Open-source 128-channel bioamplifier module for ambulatory monitoring of gastrointestinal electrical activity

Jonathan C. Erickson*, Beth Reed, Jeremy Wharton, Utkrist Thapa, Jack Robey, and Riwaj Shrestha

***Abstract*— We present an open-source, low-cost, portable, 128-channel bioamplifier module designed specifically for ambulatory, long-term (≥24 hr) monitoring of gastrointestinal (GI) electrical activity. The electronics hardware integrates state-of-the-art, commercial-off-the-shelf components on a custom PCB. Features include on-board data logging, wireless data streaming, subject motion monitoring, and stable operation up to the maximum 2 kHz/channel sampling rate tested. The new device operates for ≈ 30 hr continuously powered by a single 3.7 V, 2500 mAh LiPo battery. The 3D-printed ABS mechanical enclosure is robust and small (13.1 × 8.8 × 2.5 cm), so that the device can be carried in a standard Holter monitor pouch. Results from initial 128-channel, high spatial resolution body surface colon mapping experiments demonstrate the utility of this new device for GI applications. The new bioamplifier module could also be used for multichannel recording experiments in a variety of biomedical domains to study electrical activity patterns of the neuromuscular system (EMG), uterus (EHG), heart (ECG), and brain (EEG).**

I. INTRODUCTION

Multichannel electrical recordings find widespread use in variety of biomedical domains to assess heart (ECG), brain (EEG), neuromuscular (EMG), and uterine (EHG) function. One rapidly growing application area is the gastrointestinal (GI) field. For example, multichannel recordings have recently been used in research and clinical diagnostic settings to map the propagation of gastric slow waves using a minimally invasive endoscopic device as well as a noninvasive cutaneous electrode array [1], [2]. Similarly, electrocolonography (EColG) was recently introduced for noninvasively identifying cyclic motor patterns in the distal colon using an array of skin-surface electrical recordings [3]. As these GI technologies continue to mature, their capability to identify meaningful physiological information may be improved and extended by making recordings with increased spatial density and/or area coverage over a longer multi-day (≥ 24 hr) monitoring period.

To this end, we have developed a novel low-cost, open source, portable device with 128 input channels and on-board data logging capability. The new device, coined "Intsy-128", is a substantial upgrade over the 32/64-channel electronics module previously developed in our lab, which was validated for making high-quality GI signal recordings [3], [4]. Specific new and upgraded features include: the maximum channel count has been increased from 64 to 128 channels; on-board microSD card data logging has been added to enable ambulatory applications; an accelerometer plus a flex sensor have been added to monitor participant movement; and a more powerful microcontroller has been integrated to support higher sampling rates. Additionally, we developed a small footprint, robust, custom 3D-printed ABS enclosure for the electronics board, which makes the new Intsy-128 device well suited for portable, ambulatory applications.

The remainder of this paper details the electronic and mechanical design of the new Intsy-128 module. Herein, we also demonstrate the utility of this device in the GI field through initial experiments mapping colonic cyclical motor patterns stimulated by food intake using recordings from a 128-channel body surface electrode array. While the Intsy-128 was developed specifically with GI applications in mind, it could also be used in multichannel recording applications to study cardiac, neural, musculoskeletal, and uterine electrical activity patterns (e.g. [5]).

* Corresponding author: ericksonj@wlu.edu. The authors are with the Department of Physics and Engineering, Washington and Lee University, Lexington, VA 24450 USA.

II. MATERIALS AND METHODS

A. Electronics Hardware System Design

The Intsy-128 electronics hardware is comprised of six main components integrated on a custom PCB (Figure 1 a-b). These include: Teensy 3.6 microcontroller (PJRC; Sherwood, OR); four Intan RHD2132 amplifier boards (Intan Technologies; Los Angeles, CA), two Texas Instruments SN65LVDT41 LVDS-CMOS transceivers for SPI over LVDS; one ADXL335 3-axis accelerometer (Adafruit Industries; New York City, NY) and a RN-42 "SilverMate" Bluetooth modem (Sparkfun; Niwot, CO). The custom PCB was designed using the free version of Eagle PCB design software (version 9.4). The module can be easily assembled in about 4 hrs using basic through-hole and surface mount soldering techniques.

