Novel Capacitive Electrode for Cardiac Model

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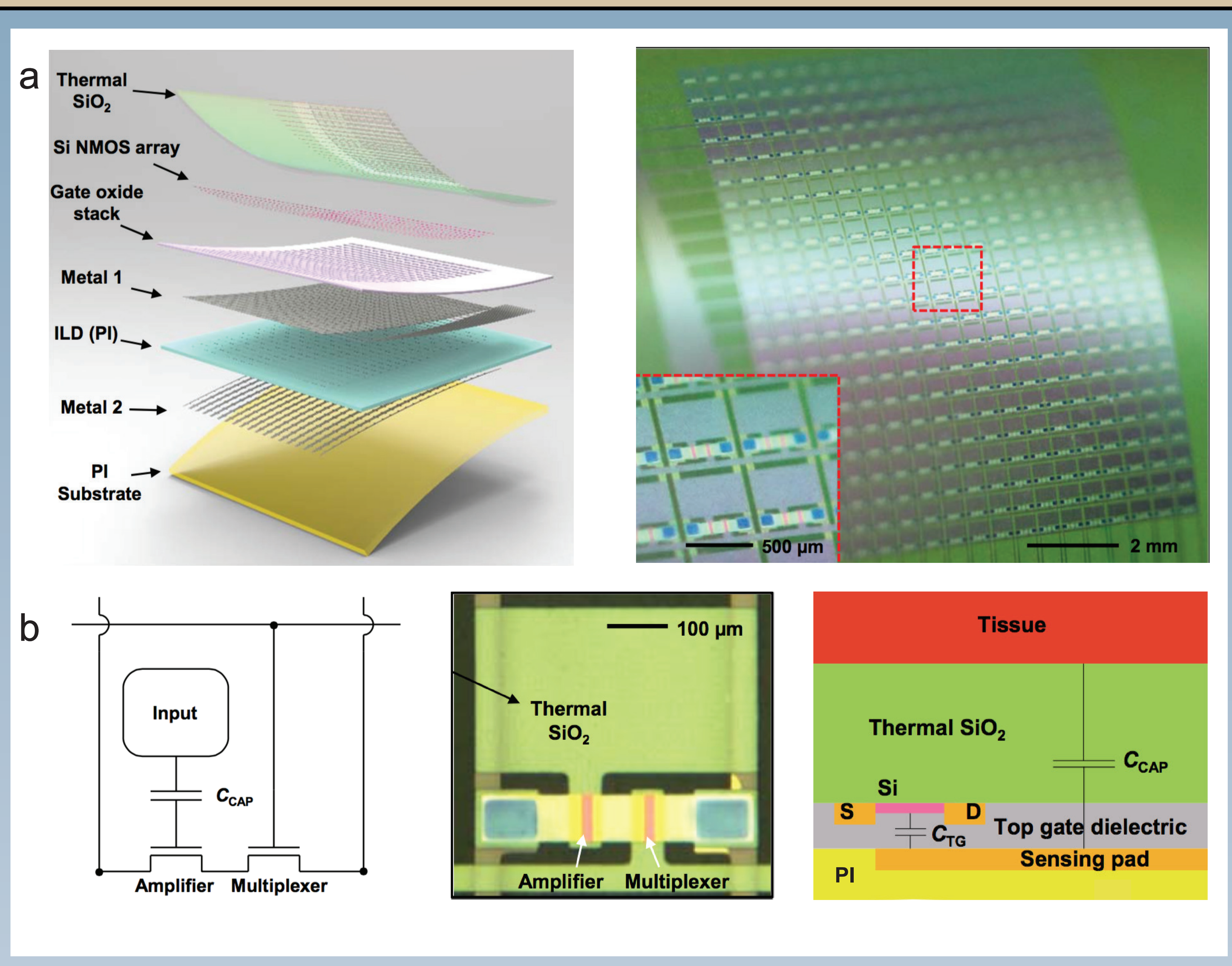
Introduction

Multi-parametric high-resolution mapping of the heart is fundamental to furthering our understanding of the pathophysiology of various disease states. Recent developments in flexible/stretchable electronics have created a set of tools and fabrication processes capable of creating conformal cardiac devices able to withstand chronic deployment. Additionally, they are capable of versatile scaling allowing them to map the entire heart surface or be condensed to provide sub-millimeter resolution. In order to function as a chronic implant, the limitations of standard metal oxide electrodes, primarily degradation in physiologic environment and tissue necrosis, must be overcome. Here we present a novel capacitive electrode capable of measuring relevant cardiac electrical activity while overcoming the limitations of metal oxide electrodes.

