**Methods**

Patient recruited from a population referred for implantation of deep brain stimulators for Dystonia. Subject was evaluated by a movement disorders neurologist and met diagnostic criteria for PD1. Baseline motor function was evaluated using the Movement Disorders Society (MDS) Unified Parkinson’s Disease Rating Scale (UPDRS), parts I-IV. The motor subscale (UPDRS-III), was rated both “off” (12 hour after withdrawal of antiparkinsonian medication) and “on” (after a supratherapeutic dose of levodopa/carbidopa). Patients were evaluated by a neuropsychologist to exclude significant cognitive impairment or untreated mood disorder. Inclusion criteria were: Motor fluctuations with prominent rigidity and bradykinesia in the off medication state, baseline off medication UPDRS-III scores between 20 and 80, greater than 30% improvement in UPDRS-III on medication compared to off medication, and absence of significant cognitive impairment (score of 20 or above on Montreal Cognitive assessment). The study was approved by the hospital institutional review board (IRB) under a physician sponsored investigational device exemption (IDE), protocol # G180097. The study was registered at Clinical Trials.gov (NCT03582891). Patients provided written consent in accordance with the IRB and the Declaration of Helsinki.

*Surgery, device models and lead localization:*

Patient underwent bilateral placement of cylindrical quadripolar deep brain stimulator leads into the subthalamic nucleus (Medtronic model 3389, 1.5 mm contact length and 2.0 mm intercontact spacing), bilateral placement of paddle-type quadripolar cortical paddles into the subdural space to cover precentral gyrus (Medtronic model 0913025, 4 mm contact diameter and 10 mm intercontact spacing), and bilateral placement of investigational sensing implantable pulse generators (IPGs) in a pocket over the pectoralis muscle (Medtronic Summit RC+S model B35300R). The IPG and leads were connected by 60 cm lead extenders (Medtronic model 37087), two on each side (Figure #). STN leads were initialized as contacts 0 to 3 (0 is the deepest contact)(Figure 2a). Cortical leads were initialized as contacts 8 to 11 (8 is the most posterior contact)(Figure 2c).

The surgical technique for placement of permanent subdural paddle leads during DBS implantation surgery was previously described in detail. . Briefly, the paddle lead was placed in the subdural space through the same frontal burr hole used for the subthalamic lead. At least one contact covered the posterior precentral gyrus (presumed primary motor cortex), approximately 3 cm from the midline on the medial aspect of the hand knob. Adequate localization of the ECoG strip was confirmed using intraoperative CT computationally merged to the patient’s preoperative MRI3 (Stealth8 Cranial software, Medtronic Inc.) Functional localization of the ECoG strip was verified by reversal of the N20 somatosensory-evoked potential from median nerve stimulation (Figure #). The exiting wire from the cortical contact array was secured to the skull with a titanium miniplate.

The subthalamic lead was placed using frame-based stereotaxy and confirmed by microelectrode recording in the awake state using standard methods4 . Proper location in the motor territory of the STN was verified by eliciting movement-related single-cell discharge patterns. The DBS lead was placed with the middle two contacts in the dorsal (motor) STN, the most superior contact dorsal to the STN, and the most inferior contact in ventral STN (Figure 2a). The free ends of the cortical and subthalamic leads were coiled under the ipsilateral parietal scalp. The remaining hardware was placed under general anesthesia. The free ends of the cortical and subthalamic leads were connected to the lead extenders, which were tunneled down the neck to the IPG. Each IPG was connected to the ipsilateral cortical and STN leads. Medical adhesive was placed at the junction of the lead extenders and IPG to reduce contamination of neural signals by EKG artifacts. Two months postoperatively, locations of leads were again verified, by postoperative CT computationally merged to the patient’s preoperative MRI using Stealth8 Cranial software (Figure 2c)

*RC+S device characteristics and programming.*

The Summit RC+S is an investigational rechargeable bidirectional neural interface that offers the researcher a great degree of flexibility through access to the device’s application programming interface (API)5,6. It is a 16-channel device that can simultaneously stream four bipolar time domain channels (250/500Hz) or two channels at 1000Hz. It can simultaneously provide standard therapeutic stimulation on up to two quadripolar leads, and can also perform adaptive deep brain stimulation using algorithms programmed on the device (“embedded” mode) or algorithms on an external computer, through (which was not certified by peer review) is the author/funder. All rights reserved. In addition to voltage time series data, RC+S can stream up to 8 predefined “power channels” (spectral power within a predefined frequency band), event markers, stimulation parameters, embedded adaptive DBS performance parameters, and triaxial accelerometry from an embedded accelerometer.

For all research functions including configuring and initiating sensing, and embedded or distributed adaptive DBS, investigators control the device by writing software in C# within the device API, accessed using a “research development kit” (RDK, Medtronic model 4NR013) provided by the manufacturer. We wrote two graphical user interface (GUI)-based applications to configure and initiate streaming data from one or two RC+S devices simultaneously. One application is used by the research team and allows configuration of sensing parameters and streaming data in-clinic. The other application is “patient facing” and contains a simplified application that allows the patient to control streaming in a home environment and report symptoms or medications taken.

Applications rely on a dynamic linked library (DLL), supplied by Medtronic, Inc., that is specific for Microsoft Windows operating systems and Intel processor platform. The DLL provides the API to investigators and is not compatible with streaming data to mobile devices. Both applications are available at https://openmind-consortium.github.io. We wrote and documented software in compliance with FDA code of federal regulation CFR 820.30, which specifies design controls for implantable human devices. Figure 1 provides a schematic of the data streaming configuration.