The Teensy 3.6 microcontroller was selected because it offers multiple SPI ports; a relatively fast and powerful CPU (180 MHz ARM Cortex-M4); and native microSD support via a 4-bit SDIO interface with a maximum 12 MB/s write speed. On-board data logging is required for ambulatory studies. Each of four Intan RHD2132 amplifier boards has 32 inputs for a total of 128. The amplifier boards are interfaced to two SPI ports on the Teensy 3.6. The TI SN65LVDT41 ICs are used to translate TTL/CMOS signals used by Teensy 3.6 to low-voltage differential signaling (LVDS) used by the Intan headstages.

The RN-42 wirelessly streams data to a host PC for real-time signal visualization and analysis. RTS/CTS flow control was enabled for robust data transfer. Additionally, the Teensy firmware configures the wireless data stream to transfer the maximum possible number of channels at full

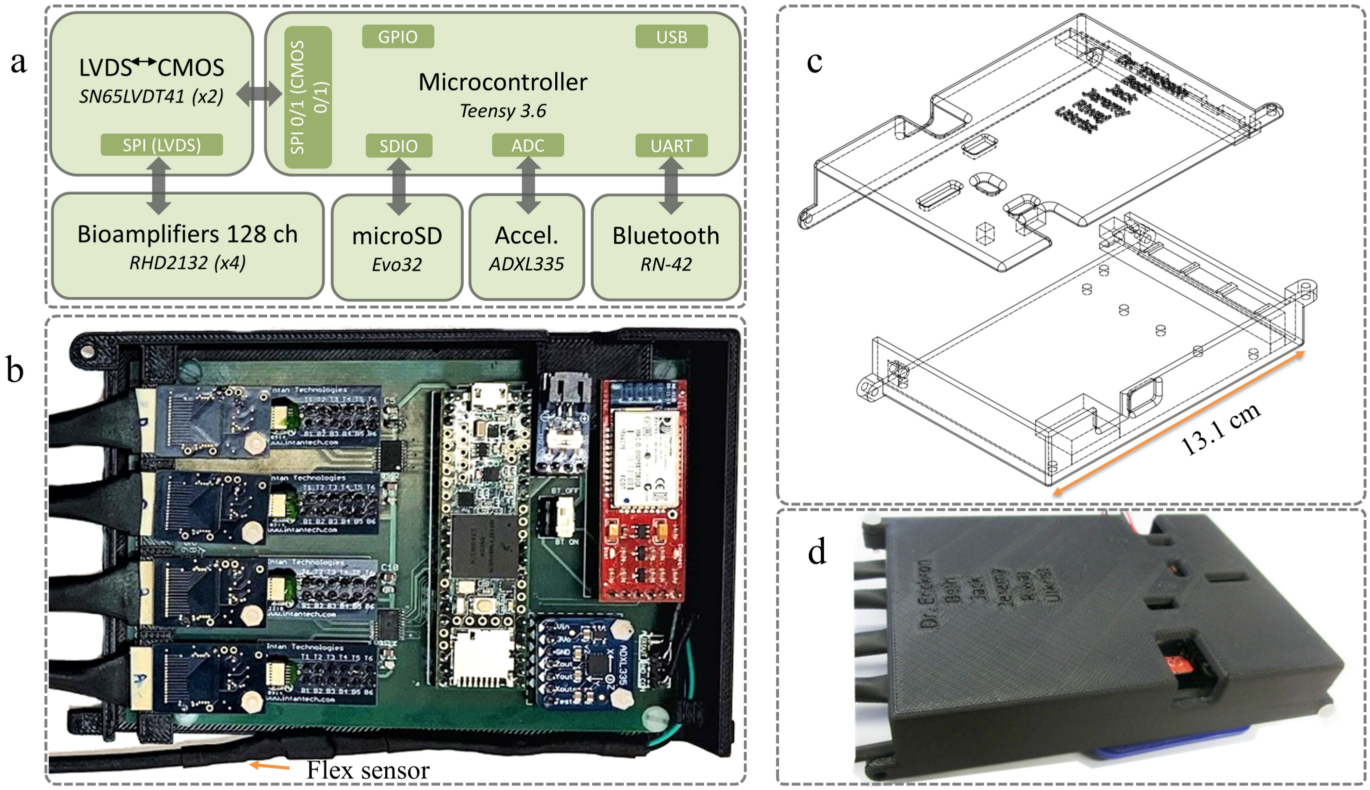

Fig. 1. System overview of the Intsy 128 device. **a**: Electronics design block diagram; **b**: Fully assembled PCB mounted in base of enclosure; **c**: 3-D CAD rendering of enclosure assembly showing base and lid. **d**: Fully assembled Intsy-128 module.

