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WIMAGINE®: 64-channel ECoG recording implant for human applications

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Abstract— **A wireless 64-channel ElectroCorticoGram (ECoG) recording implant named WIMAGINE® has been designed for clinical applications. This active implantable medical device is able to record ECoG on 64 electrodes with selectable gain and sampling frequency, with less than 0.7µV_{RMS} input referred noise in the [0.5Hz – 300Hz] band. It is powered remotely through an inductive link at 13.56MHz, communicates wirelessly on the MICS band at 402-405MHz with a custom designed base station connected to a PC and complies with the regulations applicable to class III AIMD. The design of the housing and the antenna have been optimized to ease the surgery and to take into account all the requirements of a clinical trial in particular patient safety and comfort.**
The main features of this WIMAGINE® implantable device and its architecture will be presented, as well as its performances and *in vivo* validations.

I. Introduction

The recording of neural signals can address many medical applications, such as monitoring applications of brain activity (e.g. epilepsy), or applications based on Brain-Computer Interface (BCI) technology, like neuroprosthesis, that restore neurological functions to disabled subjects or that improve the rehabilitation of stroke patients.
Neuronal activity can be recorded using scalp electrodes[1], cortical (epidural or subdural) electrodes[2], and intraparenchymal microelectrode arrays[3]. EEG (ElectroEncephaloGram) recording is comparatively safe and inexpensive, but the signal quality is not sufficient for some of the applications addressed due to poor spatial resolution and temporal resolution. Microelectrodes are exquisitely sensitive tools to record spikes and local field potentials, avoiding low signal to noise ratios encountered in EEG. They are however highly invasive, with unsolved problems with long-term robustness of the recorded signals. Fully implantable devices based on microelectrode array are under development [4]. The choice of cortical grids to record ElectroCorticoGrams (ECoG) is a good compromise since it provides significantly better signal quality (better spatial and temporal resolution and better signal to noise ratio) than EEG and presents fewer side effects than microelectrodes. Again, fully implantable device are under development [5].
It is important to notice that most of the studies using implanted devices have been limited to short-term experiments in patients temporarily implanted with electrode arrays prior to epilepsy surgery [2] and only a few use interfaces dedicated to the sole purpose of BCI. This is of course related to the technical challenges intrinsic to long-term active implantable medical devices (AIMD)
To address this challenge, CEA/LETI/CLINATEC® is currently conducting a project to develop a long-term implantable medical device for real-time recording and wireless transmission of the ECoG signals from each of 64 electrodes available to an external computer housing the control software.

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II. The WIMAGINE® Implant Architecture

The WIMAGINE® (Wireless Implantable Multi-channel Acquisition system for Generic Interface with NEurons) implantable device was developed for recording ECoG signals on 64 electrodes for long-term human implantation. The raw ECoG recorded data are streamed to the PC over a proprietary UHF link in the Medical Implant Communication Service (MICS) band using a custom protocol. The data analysis and feature extraction is achieved on the PC in order to provide maximum flexibility. The system is powered entirely remotely through an inductive link able to provide up to 100mW by the means of an external antenna and field generator.
This implant is composed of an array of 64 biocompatible electrodes which will be in contact with the dura mater, a hermetic titanium housing including the electronic board and biocompatible antennae (fig. 1A).
The design of the WIMAGINE® implant takes into account all the constraints of an implantable medical device: ultra-low power, miniaturization, safety and reliability. In particular, the regulatory requirements applicable to class III AIMDs have been addressed (i.e. European Council Directive 90/385/EEC and European standard EN 45502-2-1).

A. Packaging

For long term application and hermeticity requirements, the electronic board is put inside a hermetic housing.
Thus a dedicated titanium packaging was designed with dedicated hermetic feedthroughs (fig. 1B). The latter are

based on a ruby insulator and the hermeticity is achieved by gold brazing. These parts are all individually tested in terms of helium leakage. Once the electronic PCBs are placed into the titanium housing by the means of plastic fixing parts, the two titanium parts and the feedthroughs are laser welded together. The leakage of each assembly is the tested again and the maximum leakage level is below 3.10^{-9} bar.cm^3.s^{-1} (EN 60608-2-17 compliant).

