This is the author's version of an article that has been published in this conference. Changes were made to this version by the publisher prior to publication. The final version is available at http://dx.doi.org/10.1109/ICCDCS.2017.7959710

Design and Validation of a Portable Radio-Frequency Diathermy Prototype

Antonio Corres-Matamoros, Esteban Martínez-Guerrero, and José E. Rayas-Sánchez, *Senior Member, IEEE*

***Abstract*— In this work we present the design of a portable radio-frequency diathermy (RFD) prototype and its initial medical validation. The electronic circuit consists of a voltage-controlled oscillator, a low-frequency oscillator and a voltage amplifier powered by a rechargeable battery. Circuit was designed to develop a pulsed output of 120 V at a frequency ranging from 500 KHz to 1 MHz. The RFD circuit was implemented with commercially available components and assembled on a printed circuit board (PCB). The complete product, including flexible electrodes, was assembled on a 6 cm x 9 cm x 3 cm cabinet. Experimental results show that the output can reach a pulsed voltage of 84 Vpp and a current of 120 mA during 8 hours of continuous operation, which fulfills the autonomy requirement of portable devices for low power RFD applications. A comparative study according to physical rehabilitation protocol was carried out on a universe of 20 patients with lumbago disease with continuous RFD treatment using our prototype versus a traditional RFD treatment. Preliminary results show that muscle healing was more effective in patients with continuous RFD treatment, validating this prototype for therapeutic applications.**

Index Terms— low-frequency oscillator, voltage-controlled oscillator, inductive-load voltage amplifier, radio-frequency diathermy, RFD, characterization, prototype, product design.

I. Introduction

HEAT has been used for many years for healing injured muscle tissue. Although there are many techniques in which heat can be applied to patient's tissues, the two most recognized are ultrasound and diathermy. Diathermy uses alternating currents that oscillate at frequencies in the nonionizing RF band of the spectrum, heating localized regions of the body at depths of about 3 cm, without overheating the overlying structures of skin and subcutaneous tissues [1], [2]. The heating results from both ionic conduction and vibration of the dipole molecules of water and proteins of tissue [3].

For treating some muscle illness, such as reducing pain and inflammation, decreasing joint stiffness, relieving muscle spasms by increased local blood flow, and treating other rheumatic diseases, diathermy devices operate at frequencies in the range of 100 KHz – 4 MHz [4], [5].

A. Corres-Matamoros is with Cormat Inc., Zapopan, 45079 Mexico (e-mail: antoniocorres@cormat.mx). E. Martínez-Guerrero (e-mail: margres@iteso.mx) and J. E. Rayas-Sánchez (e-mail: erayas@iteso.mx) are with the Department of Electronics, Systems, and Informatics, ITESO – The Jesuit University of Guadalajara, Tlaquepaque, Jalisco, 45604 Mexico.

A. Corres-Matamoros is funded through a CONACYT scholarship (*Consejo Nacional de Ciencia y Tecnología*, Mexican Government).

RFD devices are typically bulky and require AC power supply. When an RFD treatment is prescribed, generally patients must go to the specialist's office for therapy and progress evaluation. Typical RFD treatments include the application to the patient of a high frequency signal for about 20 minutes in weekly sessions during at least one month, yielding long time treatments. The aim of this work is to contribute to the improvement of RFD treatments by means of a low-cost portable RFD prototype for continuous-mode RFD application. We describe in general terms the design of a small-size and portable RFD prototype to generate a voltage of amplitude in the range of 50 V to 120 V and frequency sweep in the range of 500 kHz to 1 MHz, with the capability to repeat this sweep every second. As an initial validation of this prototype, a study using a physical rehabilitation protocol was performed on a universe of 20 patients with lumbago disease. Preliminary results show that the healing of the muscle with continuous mode RFD treatment was more effective and the time to relieve pain was drastically reduced.