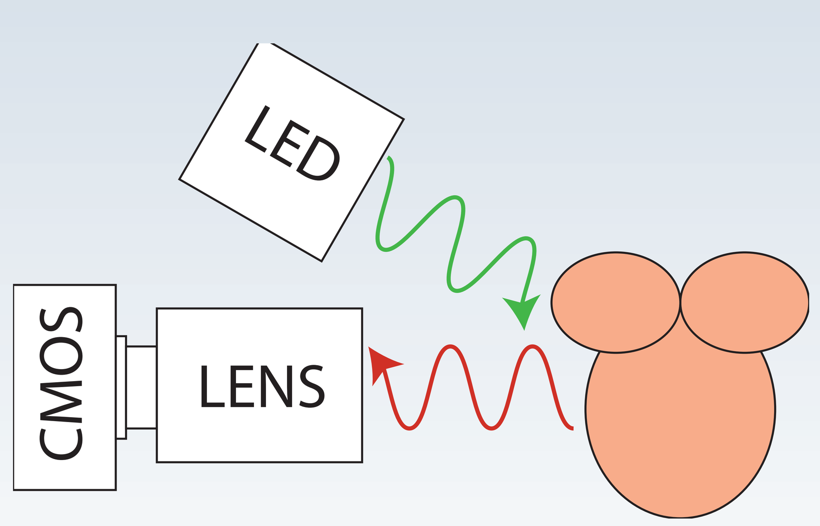
Methods - Electrode Design



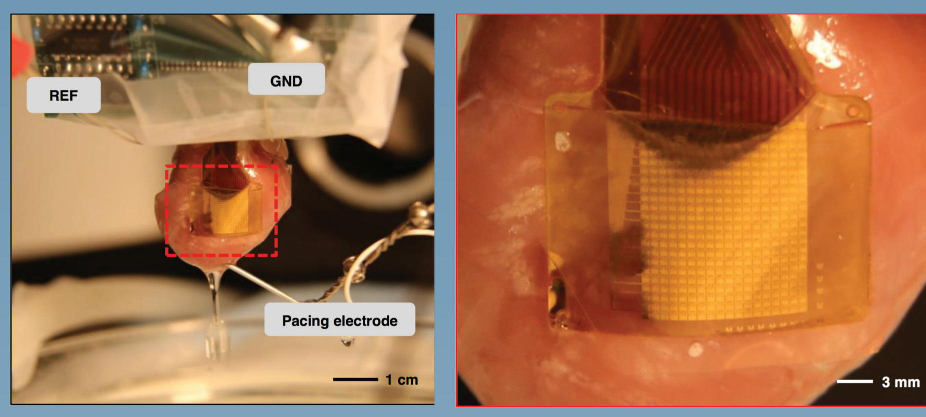
(a) Exploded-view schematic illustration (left) and a photograph (right) of a completed capacitively-coupled flexible sensing system with 396 nodes in a slightly bend state. The arrows in the left illustration highlight the key functional layers. Inset on the right shows a magnified view of a few nodes. (b) Circuit diagram for a node in this capacitively coupled array, with annotations for each component (left), and an optical microscope image of the cell (middle). A schematic of the circuit cross section (right) illustrates the mechanism for capacitively coupled sensing through a SiO2 layer to an underlying transistor.

Methods - Electrophysiology Study

- Rabbit heart excised via thoracotomy
- Cannulated and perfused with oxygenated Tyrodes solution
- Maintained at constant temperature of 37°C and constant pressure of 60-80 mmHg
- Contraction arrested with 50 µM blebbistatin
- 20 µM voltage sensitive dye (di-4-ANEPPS) administered
- di-4-ANEPPS excited by 520 nm green LED