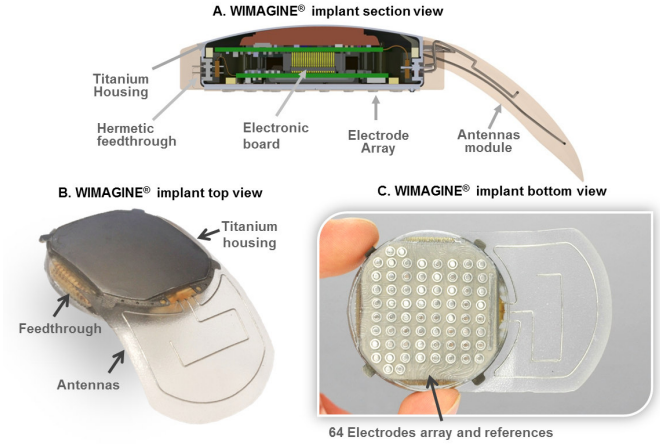

Figure 1: WIMAGINE® implant packaging

The design of the device facilitates the surgical procedures and ensures the patient safety. The implant is a monolithic system including the set of antennas in a medical grade silicone cap and an electrode array under the bottom titanium part. The electrode array (fig. 1C) is composed of 64 recording electrodes and 3 reference electrodes. The electrodes are made of Platinum-Iridium alloy (Pt90Ir10), and the active part is a 2mm disk, 0.15mm below the medical grade silicone sheet.

Hence, to place the electrode array on the dura-mater, a circular craniotomy (50mm) is made by the surgeon (fig. 2) and the bone is replaced by the implant.

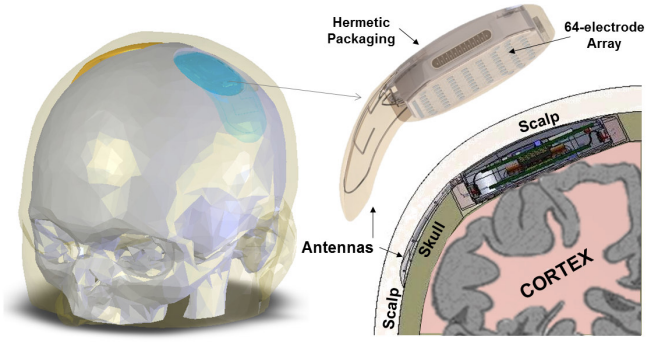

Figure 2: schematic representation - WIMAGINE® brain implantation site

B. *Electronic architecture*

The electronic architecture of the implant was designed to be modular and evolutive [6]. For this first version, we decided not to embed all the functionalities required for an ECoG recording implant into an application specific circuit (ASIC) but rather to use as much of the shelf components as possible. Moreover, we decided to separate functionalities as much as possible in order to build future generations with as little redesign as possible. The architecture of the WIMAGINE® implant as described in fig. 3.

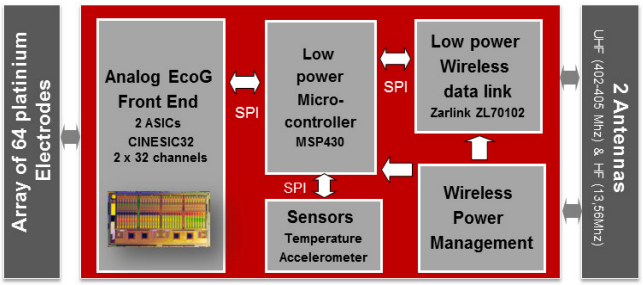

Figure 3: WIMAGINE® functional architecture

The electronic requirements for an ECoG recording implant are closely related to the targeted ECoG signal characteristics: in our case the targeted signal have a [0.5hz-300Hz] bandwidth and a [5µV – 3mV] amplitude, recorded through a platinum electrode array (Fig. 1c). In order to expand the range of possible applications (Epilepsy recording, BCI recording, …) no signal processing functionality was embedded into the designed implant, but the raw recorded signals are transmitted in real time to a computer where the analysis or recording is performed.

Embedding a high throughput communication function into an implantable electronic architecture hugely constrains the power budget for the remaining functionalities. As an ultra-low power component for recording low amplitude, low noise signals was not available commercially, it was decided to design an application specific circuit for ECoG recording. This ASIC, the CINESIC32 is able to amplify and digitize 32 channels with an input referred noise of less than $0.7\mu V_{RMS}$ in the [0.5Hz–300Hz] range [7]. Two CINESIC32 ASICs were implemented on the WIMAGINE® board in order to perform an ECoG signal amplification and analog to digital conversion on 64 channels.

The implant is powered entirely remotely through an inductive link at 13.56MHz which can provide up to 100mW. In order to respect the modular architecture and simplify the developments of future generations where a battery may be embedded, we decided to use a separate link for the communication between the implant and the PC. A UHF communication based on the MicroSemi ZL70102 was chosen as it offers the best throughput/power consumption ratio and a custom high level communication protocol was implemented in order to maximize throughput (400-450kps) and data reliability.

In order to manage the two CINESIC32 ASICs, the sensors, the UHF communication link and the inductive power supply, the MSP430F2618 was chosen. The embedded firmware running on this low power microcontroller maximizes the use of the low power modes of the MSP430, thus reducing power consumption, is remotely upgradable and has been designed in compliance with IEC 62304. The general characteristics of the WIMAGINE® Implant are listed in the Table 1.