II. Design of a Portable Radio-Frequency (RFD) Prototype

Here we describe in general terms[1] the design of the proposed RFD prototype. Its block diagram is presented in Fig. 1. The low-frequency oscillator (LFO) and the voltage-controlled oscillator (VCO) blocks are implemented with an 8-bit PIC10F200-I/P microcontroller from Microchip Co. This component operates at a frequency of 4 MHz. The internal timer of this microcontroller is used to generate the time references needed to produce a signal with an amplitude in the range from 0 to 5 V and a frequency sweep from 500 kHz to 1 MHz. A subroutine in assembly-language with a variable delay is used to change every cycle the value of an output pin in the microcontroller (see code in Fig. 2). This variable delay is increased every 65 ms until the minimum output frequency is reached. A reset in the value of the variable delay is used to generate the maximum output frequency (see Fig. 2). Fig. 3 shows an example of output signal generated by the microcontroller at 947 kHz.

The voltage amplifier block in Fig. 1 is designed to get a pulsed voltage output between 50 and 120 Vpp. A simple common-source configuration was chosen exploiting its high voltage gain and power management. The voltage amplifier was designed for a voltage gain of 24 V/V using an nMOS

[1] A patent registration of this prototype is in progress (international application number PCT/MX/000030; date: 13/03/2017)

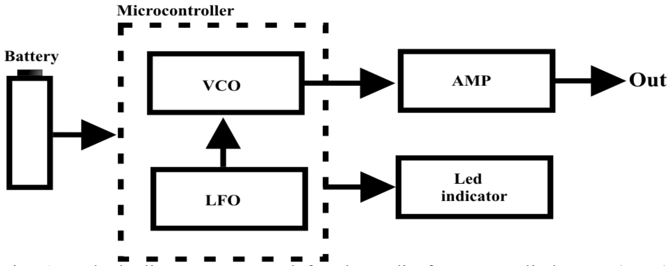

Fig. 1. Block diagram proposed for the radio-frequency diathermy (RFD) prototype.

```
MAIN                    MOVLW  0X7F
                        MOVWF  FMIN
      CHECK      MOVF          FMIN
                        MOVWF  TIM
                        BTFSC  GPIO,0
                        GOTO   OFF
      ON                BSF           GPIO,0        ;ON TIME
                        DECFSZ TIM,1
                        GOTO          ON
                        GOTO          CHECK
      OFF               BCF           GPIO,0        ;OFF TIME
                        DECFSZ TIM,1
                        GOTO          OFF
                        DECFSZ FMIN,1
                        GOTO          CHECK
                        GOTO   MAIN
END
```

Fig. 2. Assembler code for frequency sweep of the signal.

transistor with a passive inductor load.

The load inductance value was calculated in terms of the amplitude of the required output voltage and the characteristics of the square waveform provided by the microcontroller,

$$V_{out} = L\frac{di}{dt} \quad (1)$$

where V_{out} is the amplitude of output voltage and di/dt is the instantaneous current rate of change through the inductor on the rising edge of the input signal. We use (1) to obtain an inductance $L = 1$ mH. A commercial inductor of 1 mH capable to work with an $I_{max} = 150$ mA [6] was chosen as passive load for the voltage amplifier implementation.

The nMOS transistor was selected in terms of the required transconductance g_m and drain current I_D. g_m was derived from the voltage gain relationship of a common-source amplifier without source-resistance degeneration,

$$A_v = -g_m R_{out} \quad (2)$$

where R_{out} is the parallel combination of Z_L and r_{ds}, being Z_L the inductor impedance and r_{ds} the MOSFET drain-source resistance. From (2), we obtain a g_m in the range of 3.82 – 5.46 mA/V. Then, considering the relationship