sampling rate without exceeding the total Bluetooth bandwidth. Alternatively, data may be streamed in real-time over the USB port for higher bandwidth applications. Independent of data streaming, all data bytes are always logged on-board to a microSDHC UHS-I memory card (Samsung EVO Plus 32GB). Data logging write-speed was optimized by pre-allocating the data file and writing 512-byte (1-page) blocks to the microSD card data file. Each data frame consists of 270 bytes, including 256 bytes for electrical recordings (2-bytes for each of 128 amplifiers), 4-byte microsecond timestamp, and 10 bytes of “magic number” synchronization characters used to verify fidelity of SPI and SDIO interfaces.

The 3-axis accelerometer (ADXL335) and a custom flex sensor are used to measure subject motion during the study. The flex sensor is configured as a standard voltage divider comprised of a 47kΩ fixed resistor in series with a *approx* 20-400kΩ flexible resistor (Sparkfun) and is powered by a 3.3 V digital output pin on the Teensy 3.6. The accelerometer readings could be used for analysis of multi-day ambulatory monitoring applications [6]. Similarly, the flex sensor is more sensitive to subtle motions, such as bending or twisting of the abdomen, and may be used in the future to improve automated artifact reduction techniques [7].

The Insty-128 module is powered by a 3.7 V, 2500 mAh LiPo flat pack battery with an easily accessible switch to turn the device on or off. A separate power switch independently controls the Bluetooth module allowing users to save battery power when real-time wireless streaming is not required. LED indicator lights on both the Bluetooth module and Teensy 3.6 serve as system status indicators.

B. 3D-Printed Enclosure

The electronics hardware module is secured inside a custom 3D-printed ABS enclosure case, which is durable and protects internal hardware from mechanical impacts experienced during an ambulatory subject experiment. The enclosure consists of a base and lid (Figure 1c). Seven nylon nuts and bolts secure the PCB circuit board and the lid onto the base of the case providing quick and efficient assembly (Figure 1d).

A wide-tooth “comb” pattern of indentations (15 mm wide with 2.5 mm gaps) was carefully incorporated into the base and lid to secure the connection between the electrodes and the amplifiers. Additionally, multiple ports are provided for viewing status-indicator LEDs, toggling power switches, and conveniently accessing the microSD card and USB port.

The design focused on making a light and slim device conducive for ambulatory studies. The case dimensions are 13.1 $\times$ 8.8 $\times$ 2.5 cm, approximately the same size as a typical Holter cardiac monitor; thus, it can be easily carried in a Holter monitor pouch. The Intsy-128 module weighs a total of 216 grams, including the the fully-assembled PCB, ABS enclosure, and LiPo battery mounted externally on the enclosure’s base in a vinyl cell phone wallet pouch.

C. Software User Interface

A user-friendly custom suite of software built in Labview 2017 (National Instruments; Austin, TX) was used for device configuration and visualizing signals in real-time. This interface allows the user to configure the sampling rate, band-pass filter cutoffs for the Intan RHD2132, and SD card log file name. The LabView interface is also used to configure and optionally apply digital filters, as well as select a subset of channels, prior to display.

A file reader utility developed in Matlab 2019a (The Mathworks Inc; Nattick, MA) was used to import and convert the raw binary data files into physical values for further analysis. Firmware for the Teensy 3.6 was programmed using Teensyduino [8] in the Arduino IDE. All custom software, PCB and CAD design files are freely available and fully open-source [9].

D. Meal-response experiment

To demonstrate the utility of the Intsy-128 device, we performed initial body surface colon mapping experiments with $n = 5$ human subjects, following the protocol described in [3]. This study was approved by the Institutional Review Board of Washington and Lee University. In this study, we placed a 128-channel electrode array on the lower abdomen toward lower subject's left side, approximately covering the sigmoid and descending colon. The 128-channel array was formed using two 64-channel (8×8) grids with 10 mm spacing (OTbioelettronica; Torina, Italy). We recorded signals for $\approx$90 min in the fasted state, and another 90 min in the fed state. The sampling rate was set to 100 Hz. Colonic signal analysis was based on the Continuous Wavelet Transform (CWT) [3]. Additionally, we quantified the acceleration magnitude as: $A = \sqrt{a_x^2 + a_y^2 + a_z^2}$.