TABLE 1: GENERAL CHARACTERISTICS OF THE WIMAGINE® IMPLANT

Analog Front-end : 2 ASIC CINESIC32	
Number of channels	64 (selectable)
Variable gain	1, 5, 280, 990 or 1370 (adjustable for each electrode)
Detection range	+/- 1.3mV (gain 990)
Bandwidth	0.25Hz to 300Hz (32nd order)
Resolution	12 bits - ADC architecture : SAR
Input referred noise	0.7µV RMS (in gain 990 and on BW [0.5Hz;300Hz])
Sampling frequencies	390Hz, 585Hz, 976Hz, 2.9kHz per channel (selectable)
Microcontroller and sensors	
Microcontroller	MSP430F2618-EP (Texas Instrument)
Embedded sensors	Accelerometer, temperature, consumption, supply voltage
Firmware	Reprogrammable remotely, compliant with IEC62304
UHF link	
Component	Transceiver MicroSemi ZL70102 (Zarlink)
Frequency	402-405 MHz (10 MICS channels)
Rate & Range	450 kbps over 2m with custom Pt antenna
HF Inductive wireless power management	
Frequency	13,56MHz
Transmitted power	Adjustable, up to 100 mW (30mA @ 3.3V)
WIMAGINE® Implant	
Respected regulations	Class III AIMDs regulatory : EN 45502-2-1
Power requirements	25mA / 3,3V (on typical use: 32 channels sampling at 1kHz wirelessly transmitted)

As shown in Fig. 4 the WIMAGINE board is made up of two PCBs (diameter ~40mm) linked by a board to board connector. Both ASICs CINESIC32 and their external components are placed on one side of the PCB (at the bottom) while the other PCB (at the top) contains the MSP430 microcontroller, the wireless power module and the RF link components.

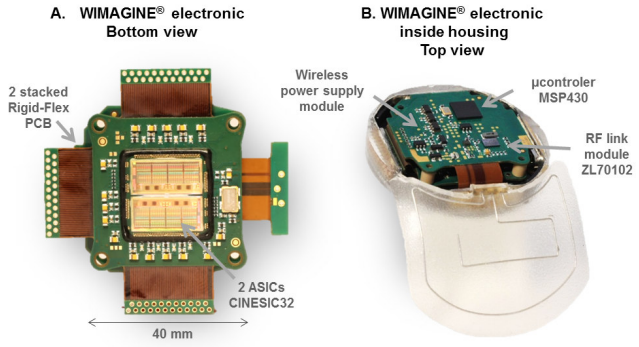

Figure 4: Photographs of the WIMAGINE board

C. *Antennas*

The antenna module is placed outside the titanium housing. Two antennas are designed for the two separate links, one for UHF communication and the other for the inductive power supply

The HF antenna, allowing the inductive power supply, with an area of 10 cm² is made of a platinum wire. This antenna is designed to provide 30mA at 3.3V and is associated to an RF front-end, embedded on the electronic board, comprising a rectifying stage, a shunt regulator and ultra-low noise LDOs (low-dropout linear regulator). The HF implant antenna and the HF generator antenna were dimensioned together by optimizing the transmitted power for a nominal distance of 2cm between both antennas.

The UHF antenna was also designed using a platinum wire encapsulated in a medical grade silicone rubber. The UHF antenna is connected to the electronic board through a matching network and a SAW filter which was employed to prevent interference from strong out-of-band RF signals. Throughput tests have been performed by means of an experimental set-up based on the WIMAGINE® board and the antenna in a human phantom. An effective data throughput between 400 kbps and 450 kbps was measured over several hours, by employing 4-FSK modulation at few meters distance between the implant and the external device. These tests confirmed the feasibility of transmitting 32 channels with a 12-bit resolution sampled at 1 kHz per channel.

These two HF and UHF antennas are inserted one in the other, in order to optimize the surface of the external implant antenna module, and are designed and optimized to perform simultaneously.

D. *The WIMAGINE® platform*

The WIMAGINE platform is made up of two WIMAGINE® implants, a base station and a PC application (fig. 5). The base station has been designed to act as a gateway between the PC application and up to two implantable devices. It provides the inductive link for powering each implant, the means for establishing a communication with each implant in the MICS band and can be connected to a PC through Ethernet or USB. It also includes isolated analog and digital inputs and outputs that can be used for instance for synchronous BCI protocols.