*In-clinic data recording in defined on/off states.*

STN and cortical field potentials were sampled at 500 Hz in clinic three weeks postoperatively in both “on” and “off states (during which levodopa medication was withdrawn for at least 12 hours), and a movement disorders neurologist administered the UPDRS-III rating scale in both states. The three week time point was chosen to allow recovery from the “microlesion” effect of lead insertion7,8, but prior to initiating chronic therapeutic stimulation at 1 month after surgery. Recordings were done at rest, and during a binary choice iPad reaching task which has been previously described9 . Rest recordings were one to two minutes long, and iPad reaching task recordings were 3-5 minutes long

*At home data streaming paired with wearable monitors*

Patient initiated home recordings using the patient-facing GUI on a Microsoft Surface Go computer with broadband cellular service (weight 1.15 pounds, dimensions - 245.00 x 175.00 x 8.30mm (height, width thickness)). We provided this computer to each study subject along with training in its use. Streamed data contained no personal health information (PHI). Data were encrypted and uploaded to a secure cloud environment operated by UCSF. Patients were able to use the application to report medications taken and to rate their motor signs. The application automatically connects to the device when patients are in range (approximately 12 meters). Patients collected data in 1-2 week recording “sprints” in which they were instructed to carry the computer with them and stream continuously if possible

The summit RC+S system uses a user datagram protocol (UDP). Data are transmitted in discrete intervals or “packets” of variable duration averaging 50 ms. Occasional data packets are lost and these “dropped packets” must either be interpolated or discarded. This can also be partially mitigated by changing sampling rates and using a lower data streaming rate bitrate. Failure of packet transmission (“dropped packets”) occurred for 1-5% of packets, even when patients were in range of receiving devices. Data are time stamped using the pulse generator clock time. Data were recorded at 250Hz in at the patient’s home, lower than the in-clinic rate of 500 Hz. Four time domain channels were streamed using a bipolar recording configuration in which we verified adequate signal during a montage recording obtained one to two days postoperatively. Patients also streamed actigraphy at 64Hz from the embedded accelerometer, event related information and power channels. The Summit RC+S device has several configurable device filters that must be chosen. All filters are applied after digitization, and low pass filters are applied twice – before and after amplification. In the absence of therapeutic stimulation, we used a high pass filter of 0.85Hz and low pass filter of 450 Hz before amplification and 1700Hz after amplification.

*Maintaining continuity of data streaming*

Benchtop tests show that streaming of four time domain channels at 500Hz while providing therapeutic stimulation, can be done for approximately 30 hours before recharging the RC+S pulse generator. However, several factors may reduce the duration of continuous streaming. The CTM relay device (Figure #), as supplied by the manufacturer, is powered by two AAA batteries that only last for 4-5 hours during streaming. We therefore developed an external “battery pack” for the CTM that extends this range to 12 hours. Both RC+S pulse generators can be recharged simultaneously in 30 minutes. For most home streaming we used lower sampling rates (250Hz) than the device allows, in order to cap the bitrate at 4500 bits/second but allows for longer range and fewer dropped packets. Our patients wore a specialized vest with pockets for the CTM so that it remained in close proximity to the DBS device to avoid frequent packet drops.

*Therapeutic continuous stimulation and recording during stimulation.*

To implement standard DBS therapy, clinicians are provided with a tablet programmer (Medtronic model 4NR010) to allow setting parameters for standard continuous therapeutic stimulation, and a patient programmer (Medtronic model 4NR009) that allows the patient limited control over some parameters under limits set by the clinician. One month after implantation, study clinicians began programming the STN lead(s) to achieve the best clinical result. The cortical lead was never used for stimulation. Clinicians attempted programming using monopolar mode from one of the middle two contacts (contacts 1 or 2), as these montages are compatible with bipolar sensing in a “sandwiched configuration” around the stimulating contact. Sensing from STN leads programmed to stimulate in a bipolar mode or programmed with a stimulation montage that includes contacts 0 or 3, precludes STN sensing during stimulation because of excessive stimulation artifact. For some subjects, 80 hours of data were streamed at home during therapeutic stimulation, to document effects of stimulation on STN and cortical field potentials. Both on-device low pass filters were set at 100Hz for STN recordings during stimulation to limit stimulation artifacts). Sense blanking was set at 0.33ms.

Data extraction and management of lost data. Data streamed to the researcher or patient facing applications are assembled into JavaScript Object Notation (.JSON) format. This is a lightweight data-interchange text-based format that in RC+S merges meta-data and actual data across several different file types distributed. Data are polled from the device in configurable intervals (50 ms in our case) in first-in, first-out (FIFO) fashion. The IPG has a 16 bit clockdriven tick counter that rolls over every 6.553 seconds (least significant bit (LSB 100 microseconds)). This can be combined with an estimate of system time (LSB seconds) to accurately account for lost packets. We wrote Custom software in Matlab to extract the data from the .JSON format and discard packets that have corrupted data

*Data Processing*

All data processing was conducted using MATALB. Data was divided into 60 second contiguous chunks in which no packet loss occurred. We calculated power spectral density (PSD) using the Welch Method (pwelch, 250ms window, 125ms overlap). Data were averaged in the power domain between 1-60Hz (range selected to avoid frequency bands of physiological interest). Data were normalized by dividing each PSD by the average power between 3 and 90 Hz. In addition to the PSD, the magnitude squared coherence was also computed for the four possible contact pairs each recording montage (mscohere in Matlab, 250 ms window, 50% overlap, 250 discrete Fourier transform points).

*Statistical analysis*

All Statistical analysis was performed using MATLAB.