III. RESULTS

A. Hardware Performance Benchmark

Data logging was accurate and robust; zero errors were observed during approximately 60 hours of hardware validation experiments. The device remains stable at sampling rates up to 2000 Hz, the highest sampling frequency tested. The total current draw was measured be $\approx$100 mA; the LiPo battery continuously powered the module for $\approx$ 30 hr before it needed to be recharged. Users reported the device was unobtrusive and comfortable to wear over the duration of a 3-4 hr study.

B. Proof of Concept GI recordings

The Intsy-128 device made high-quality recordings of bioelectric activity. Figure 2 illustrates representative results for the body surface colon mapping experiments from one test subject. We visually assessed the ECG waveform (digitally high-pass filtered, 1 Hz cutoff) with the QRS complex and T-wave clearly visible as a proxy indicator for good-quality, low impedance electrode-skin contact (Fig. 2a). The EColG time-domain signal (digitally band-pass filtered, 0.5-10 cpm) indicates a clear increase in colonic activity at a dominant frequency of 3.2 cylces per minute (cpm) in the fed vs. the fasted state (Fig. 2b). CWT spectral analysis shows the time-course of increased colonic activity following meal-ingestion (Fig. 2c). Note that the time-course of increased subject motion during eating (acceleration A low-pass filtered at 1 Hz, gray trace), does not explain a proportionally much larger rise in post-meal colonic activity (Fig. 2d). The time-course of increased post-meal colonic activity beginning about 12 min after eating and lasting for about 30 min is strongly concordant with the cyclic motor activity in the distal colon previously characterized [3], [10]. Fig. 2e shows the 128-channel electrode array placed on the lower abdominal surface below umbilicus (overhead view). The flex sensor is visible as finger-like projection on the left-side of the photo (subject's right). The overlaid black curves indicate the approximate location and orientation of a segment of the colon identified from body surface mapping localization. The body surface heat map computed from the power-percent difference in pre- vs. post-meal activity [3] localizes the active colonic regions to the infraumbilical region, toward the left iliac crest (Fig. 2f). The velocity field map (Fig. 2g) was derived using the surface Laplacian and phase-based analysis [11] indicates retrograde wave activity originating near the rectosigmoid region propagating at of 5.3 $\pm$ 2.0 mm/s (mean $\pm$ s.d.), in reasonable accord with findings from previous high-resolution manometry studies [10].

IV. DISCUSSION

A. Comparison to other modules

The new Intsy-128 device is a low cost, open-source, easy to assemble bioamplifier module well-suited for ambulatory bioelectrical signal acquisition and analysis. Table I compares Intsy-128 to similar and academically-sourced and open-sourced hardware. Intsy-128 offers the highest channel count and sampling frequency compared to other devices in its class. The on-board data logging capability and motion monitoring make it especially well-suited for ambulatory studies. The Intsy-128 may be an attractive option for budget-conscious labs, fostering new discovery and innovation throughout the scientific community.

	Intsy-128	Ref [12]	OpenBCI [13]
Number channels	128	64	16
Resolution (bits, μV/bit)	16, 0.195	10, 1.56	24, 0.006
Dynamic Range (mV)	$\pm$5	$\pm$3	$\pm$104
Analog filter	0.02 Hz-5kHz	0.016-1.6 Hz	no filter
Max Sampling Rate (kS/s)	256	64	16
Validation *in vivo*	Yes	No	Yes
Cost/channel (USD)	35	unknown	59

TABLE I

COMPARISON OF AMBULATORY-READY SYSTEMS.

B. Potential applications and future work

In the future, the size and cost of the Intsy-128 module could be optimized by combining all individual components on a single custom PCB using all surface mount assembly, as opposed to mounting relatively large submodules with through-hole soldering. The addition of WiFi capability would allow for higher bandwidth streaming, which is important for applications with much higher sampling frequencies (≥ 500 Hz), as are typical in the neural and cardiac fields.