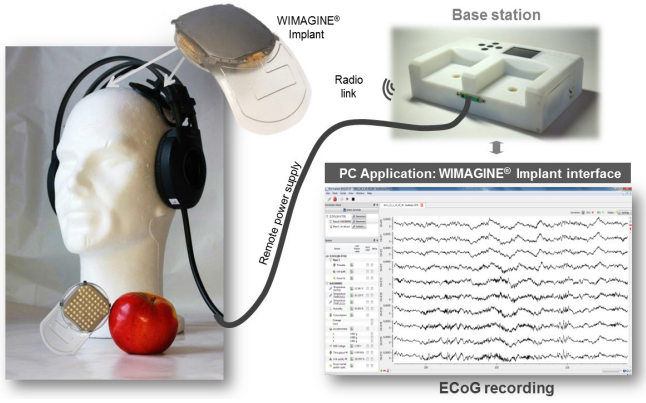

Figure 5: WIMAGINE® ECoG Recording Platform

A PC application has been designed for interfacing the implants and the base station through the high level communication protocol. It controls the power supply of each implant, relays the configuration commands from the user, reads the different sensor values and displays the acquired ECoG signals according to the users' request. Most importantly, it is able to record the ECoG signals in a standard SMR format and can stream the signals in real time through a "Fieldtrip" protocol [8].

III. THE WIMAGINE® IMPLANT EVALUATIONS

A. Long term biocompatibility evaluation

Local tolerance was studied on two non-human primates thanks to a 1:2 scale device made with the same materials than the final WIMAGINE® implant. Histological assessments were carried out post-mortem, 13 and 26 weeks after implantation, for all two animals. In these two cases we found: absence of device encapsulation, no detection of reactive astrocytes, an intact glial limiting membrane, no signs of microglial activation and absence of degenerating neurons. Moreover, the dura mater was not modified under the 1:2 scale implants, and the implants were freely removed from the dura mater at the end of the protocol.

B. In vivo recording evaluation

In order to validate the functionalities of the WIMAGINE® platform, we performed *in vivo* validation tests. The goal was to record the ECoG of a non-human primate implanted with a silicone-platinum cortical electrode array. Ethical approval for this experimental procedure was obtained from ComEth in accordance with the European Communities Council Directive of 1986 (86/609/EEC) for care of laboratory animals.

The WIMAGINE® implant is too large to be implanted on a non-human primate cortex. So the WIMAGINE® implant (thanks to a specific test bench) and also SD64 system from Micromed have both been connected successively to an ECoG electrode array through a transcutaneous connector. The ECoG signals were recorded during diffuse light stimulation and the recorded signals were synchronized with the light trigger. The epochs corresponding to 250 stimuli were filtered (band pass [1Hz–30Hz]), baseline corrected and averaged. The results displayed no response in the motor cortex and the visual cortex exhibited the characteristic shape of visual evoked potentials (VEPs). The signals recorded with the Micromed setup exhibit the same latencies and amplitudes with a typical component at 90ms and a second one with inverse polarity at 120ms (see fig.6) and are consistent with the shape and amplitude expected for VEP in non-human primates [9].

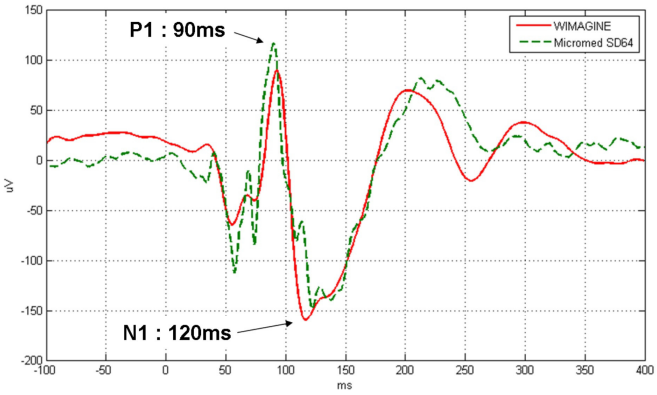

Figure 6 : VEP recording on the same electrode with Micromed SD64 (F_s = 1024Hz) and WIMAGINE (F_s = 976Hz)

C. Heating evaluation

This risk of heating tissue is still under assessment. Moreover, we worked on the reduction of hot point at the titanium implant surface, thanks to a stack of gap pad and gap filler coupled by a copper sheet. First results were obtained with the implant immerged in water and powered by the inductive link. The implant is equipped with thermocouples on its titanium surface, on the case and on the PCB close to the hot point. The temperature is made homogeneous on the titanium surface (dispersion: 0.35°C) and transferred to the skin which is considered less sensitive than the brain. The next step is to take into account the biothermal effects through a Finite Element Simulation.

IV. CONCLUSION

A long term wireless 64-channel ECoG recording implant has been designed for clinical applications. The design of the WIMAGINE® Implant takes into account the constraints of an implantable active medical device (AIMD): ultra-low power, miniaturization, safety, reliability and regulation compliance (EN 45502-2-1). Evaluations of the WIMAGINE® implant design were successfully performed, such as biocompatibility evaluation and in vivo recording evaluation. The next steps are the manufacturing according to qualified industrial processes under certification ISO 13485, and the qualification of the implant according to standards.

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