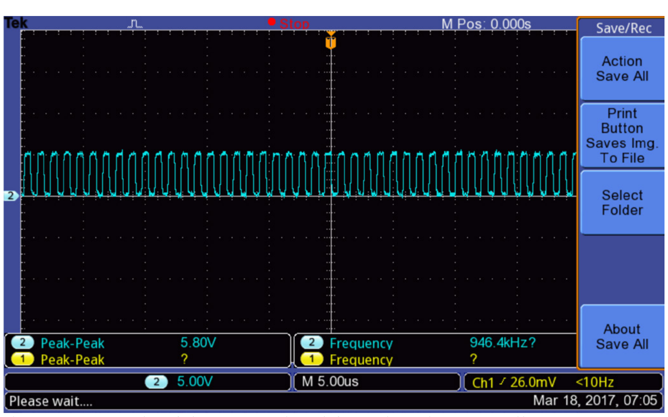

Fig. 3. Example of the output signal from the microcontroller.

$$g_m = 2\frac{I_D}{V_{eff}} \quad (3)$$

where $V_{eff} = V_{GS} - V_{Th}$ is the transistor overdrive voltage, we find the required minimum I_D of 5.73 mA. Thus, to ensure proper operation, we select a power MOSFET with much larger I_D than the previously calculated. A commercial MOSFET with such features is the IRF640, that has a $V_{Th} = 2$ V and can manage an $I_{Dmax} = 11$ A [7]. Additionally, we have added a red LED as a luminous indicator of on/off state of the equipment.

The total current consumption of the entire circuit I_{bat} was experimentally verified on several patients under RFD treatment, finding an average value of $I_{bat} = 23$ mA (see Fig. 4). In order to fulfill the portability requirements, we use a rechargeable battery as power supply. This battery was chosen in terms of its operation time T_o (or battery life), given by

$$T_o = 0.7\frac{C_{bat}}{I_{bat}} \quad (4)$$

where C_{bat} is the battery charge capacity. Considering at least 48 hours of continuous operation and a total current consumption $I_{bat} = 23$ mA, from (4) a $C_{bat} = 1{,}577$ mAh is needed. We selected a commercial battery with $C_{bat} = 2{,}000$ mAh and an output voltage of 5 V_{DC} [8].

Electronic components were assembled on a printed circuit board (PCB). The PCB was designed to achieve as much as possible circuit miniaturization considering the size of all circuit components and connectors. The PCB layout was generated with Eagle v7 CAD tool. Fig. 5 shows the assembled RFD prototype, in which we can observe a very small-size circuitry. Finally, Fig. 6 shows the plastic cabinet in

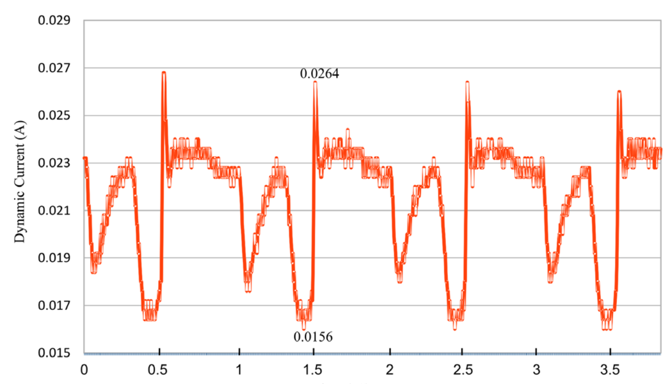

Fig. 4. Instant current consumption of the radio-frequency diathermy (RFD) prototype measured during treatment of several patients.

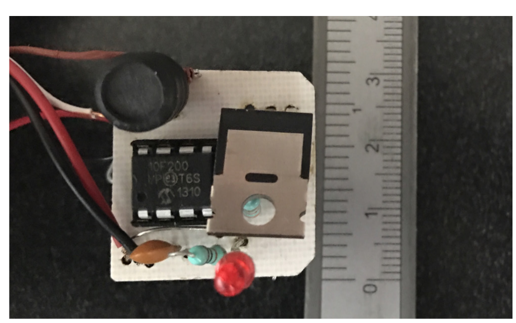

Fig. 5. Radio-frequency diathermy (RFD) circuit assembled on a PCB.