V. CONCLUSIONS

We have developed a novel low-cost, open-source, 128-channel bioamplifier module, suitable for ambulatory studies. Results from $\approx$3 hr colonic meal response study conducted in a laboratory setting demonstrate its potential use in high-resolution mapping studies of GI electrical activity patterns. In the future, it can also be used for longer-term monitoring and diagnostic studies. The Intsy-128 bioamplifier module could also be used to study electrical activity patterns of the brain, heart, skeletal muscle, and uterus.

VI. ACKNOWLEDGMENT

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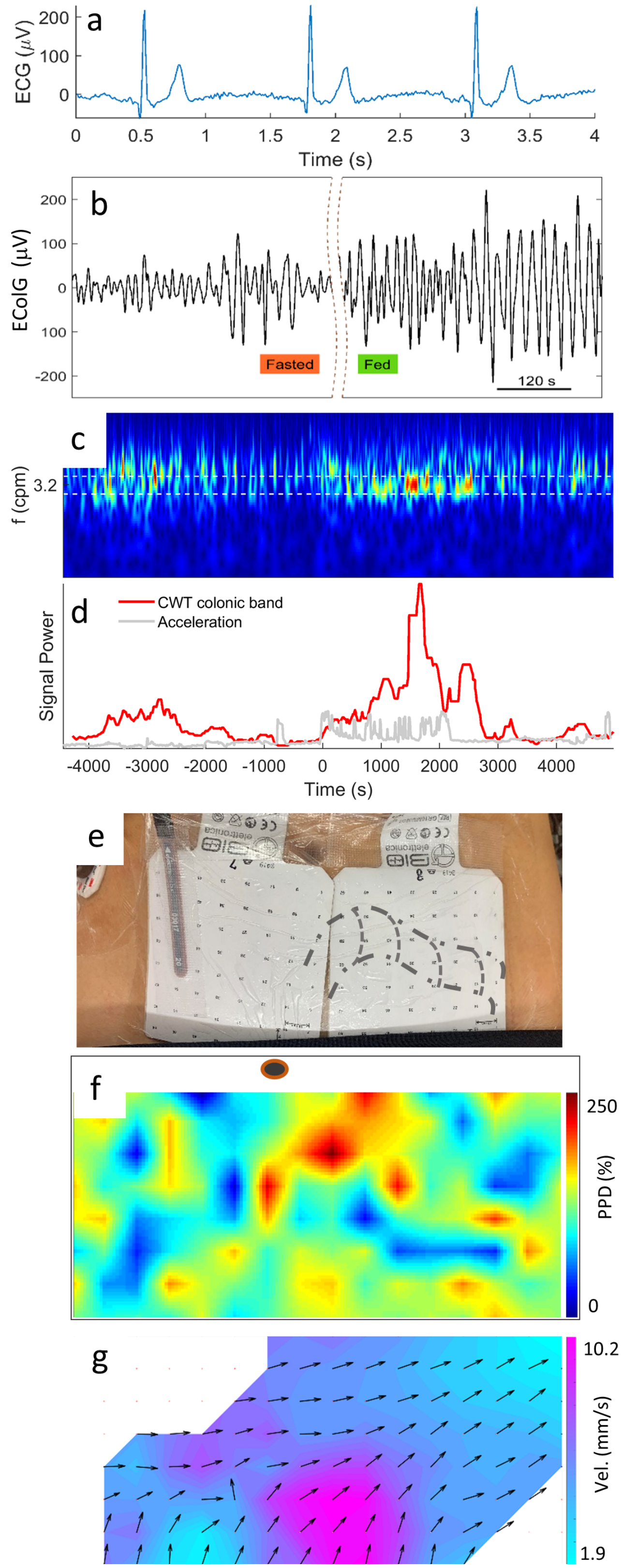

Fig. 2. EColG meal-response experiment representative results. **a**: ECG waveform. **b**: EColG signals in fasted and fed state; note the "broken" time axis. **c, d**: CWT analysis showing strong post-meal activity with a dominant frequency of 3.2 cpm; **e**: Photo of electrode array positioned on lower abdomen spanning subject's midline; **f**: Heat map localizing colonic post-meal activity. Brown circle denotes belly button position; **g**: Velocity field map indicating a retrograde motor pattern.