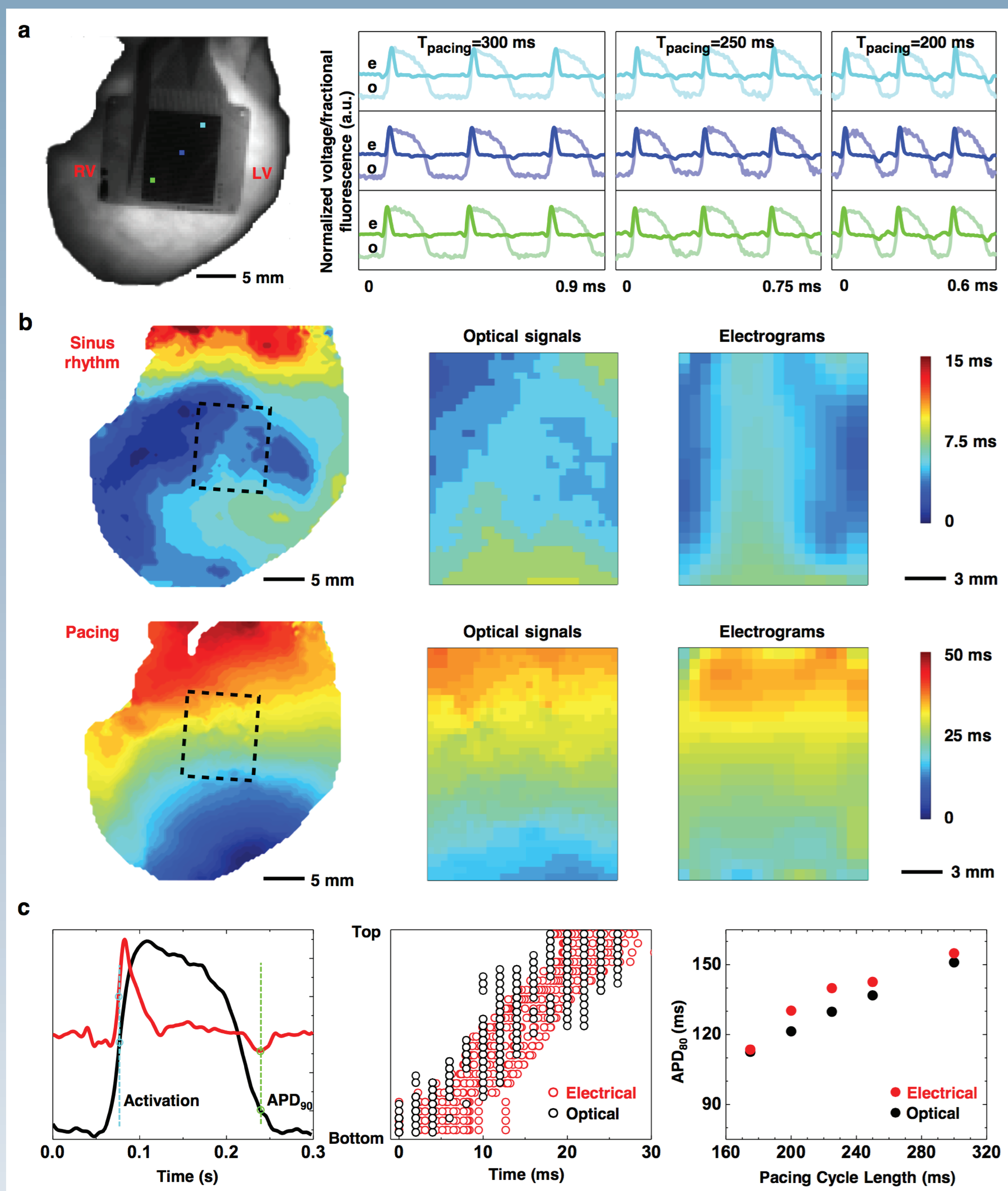


Methods - Electrophysiology Study Cont.



