Wireless Dopamine Sensing Brain Implant: The Concept and First Results

Stefanus Wirdatmadja
Faculty of Medicine and Health Technology
Tampere University
Tampere, Finland
stefanus.wirdatmadja@tuni.fi

Nikta Pournoori
Faculty of Medicine and Health Technology
Tampere University
Tampere, Finland
nikta.pournoori@tuni.fi

Toni Björninen
Faculty of Information Technology and Communication Sciences
Tampere University
Tampere, Finland
toni.bjorninen@tuni.fi

Lauri Sydänheimo
Faculty of Medicine and Health Technology
Tampere University
Tampere, Finland
lauri.sydanheimo@tuni.fi

Merja Voutilainen
Faculty of Pharmacy
University of Helsinki
Helsinki, Finland
merja.h.voutilainen@helsinki.fi

Leena Ukkonen
Faculty of Medicine and Health Technology
Tampere University
Tampere, Finland
leena.ukkonen@tuni.fi

***Abstract*— In Parkinson’s disease (PD), dopamine neurons degenerate in the Substantia Nigra, and there is a reduction of dopamine in the caudate-putamen. The diagnosis of PD is principally clinical, although specific investigations (such as PET scans) can help the differential diagnosis from other forms of parkinsonism. A brain implant that enables continuous dopamine monitoring would be helpful for Parkinson’s disease patients. We address an RFID-based solution for data transmission and power transfer that facilitate the implementation of a fully implantable and batteryless brain implant. The wireless operation takes place on three frequency bands of 402, 902, and 2400 MHz for data telemetry, power transfer, and switching control, respectively.**

Keywords—Dopamine sensing, electrodes, brain implant, electrochemical detection, implantable antenna, PIFA, wireless communication link

I. INTRODUCTION

As the aging population increases, the people suffering from Parkinson's disease follow the same trend. The medical facilities and personnel should meet this increasing demand. One of the methods to measure dopamine level is by using high-performance liquid chromatography (HPLC) which is usually used for animals in the research laboratory. Therefore, it would be essential to develop a sensor measuring dopamine levels inside the brain, which could wirelessly send the information of dopamine levels. The other challenge for this implementation is miniaturizing the sensing equipment for dopamine monitoring [1]. Dopamine is a neurotransmitter in the brain that is responsible for the regulation of motivation and is produced by dopaminergic neurons located in the midbrain nuclei, particularly in the ventral tegmental area (VTA) and substantia nigra pars compacta (SNc). Dopamine plays a vital role in many neurological disorders. In Parkinson’s disease, dopamine neurons degenerate, whereas, in schizophrenia, there are alterations in dopamine regulation. Dopamine can be oxidized to dopamine-o-quinone by losing its two electrons; then, it can be reduced back to dopamine. This reaction is fundamental to electrochemical analysis that is useful for detecting not only dopamine but also other neurotransmitters. Cyclic voltammetry is one of the methods for this purpose but is available only for in vitro or animal studies. The dopamine concentration can be estimated by monitoring the peak redox current [2].

This paper presents the attained results of the electrochemical detection technique for sensing the dopamine level by employing three electrodes in the dopamine solution. Furthermore, we introduce a promising platform for wireless brain implants to establish a complete biomedical telemetry system with therapeutic actuation purposes for Parkinson’s disease and schizophrenia. Fig. 1 demonstrates the proposed platform for a biomedical telemetry system, including in-body and off-body units for dopamine monitoring. The implant consists of three main parts, i.e., sensing electrodes, signal/data processor, and wireless communication part. Sensing electrodes should contain great electrical and chemical properties to represent adequate detection sensitivity. To this end, carbon-based electrode, namely multilayer graphene (MLG), is an appropriate option. System on Chip (SoC) technology can be applied to process the signal for data management. A far-field wireless communication link in a biomedical telemetry system is an imperative implementation to transmit the physiological data to an exterior monitoring unit [3], [4]. To institute this communication link, a compact implantable antenna placed in the cerebrospinal fluid (CSF) and a radio frequency (RF) energy harvester will be integrated to power the sensing electrodes wirelessly.

