubble output to the walls of the the desired $70 \mu m$ diameter. The microbubbles are returned
to the tank via an outflow ring. A plastic partition restricts
the microbubble output to the walls of the aquarium, until
the current draws them back into the in to the tank via an outflow ring. A plastic partition restric
the microbubble output to the walls of the aquarium, unt
the current draws them back into the intake. Thus the
aquarium walls and water surface are insulated wit the microbubble output to the walls of the aquarium, untiface the current draws them back into the intake. Thus the aquarium walls and water surface are insulated with a stream of microbubbles. Note that the figure is not the current draws them back into the intake. Thus the
aquarium walls and water surface are insulated with a
stream of microbubbles. Note that the figure is not drawn
to scale aquarium
stream of
to scale.

activity (Mensinger *et al.* 1997). The telemetry tag was charged activity (Mensinger *et al.* 1997). The telemetry tag was charged via magnetic induction and submerged in the test aquarium. activity (Mensinger *et al.* 1997). The telemetry tag was charged
via magnetic induction and submerged in the test aquarium.
Acoustic telemetry was conducted in the presence and absence
of migrabubbles. The triple ware th via magnetic induction and submerged in the test aquarium.
Acoustic telemetry was conducted in the presence and absence
of microbubbles. The trials were then repeated with the tele-
matry tag attached to a microwing implan Acoustic telemetry was conducted in the presence
of microbubbles. The trials were then repeated w
metry tag attached to a microwire-implanted fish. metry tag attached to a microwire-implanted fish.
3. RESULTS

Figure 2 shows the effects of microbubble generation on signal discrimination. Figure $2a$ ^{$-c$} was generated during Figure 2 shows the effects of microbubble generation on
signal discrimination. Figure $2a-c$ was generated during
acoustic telemetry by the model fish. The lower trace in
each set is the direct recording of the signal from signal discrimination. Figure $2a-c$ was generated during
acoustic telemetry by the model fish. The lower trace in
each set is the direct recording of the signal from the
model fish and the unner trace is the reconstructio acoustic telemetry by the model fish. The lower trace in each set is the direct recording of the signal from the model fish and the upper trace is the reconstruction of this signal following telemetry. In figure $2a$, the each set is the direct recording of the signal from the model fish and the upper trace is the reconstruction of this signal following telemetry. In figure $2a$, the pump is off and the multinath dominates the signal at a model fish and the upper trace is the reconstruction of
this signal following telemetry. In figure $2a$, the pump is
off, and the multipath dominates the signal at a distance
beyond a few centimetres. Figure $2b$ illustra this signal following telemetry. In figure $2a$, the pump is
off, and the multipath dominates the signal at a distance
beyond a few centimetres. Figure $2b$ illustrates the initial
effects of microbubble production follow off, and the multipath dominates the signal at a distance
beyond a few centimetres. Figure $2b$ illustrates the initial
effects of microbubble production following 10 s of water
flow. Note that the reconstituted signal is beyond a few centimetres. Figure $2b$ illustrates the initial effects of microbubble production following $10s$ of water flow. Note that the reconstituted signal is marginally clearer as the initial microbubble generation effects of microbubble production following 10s of water
flow. Note that the reconstituted signal is marginally
clearer as the initial microbubble generation begins to
absorb the extraneous sound energy Figure 2c shows the flow. Note that the reconstituted signal is marginally clearer as the initial microbubble generation begins to absorb the extraneous sound energy. Figure $2c$ shows the effect of maximal microbubble production. The water clearer as the initial microbubble generation begins to absorb the extraneous sound energy. Figure $2c$ shows the effect of maximal microbubble production. The water absorb the extraneous sound energy. Figure 2ϵ shows the effect of maximal microbubble production. The water pump has been active for over 30s . This type of signal discrimination was independent of fish or hydropho effect of maximal microbubble production. The water
pump has been active for over 30s. This type of signal
discrimination was independent of fish or hydrophone
position anywhere within the confines of the plastic pump has been active for over 30s. This type of signal
discrimination was independent of fish or hydrophone
position anywhere within the confines of the plastic
partition Figure 2d shows the reconstruction of spontadiscrimination was independent of fish or hydrophone position anywhere within the confines of the plastic partition. Figure $2d$ shows the reconstruction of spontaposition anywhere within the confines of the plastic
partition. Figure 2d shows the reconstruction of sponta-
neous neural signals from an unrestrained experimental
fish placed in the test aguarium during microbubble partition. Figure $2d$ shows the reconstruction of spontaneous neural signals from an unrestrained experimental fish placed in the test aquarium during microbubble generation generation.