Fig. 6. Assembled RFD prototype.

which the RFD system described above is contained. Flexible electrodes fabricated in copper-zinc alloy brass were added to the prototype to facilitate the applications of RFD signal to patients.

III. Experimental Validation and Discussion

The electrical signals generated by the prototype were measured with a Tektronix TBS 1102B oscilloscope. In Fig. 7 we observe a pulsed voltage signal at 679 KHz and 84 Vpp amplitude, which is in the expected range. The prototype was kept turned-on during 8 hours and showed insignificant battery discharge, evidencing the apparatus autonomy in continuous work modality.

Next the prototype was tested with a universe of 20 patients with recent lumbago (lower back pain) illness, following the physical rehabilitation protocol. Firstly, a clinical history was recorded up for each patient (information included: name, age, weight, height, number of children, occupation, marital status, hereditary medical history, and personal medical history).

Secondly, patients were divided into two groups of similar pairs, for example, two patients with obesity, two elderly patients, or two female patients, etc. (see details in Table I). A group of 10 patients received conventional electrotherapy treatment (Group A), while the other 10 patients group received conventional electrotherapy plus continuous RFD treatment at home using the proposed prototype (Group B). The conventional electrotherapy treatment consisted of the application of 1 MHz of ultrasound at an intensity of 2.4 W/cm^2 during 10 minutes, followed by 10 minutes of electro-stimulation with a pulsed electrical current at an intensity of 40 mA. This treatment was applied with a commercial electrotherapy device of Cormat Co. [5], two times per week.

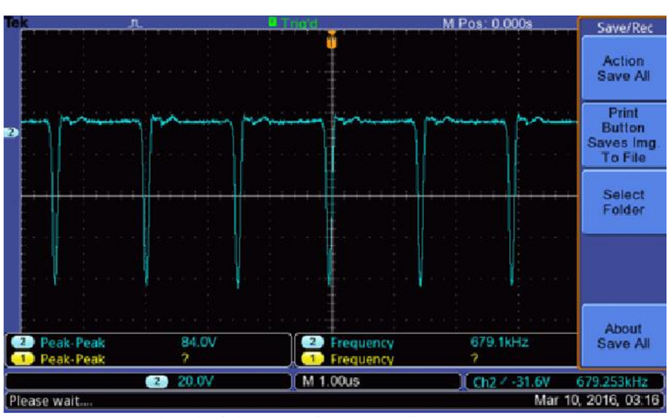

Fig. 7. Output signal of the radio-frequency diathermy (RFD) prototype.

TABLE I
MEDICAL RECORD OF PATIENTS UNDER STUDY

No. Patient / Group	Age (years)	Sex	History of diseases	Personal background
1/A	37	F	HT+DIA+OW	Scoliosis
2/A	84	M	HT+CA	DIA
3/A	31	M	HT+DIA	Smoker
4/A	54	F	HT	----
5/A	49	F	DIA+CA	Hypotension
6/A	17	M	HT+DIA+VI	Surgery
7/A	32	F	CA+DIA	Ovarium tumor
8/A	51	M	HT+CA	OW
9/A	21	M	----	Fracture
10/A	19	M	DIA	----
1/B	62	F	HT+DIA	Surgery
2/B	70	F	HT	Gastritis
3/B	56	F	DIA	DIA
4/B	63	F	HT+DIA	Surgery
5/B	59	F	CA	Hypotension
6/B	22	F	CA+DIA	Gastritis
7/B	18	M	DIA+HT	----
8/B	23	M	DIA	Dysplasia
9/B	22	M	HT+DIA+CA	Amputation
10/B	23	M	----	Surgery

HT: hypertension; DIA: diabetes; OW: overweight;
VINS: vein insufficiency.