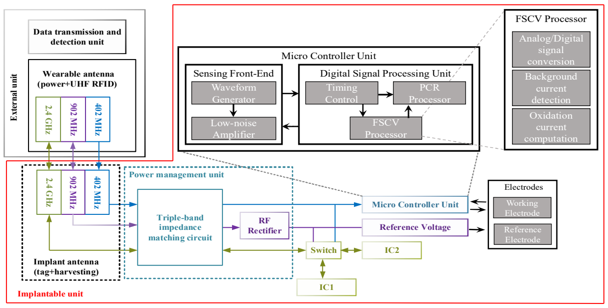

Fig. 1. The proposed platform of in-body and off-body units for wireless dopamine monitoring.

II. WIRELESS BRAIN IMPLANT FOR DOPAMINE DETECTION

A. *Electrochemical detection method*

The front-end element of the dopamine sensing implant is the electrodes. The raw data from these electrodes will be processed and sent to the reading equipment. To simulate this, we conducted a wet-lab experiment showing the data generated and transmitted. In this experiment, we utilized CompactStat from Ivium to measure 50 mM dopamine solution using the cyclic voltammetry method. We set a three-electrode configuration with this equipment, Pt as working

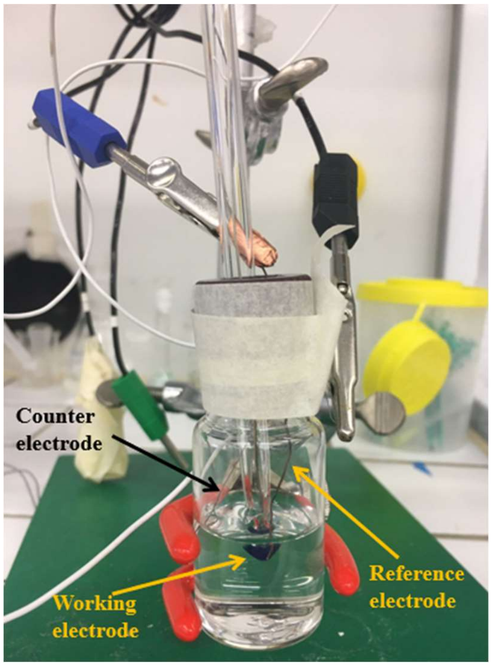

Fig. 2. Three-electrode configuration for cyclic voltammetry employing Pt as working and counter electrodes, and Ag/AgCl as reference electrode.

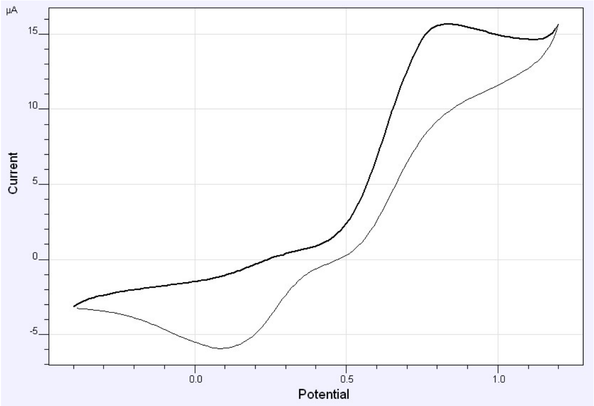

Fig.3. Voltammogram of 50 mM dopamine in 0.01 M HCl.

and counter electrodes and Ag/AgCl as reference electrode, as shown in Fig. 2. A triangular waveform is applied to the working electrode from −0.4 to 1.2 V with a scan rate of 0.1 V/s. The oxidation and reduction peaks can be observed from the voltammogram at 0.82 and 0.12 V, respectively, as represented in Fig. 3. Considering the oxidation and reduction peak voltage differences and their current values, this redox reaction is quasi-reversible since not all oxidized dopamine (into dopamine-o-quinone) is fully converted back to dopamine. However, at this point, the result shows a positive result for dopamine detection. The sensed voltage signal will be amplified with a low noise amplifier (LNA), converted by analog-to-digital conversion (ADC), and digitally processed.