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Figure 2. The effects of microbubble generation on signal discrimination. $(a-c)$ Generated during acoustic telemetry by the model fish. The lower trace in each set is the direct recording of the signal from the model fish, Figure 2. The effects of microbubble generation on signal discrimination. $(a-c)$ Generated during acoustic telemetry by the model fish. The lower trace in each set is the direct recording of the signal from the model fish, model fish. The lower trace in each set is the direct recording of the signal from the model fish, and the upper trace is the
reconstruction of this signal following acoustic telemetry. In (*a*), the pump is off, and the m reconstruction of this signal following acoustic telemetry. In (a) , the pump is off, and the multipath environment degrades the signal at a distance of 10 cm. (b) The initial effects of microbubble production following 1 reconstituted signal is marginally clearer as the initial microbubble generation begins to absorb the extraneous sound energy. reconstituted signal is marginally clearer as the initial microbubble generation begins to absorb the extraneous sound energy.
(*c*) The effect of maximal microbubble production. This type of signal discrimination was ind (c) The effect of maximal microbubble production. This type of signal discrimination was independent of fish or hydrophone position anywhere within the confines of the plastic partition. (d) Discrimination of acoustic position anywhere within the
from an unrestrained experim
individual action potentials.

4. DISCUSSION

The results demonstrate that microbubbles act as effec-4. **DISCUSSION**
The results demonstrate that microbubbles act as effec-
tive sound absorbers, and can transform even small aquaria
into anechoic chambers at acoustic telemetry frequencies The results demonstrate that microbubbles act as effective sound absorbers, and can transform even small aquaria
into anechoic chambers at acoustic telemetry frequencies.
The microbubble generation allowed acoustic neural tive sound absorbers, and can transform even small aquaria
into anechoic chambers at acoustic telemetry frequencies.
The microbubble generation allowed acoustic neural tele-
metry independent of fish and bydrophone positio into anechoic chambers at acoustic telemetry frequencies.
The microbubble generation allowed acoustic neural telemetry independent of fish and hydrophone position. The microbubble generation allowed acoustic neural tele-
try independent of fish and hydrophone position.
The difficulty in transmitting data acoustically through
enclosed area like a tank is multinath. The signal from

metry independent of fish and hydrophone position. Both is multipath an enclosed area like a tank is multipath. The signal from the task of the signal from th *Phil. Trans. R. Soc. Lond.* B (2000)

the fish is reflected off the water surface and the bottom the fish is reflected off the water surface and the bottom
and sides of the aquarium, so that the receiver detects not
only the direct signal from the fish, but also multiple the fish is reflected off the water surface and the bottom
and sides of the aquarium, so that the receiver detects not
only the direct signal from the fish, but also multiple
echoes of the signal from all directions. In fa and sides of the aquarium, so that the receiver detects not
only the direct signal from the fish, but also multiple
echoes of the signal from all directions. In fact, at ranges
beyond a few centimetres the vast majority of only the direct signal from the fish, but also multiple echoes of the signal from all directions. In fact, at ranges beyond a few centimetres, the vast majority of the energy that the receiver detects is reflected and not echoes of the signal from all directions. In fact, at ranges Because of the dominance of the scattered field, it is insufthat the receiver detects is reflected and not direct energy.
Because of the dominance of the scattered field, it is insuf-
ficient simply to scatter reflections by roughing up the
tank surfaces (e.g., lining, the bottom Because of the dominance of the scattered field, it is insuf-
ficient simply to scatter reflections by roughing up the
tank surfaces (e.g. lining the bottom with gravel).

Acoustic energy must actually be absorbed from the system by conversion into heat Acoustic energy must actually
system by conversion into heat.
At their resonant frequency At their resonant frequency, air bubbles in water have extinction cross-section which is about 100 times