After applying ultrasound and electro-stimulation treatments, patients perform flexion, extension, and rotation exercises in the affected part of body. As previously mentioned, Group B received continuous RFD treatment at home; patients were provided in their first visit with our RFD prototype placed by the therapists on the injured area. After two days of continuous treatment, patients of Group B come back to the specialist's office. In each reviewing visit, the RFD device is removed so that the patients can do their exercises. At the end of the exercise session, the device is put in place once again. These same steps were repeated during 5 sessions in a row, which take approximately two and a half weeks. Every 2 sessions the relieving pain and lower-back flexibility of both Group A and Group B was measured with typical techniques used in physical rehabilitation, i.e., Shober goniometry [9], [10] and the visual analogue scale (VAS) [11].

After the fourth reviewing visit, the relieving pain and muscle flexibility results of Group A and Group B were compared to evaluate whether the continuous RFD treatment offers an advantage when used in this type of therapy with different kinds of patients. Fig. 8 and Fig. 9 show the evolution of pain reduction and the recovery of lower-back elasticity in patients of Group A and Group B, respectively. It is clear from both figures that the relieving pain and increased elasticity was better for the Group B. The results of Fig. 8 and Fig. 9 were quantified and they are summarized on Fig. 10, in which one can observe a decrease of 80% of pain in patients who have used the RFD device continuously, as compared to 50% improvement in the patients who received traditional therapy. Regarding elasticity, a 22% of increased elasticity was estimated in the patients who have used the RFD device continuously, as compared to a 7% improvement in the

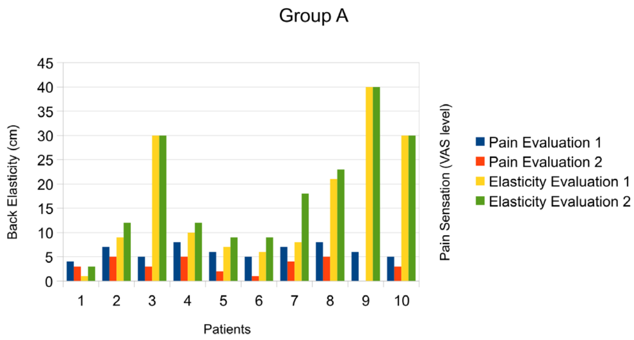

Fig. 8. Pain and elasticity evolution (Group A) from first to fourth visit.

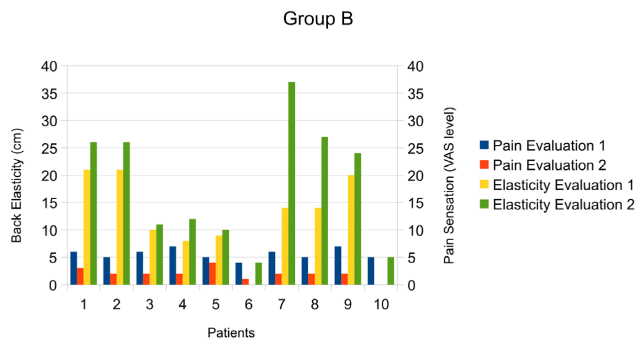

Fig. 9. Pain and elasticity evolution (Group B) from first to fourth visit.

patients who received traditional therapy. Although these results are still not concluding, in this study, it can be seen a more effective muscle healing by applying a continuous-mode RFD signal. These results can be explained by considering that the amount of energy absorbed by tissues from electromagnetic radiation depends not only on the skin properties of patients, the operating frequency, the intensity of radiation, but also on the duration of exposure [4]. This study confirms that regardless of the patient's skin properties, the longer the duration of radiation exposure, the greater the amount of energy that will be absorbed by tissue and thus a better healing muscle in a short time is obtained. It also confirms the effectiveness of the designed RFD prototype for diathermy therapy in continuous mode.