B. Biomedical telemetry communication link

Achieving a continuous bio-telemetry communication link in real-time between the brain implant and an off-body monitoring device involves several challenges. The first challenge lies in designing a small and efficient implantable antenna [4]. The second challenge relates to developing an

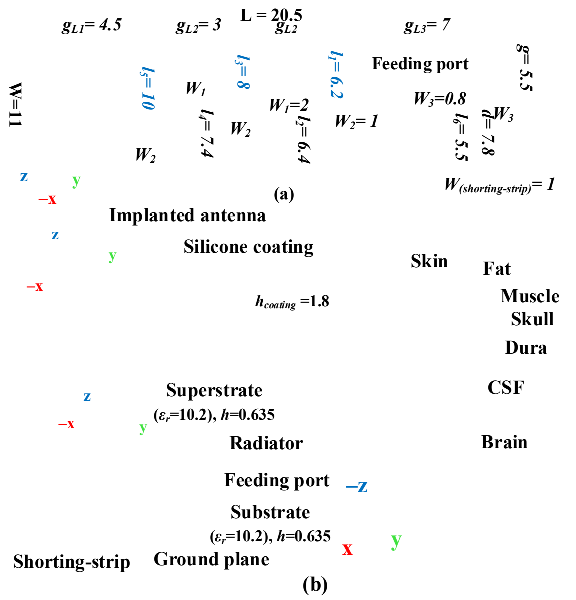

Fig. 4. The proposed triple-band meandered PIFA dimension, (b) The numerical 7-layer head model with embedded PIFA (the geometry parameters are given as millimeters) [7].

implantable RF energy harvesting circuit in combination with the proposed antenna that can approach adequate voltage and provide high power transfer efficiency to energize the sensing electrodes.

So far, we have addressed the first challenge by developing a miniature triple-band planar-inverted-F antenna (PIFA) with a size of 11× 20.5×1.8 mm^3, which fulfills the main requirements of the targeted bio-telemetry system [5]. Figure 4(a) shows the antenna. Indeed, the triple-band PIFA is proposed for data telemetry at the Medical Device Radiocommunication Service (MedRadio) band (402 MHz). Simultaneously, it intends to transfer power and control the sleep/wake-up modes at the Industrial, Scientific, and Medical (ISM) bands of 902 and 2400 MHz, respectively. The prototype PIFA implements a 0.6 mm radius pin into the radiating patch to connect to a 50 Ω coaxial cable to feed the antenna. The radiator links to the ground layer via a shorting strip in the vertical y-z coordinate plane. In the initial step, we estimated the overall size of the antenna operating at 902 MHz by applying the equation (1) [5]:

$$f = {}^{C_0}\!\Big/_{4\sqrt{\varepsilon_r}}\left(L + W + h - W_{shorting-stri}\right), \qquad (1)$$

where C_0 is the light speed in free space, ε_r denotes the relative permittivity of the substrate/superstrate, L and W depict the antenna's length and width, respectively, h is the thickness of the substrate/superstrate, and $W_{Shorting-strip}$ is the width of the shorting strip. According to the equation, employing the substrate/ superstrate with high permittivity properties materials (Rogers RO3210; ε_r =10.2, $tan\delta$=0.003, h = 0.635 mm) helps reduce the antenna's size. Furthermore, we covered the radiator utilizing a superstrate layer for insulating the PIFA from surrounding lossy head tissues. We enveloped the PIFA with a thin layer of silicone (MED-2000, Avantor Inc., U.S.; ε_r = 2.2, $tan\delta$= 0.007) to ensure the biocompatibility of the PIFA with the human tissues. Next, we employed different techniques, including adding slots and meandering the physical length of the radiator to shrink the entire antenna size. At the same time, it operates at the lower frequency of the 402 MHz. Lastly, inserting one more slot near the feeding port results in resonating the antenna at 2400 MHz [5]. We studied the developed PIFA numerically in a 7-layer head model using ANSYS High-Frequency Structure Simulator (HFSS), as demonstrated in Fig. 4(b), where the antenna was embedded at 13.25 mm depth in the cranial cavity. We assessed the prototyped PIFA characteristics in the head SAR liquid, where we achieved appropriate radiation performances to radiate in the outward direction of the human head. The measured antenna gain attained the state-of-the-art values of −43.6 dBi, −25.8 dBi, and −20.1 dBi at 402, 902, and 2400 MHz, respectively [5]. Advances upon our latest reported PIFA, we were able to optimize and characterize the prototyped antenna by studying the impact of the substrate and superstrate properties numerically on the antenna peak gain. In this sense, removing the superstrate layer and employing lower permittivity material for substrate improve 2 dB and up to 4.4 dB at MedRadio and ISM bands, respectively [6]. As a further improvement, we also investigated the four possible types of matching circuits to obtain the optimal reflection coefficient at our desired frequency bands based on the reflection coefficient value of $|S_{11}|^2 < -10$ dB. Our results demonstrated that using a T-type matching circuit offers suitable fine-tuning impedance matching and ensures a reliable wireless communication link for brain implants [7].

