

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

- | | |
|-------------------------------------|--|
| n/a | Confirmed |
| ☐ | ☒ The exact sample size (<i>n</i>) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☐ | ☒ The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☒ | ☐ A description of all covariates tested |
| ☒ | ☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☐ | ☒ For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☒ | ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☒ | ☐ Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i>), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	The discharge behaviours were collected using a Landt battery tester. EIS relied on a Metrohm system. The characteristic responses of the PTs were collected using a PalmSens4 system. ECG was collected using PowerLab and Bio Amp (ADInstruments). Six-lead ECG was recorded using Prucka CardioLab. The Perkin Elmer LAMBDA 1050 spectrophotometer measured the transmission spectra of the filters. A Thorlabs' PM200 Optical Power and Energy Meter recorded the intensities of light from LEDs.
Data analysis	The following software were used in this study: PSTrace (v5.9), Prism (v10, GraphPad), OriginLab (v2019b), EC-Lab (V11.36), Labchart (v8) and MATLAB (R2023b). Custom Python code with Python 3.8.10 and Bleak 0.12.1, Scipy 1.7.3, Numpy 1.20.2, Pandas 1.2.5 and Matplotlib 3.3.4 was used to receive and analyse ECG data. The code for connecting to the device via BLE, recording and analyzing ECG data in real time, and configuring the pacing parameters in a closed-loop system is available on Code Ocean (https://codeocean.com/capsule/9406347/tree/v1).

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

The main data supporting the results of this study are present in the paper and the Supplementary Information.

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	N/A Tissue received as declined for transplant was de-identified
Reporting on race, ethnicity, or other socially relevant groupings	Discarded and de-identified human tissue was provided by the Gift of Hope organ procurement organization (Chicago, IL). The Northwestern University Institutional Review Board (IRB) reviewed the submitted protocol of the study and determined that the proposed activity is not research involving human subjects.
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	For in vivo pacing demonstrations, a number of n=3 mice and n=5 canines were utilized. Exceptionally, in closed-loop tests (Fig. 5), the authors used one rat and successfully proved the concept. For ex vivo pacing demonstrations, a number of n=3 pig hearts and n=5 human hearts were utilized. For in vivo biocompatibility tests, a number of n=3 rats were used. For in-vivo lifetime demonstration, a number of n=4 rats were utilized. The sample size for cardiac electrical stimulation was not predetermined but was instead based on laboratory experience. It was considered adequate to illustrate the representative effects of cardiac pacing with the pacemakers.
Data exclusions	No data points were excluded from analysis.
Replication	The devices performed similarly across multiple animal groups. ECG signals were recorded in multiple groups. The ex vivo cardiac pacing results represent data from more than three independent experiments conducted using different human and porcine hearts. The in vivo rat & mice heart pacing results reflect findings from over three independent experiments performed with various devices and animals. Similarly, the in vivo dog heart pacing experiment results are based on over three independent experiments using different devices and dogs.
Randomization	All animals were randomized into experimental groups. The ex vivo human heart pacing experiments were conducted on de-identified discarded tissues that did not involve human subjects prior to their procurement for research. No significant variability in response to cardiac pacing is anticipated.
Blinding	No blinding was attempted. We ensured that control and experimental groups were tested using the same experimental conditions whenever necessary, and that data from both groups were analyzed using the same criteria and methods.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☐	☒ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☐	☒ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Eukaryotic cell lines

Policy information about [cell lines and Sex and Gender in Research](#)

Cell line source(s)	L929 mouse fibroblast cells were provided by the Developmental Therapeutics Core at Northwestern University
Authentication	Cell lines were authenticated by the vendor.
Mycoplasma contamination	Cell lines were tested negative for mycoplasma contamination
Commonly misidentified lines (See ICLAC register)	No commonly misidentified lines were used

Animals and other research organisms

Policy information about [studies involving animals; ARRIVE guidelines](#) recommended for reporting animal research, and [Sex and Gender in Research](#)

Laboratory animals	In vivo rodent pacing study was performed on mice (15–25 weeks old; C57BL/6J; Jackson Laboratory; male and female) and rats (12–14 weeks old; Sprague–Dawley; Charles Rivers Laboratory; male). In vivo demonstration of pacemaker injection and cardiac pacing in large-animal models used retired breeder female and male hound dogs (age 1.6–4.5 years, weight 39–53 kg). In vivo biocompatibility tests used male rats (12–14 weeks old; Sprague–Dawley; Charles Rivers Laboratory; male). In vivo lifetime demonstration of pacemakers were performed on rats (12–14 weeks old; Sprague–Dawley; Charles Rivers Laboratory; male); All mice and rats were housed in the animal facility at Northwestern University, where the light/dark cycle was automatically controlled, with a maintained temperature range of 70–74°F and humidity levels between 30–70%. Porcine hearts were acquired from the Center of Comparative Medicine of Northwestern University as post-euthanasia tissue transfer.
Wild animals	The study didn't involve wild animals.
Reporting on sex	Both male and female rats and hound dogs were used in the cardiac pacing experiments. Male rats were used in the in vivo biocompatibility tests of control and device groups.
Field-collected samples	The study didn't involve samples collected from the field.
Ethics oversight	All experimental animal procedures and protocols were approved by Northwestern University Institutional Animal Care and Use Committee and in compliance with suggestions from the panel of Euthanasia of the American Veterinary Medical Association and the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

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Plants

Seed stocks

N/A

Novel plant genotypes

N/A

Authentication

N/A