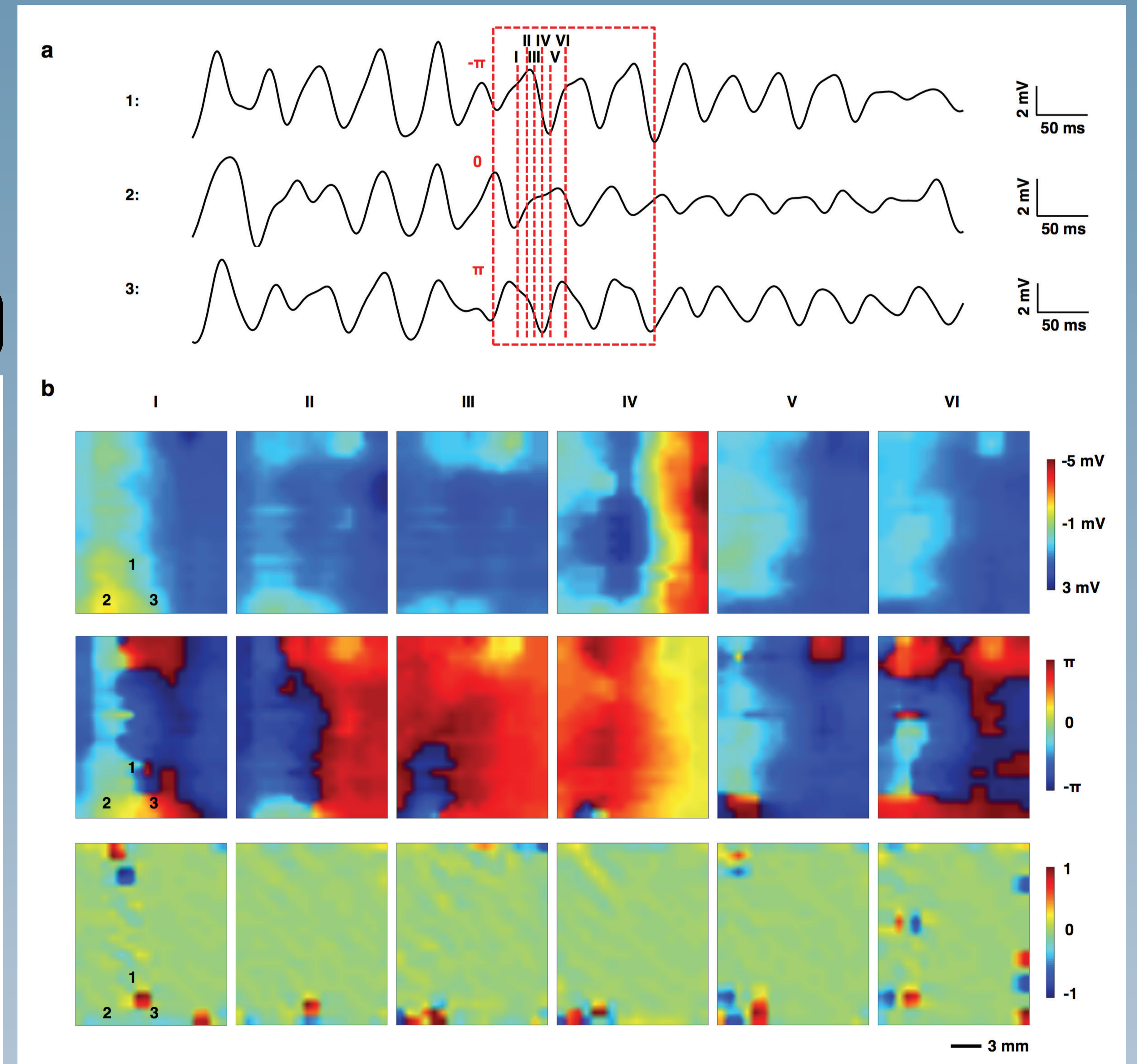
- Emission spectra filtered by 655 nm longpass filter
- Capacitive electrode placed on heart using plastic sheet and capillary action
- Pacing protocol administered
- Ventricular fibrillation induced using 20 mM pinacidil and burst pacing

Results - Comparison to Optical Mapping



(a) Representative electrical and optical signals captured simultaneously on a Langendorff perfused rabbit heart at multiple cycle lengths (300, 250, and 200 ms). (b) Interpolated spatial activation maps derived from these data. Top row shows activation as measured during sinus rhythm. Bottom row corresponds to 300 ms ventricular pacing. The dashed boxes in the whole heart illustrations depict the device area. (c) Left figure highlights a quantitative comparison of electrical and optical signals during one depolarization/ repolarization cycle. Center figure shows the comparison of activation times measured across all electronic nodes and corresponding optical field of view. Right figure shows a restitution curved (300, 250, 225, 200, 175 ms) measured using both methods.

Results - Study of Ventricular Fibrillation



(a) Three representative electronic node signals taken from a heart during VF. The dashed box specifies the window of time corresponding to two reentrant cycles of VF. The labels $-\pi$, 0, and $+\pi$ indicate the initial phase values of the respective signals at the beginning of the reentrant cycle. (b) Voltage, phase and phase singularity maps at six time points corresponding to the dash lines specified in (a). Number 1, 2, and 3 on the maps mark the locations where the signals in (a) were taken. Voltage and phase data indicate a reentrant cycle of VF. A phase singularity commonly refers to a point on a phase map around which all values of phase (i.e. $-\pi$ to $+\pi$) are represented. The phase singularities are identified as the ±1 values associated with regions of the phase map where this occurs. Optical signals from the sensing electronics area also match well with electrical recordings (data not shown).

Conclusion

Our data serves as a proof-of-concept that capacitive electrodes are capable of measuring relevant cardiac electrical activity. Comparison of capacitive electrode recordings to simultaneously recorded optical mapping measurements facilitated the establishment of morphological criteria for both activation and repolarization in capacitive signals. Future work will include the integration of the electrode into a conformal whole ventricle epicardial device and the quantification of VF characteristics.

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