IV. Conclusions

In this work, we have presented a portable RFD prototype implemented with commercial components. Characterization results of prototype shows output signals tuned in the range from 50 V to 120 V and an average current of 23 mA ranging from 500 KHz to 1 MHz. The operating autonomy tests indicated that prototype's battery would surpass 48 hours of continuous work. A comparative study on continuous mode and conventional of RFD treatments applied to patients with muscular diseases showed that the duration of exposure of RFD signal has a good impact in healing affected muscles. This investigation in the RFD field allows us to validate that the continuous application of an RFD signal in patients with a recent injury is an effective and fast-acting measure for reducing inflammation or healing muscle, ligament, and nerve injuries. The conducted study also confirms the effectiveness of the proposed RFD prototype for RF diathermy therapy in continuous mode.

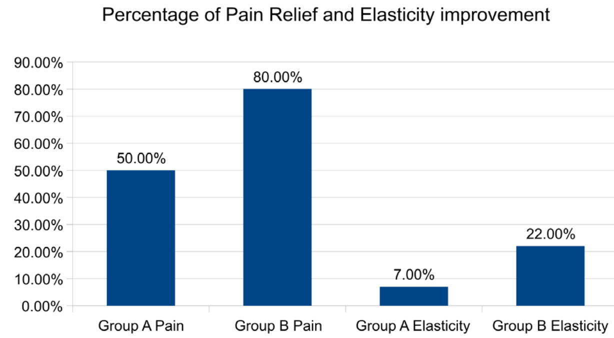

Fig. 10. Percentage of improvement in pain relief and elasticity improvement of Group A and Group B.

Acknowledgement

Authors gratefully thank Dr. Jose Antonio Rojas, Director of *Centro de Medicina de Rehabilitación "Fuerza y Equilibrio", S. C.*, for the realization of study on patients with lumbago disease.

References

[1] C. L. Garrett, D. O. Draper, and K. L. Knight, "Heat distribution in the lower leg from pulsed short-wave diathermy and ultrasound treatments," *J. of Athletic Training*, vol. 35, no. 1, pp. 50-55, Jan. 2000.

[2] C. Johnson, and A. Guy, "Non ionizing electromagnetic wave effects in biological materials and systems," in *Proc. of IEEE*, 1972, pp. 692-718.

[3] L. Guo, N. J. Kubat, and R. A. Isenberg, "Pulsed radio frequency energy (PRFE) use in human medical applications," *J. of Electromagnetic Biology and Medicine*, vol. 30, no. 1, pp. 21-45, Jan. 2011.

[4] R. W. Habash, R. Bansal, D. Krewski, and T. Hafid, "Thermal therapy, part 1: an introduction to thermal therapy," *J. Critical Reviews in Biomedical Engineering*, vol. 34, no. 6, pp. 459 – 489, Jan. 2006.

[5] Equipos Cormat (2006). *Equipos de Fisioterapia* [Online]. Available: http://www.cormat.mx/fisioterapia/radiofrecuencias, Accessed on: Jan. 20, 2016.

[6] Bourns Inc. (2010). *RLB9012-102KL RLB Series Radial Inductors*. [Online]. Available: http://www.farnell.com/datasheets/1815097.pdf?_ga=1.59674863.313887296.1487359995, Accessed on: Jan. 20, 2016.

[7] Linear Technology Corporation. (2010). *IRF640S Power MOSFET* [Online]. Available: http://www.farnell.com/datasheets/2047322.pdf?_ga=1.90560728.313887296.1487359995, Accessed on: Jan. 20, 2016.

[8] Steren de México (2016). *MOV-102 Batería de Respaldo USB* [Online]. Available: http://www.steren.com.mx/bateria-de-respaldo-power-bank-para-smartphones-de-2-000-mah.html, Accessed on: Jan. 20, 2016.

[9] M. Cameron, *Agentes Físicos en Rehabilitación*. Madrid, España: Elsevier España S.L., 2009.

[10] J. Godges, "Dissertation abstracts international: The sciences and engineering," *J. Xerox University Microfilms*, vol. 30, no. 1, Jul. 1969.

[11] R. Rivas and C. Santos, "Manejo del síndrome doloroso lumbar," *Int. J. Medicina General Integral Cubana,* vol. 26, pp. 117-128, May. 2010.