system by conversion into heat.
At their resonant frequency, air bubbles in water have
an extinction cross-section, which is about 100 times At their resonant frequency, air bubbles in water have
an extinction cross-section, which is about 100 times
larger than their geometrical cross-section. That is to say,
they absorb acoustic energy in a region very much la an extinction cross-section, which is about 100 times
larger than their geometrical cross-section. That is to say,
they absorb acoustic energy in a region very much larger
than their own size. The resonance frequency of an larger than their geometrical cross-section. That is to say,
they absorb acoustic energy in a region very much larger
than their own size. The resonance frequency of an air
bubble near the water surface is $ca \neq 6.5/D$ whe they absorb acoustic energy in a region very much larger
than their own size. The resonance frequency of an air
bubble near the water surface is *ca*. $f = 6.5/D$, where f is than their own size. The resonance frequency of an air
bubble near the water surface is *ca.* $f = 6.5/D$, where f is
the frequency in Hertz, and *D* is the diameter of the
bubble in metres (Clay & Medwin 1977) Thus for t bubble near the water surface is *ca.* $f = 6.5/D$, where f is
the frequency in Hertz, and D is the diameter of the
bubble in metres (Clay & Medwin 1977). Thus, for the
90 kHz frequency of the telemetry signal, the diam the frequency in Hertz, and D is the diameter of the bubble in metres (Clay & Medwin 1977). Thus, for the 90 kHz frequency of the telemetry signal, the diameter of a resonant bubble is 72 µm . The sound absorption b bubble in metres (Clay & Medwin 1977). Thus, for the 90 kHz frequency of the telemetry signal, the diameter of a resonant bubble is 72 µm. The sound absorption by the microbubbles proved sufficient to reduce the reverberat 90 kHz frequency of the telemetry signal, the diameter of
a resonant bubble is $72 \mu m$. The sound absorption by the
microbubbles proved sufficient to reduce the reverberation
within the tank to levels where acoustic te a resonant bubble is 72 µm. The sound absorption by the microbubbles proved sufficient to reduce the reverberation
within the tank to levels where acoustic telemetry of high
handwidth neural signals is feasible microbubbles proved sufficient to redu
within the tank to levels where acoust
bandwidth neural signals is feasible.
Although a variety of approaches to

bandwidth neural signals is feasible.
Although a variety of approaches to underwater sound
absorption have been proposed in the acoustics literature
(Hinders *et al.* 1995: Hladky-Hennion & Decarnigny Although a variety of approaches to underwater sound
absorption have been proposed in the acoustics literature
(Hinders *et al.* 1995; Hladky-Hennion & Decarpigny
1992 Lastinger 1972) the use of resonant microbubbles absorption have been proposed in the acoustics literature
(Hinders *et al.* 1995; Hladky-Hennion & Decarpigny
1992; Lastinger 1972), the use of resonant microbubbles
has several distinct advantages for biotelemetry applica (Hinders *et al.* 1995; Hladky-Hennion & Decarpigny 1992; Lastinger 1972), the use of resonant microbubbles has several distinct advantages for biotelemetry applications. The microbubbles are essentially invisible to the 1992; Lastinger 1972), the use of resonant microbubbles
has several distinct advantages for biotelemetry applica-
tions. The microbubbles are essentially invisible to the
eye, making observation possible from any angle if has several distinct advantages for biotelemetry applications. The microbubbles are essentially invisible to the eye, making observation possible from any angle if a transparent tank is used. The system is easy to clean and maintain and the introduction of microbubbles raises eye, making observation possible from any angle if a
transparent tank is used. The system is easy to clean and
maintain, and the introduction of microbubbles raises
little biocompatibility concern Finally the system is ver transparent tank is used. The system is easy to clean and
maintain, and the introduction of microbubbles raises
little biocompatibility concern. Finally, the system is very
inexpensive to implement even for large tanks maintain, and the introduction of microbubbles raises
little biocompatibility concern. Finally, the system is very
inexpensive to implement, even for large tanks.

The use of sound-absorbing microbubbles increases the inexpensive to implement, even for large tanks.
The use of sound-absorbing microbubbles increases the
feasibility of using acoustic telemetry in any size tank. It
is especially useful for the marine environment where the The use of sound-absorbing microbubbles increases the
feasibility of using acoustic telemetry in any size tank. It
is especially useful for the marine environment where the
conductivity of seawater renders radio-telemetry feasibility of using acoustic telemetry in any size tank. It
is especially useful for the marine environment where the
conductivity of seawater renders radio-telemetry ineffec-
tive at biologically relevant ranges. Althoug is especially useful for the marine environment where the conductivity of seawater renders radio-telemetry ineffective at biologically relevant ranges. Although we have confirmed that the tank is anechoic for ultrasonic conductivity of seawater renders radio-telemetry ineffec-
tive at biologically relevant ranges. Although we have
confirmed that the tank is anechoic for ultrasonic
frequencies, future studies will determine effects of micr tive at biologically relevant ranges. Although we have confirmed that the tank is anechoic for ultrasonic
frequencies, future studies will determine effects of micro-
bubble production on the sound generation within the
hearing range of the fish frequencies, future studies v
bubble production on the
hearing range of the fish.

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- within the tank to levels where acoustic telemetry of high Hladky-Hennion, A. & Decarpigny, J. 1992 Note on the validity
bandwidth neural signals is feasible. The set of using plane-wave type relations to characterize Albe **185**, 219–246.
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