To fulfill our approach, we require to develop a power management unit comprising an RF energy harvester that provides proper impedance matching with the proposed PIFA and maximizes the incident RF power at 902 MHz for energizing the sensing electrodes implanted at the deep depth of the striatum. Intending the real application scenario, developing a data managing unit is necessary for transferring the dopamine concentration level to an off-body reader at the 402 MHz resonant frequency of PIFA. Continuous real-time data telemetry generates a large amount of data that may require access and analysis both manually and algorithmically. In this regard, designing a data unit faces several challenges: obtaining high-resolution data, adequate sampling rate, sufficient storage, proper retrieval, and easily reviewing the recorded signals. At the same time, low power consumption and small size are the top design challenges. Moreover, it is noteworthy that the third operating frequency (2400 MHz) of PIFA has been introduced for switching control between two statuses of wake-up and sleep through RFID tag IC to maintain the implant's power and extend the lifetime of the brain implant. We aim to develop the data management unit and power management circuit to introduce a batteryless brain implant in a biotelemetry system in future work.

ACKNOWLEDGMENT

This research was funded by the Doctoral Programme in the Faculty of Medicine and Health Technology of Tampere University and supported by The Finnish Foundation for Technology Promotion (TES), Nokia Foundation, and Finnish Cultural Foundation.

The authors would thank the Chemistry and Advanced Material (CAM) research laboratory, Faculty of Engineering and Natural Sciences, Tampere University for guidance and supporting the voltammetry experiment.

REFERENCES

[1] H. N. Schwerdt, H. Shimazu, K. I. Amemori, S. Amemori, P. L. Tierney, D. J. Gibson, S. Hong, T. Yoshida, R. Langer, M. J. Cima, and A. M. Graybiel, "Long-Term Dopamine Neurochemical Monitoring in Primates, " Proceedings of the National Academy of Sciences, Vol. 114, no. 50, 2017, pp. 13260-13265.

[2] S. Schindler, and T. Bechtold, "Mechanistic Insights into The Electrochemical Oxidation Of Dopamine by Cyclic Voltammetry, " Journal of Electroanalytical Chemistry, vol. 836, 2019, pp.94-101.

[3] Y. Rahmat-Samii and E. Topsakal, Eds., Antenna and Sensor Technologies in Modern Medical Applications, Wiley and IEEE-Press, 2021.

[4] A. Kiourti et al., "Next-Generation Healthcare: Enabling Technologies for Emerging Bioelectromagnetics Applications," in IEEE Open Journal of Antennas and Propagation, vol. 3, 2022, pp. 363-390.

[5] N. Pournoori, L. Sydänheimo, Y. Rahmat-Samii, L. Ukkonen, and T. Björninen, "Small Triple-Band Meandered PIFA for Brain-Implantable Biotelemetric Systems: Development and Testing in a Liquid Phantom," International Journal of Antennas and Propagation, vol. 2021, Article ID 6035169, 13 pages, 2021.

[6] N. Pournoori, L. Sydänheimo, L. Ukkonen, T. Björninen, and Y. Rahmat-Samii, "Small Triple-Band Meandered PIFA for Brain-Implantable Bio-telemetric Systems: Optimization of Substrate/Superstrate Effectiveness," 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI), 2021, pp. 1049-1050.

[7] N. Pournoori, L. Sydänheimo, Y. Rahmat-Samii, L. Ukkonen, and T. Bjöminen, "Fine-Tuning Impedance Matching Circuit for a Triple-Band Meandered PIFA in Brain-Implantable Bio-telemetric Systems," 2022 16th European Conference on Antennas and Propagation (EuCAP), 2022, pp. 1-5.