Invited Paper

An Integrated-Circuit Switched-Capacitor Model and Implementation of the Heart

Jose Bohorquez, William Sanchez, Lorenzo Turicchia, and Rahul Sarpeshkar
Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology
Cambridge, MA 02139-4307
Email: {joselb, wasan79, turic, rahuls}@mit.edu

***Abstract*—We present a CMOS chip that implements a simple analog electronic circuit model of the heart. The chip may be useful in low-power body sensor networks that use analysis-by-synthesis techniques to estimate cardiovascular parameters. It may also be useful as a tutorial aid in understanding the heart. We also describe how our electronic model of the heart can be used with heart signal processors in a feedback *heart locked loop (HLL)* —analogous to a phase locked loop— for estimating cardiovascular parameters robustly.**

I. INTRODUCTION

The human heart is an electro-mechanical system used for oxygenating and distributing blood to all of the organs in the body. The electrical portion of the system is made up of a pacemaker that serves as a clock to initiate and synchronize electro-mechanical contractions. These pacemaker signals cause cells in the heart to contract and relax at a set pace, causing blood to flow in and out of four chambers called the *right atrium, right ventricle, left atrium,* and *left ventricle*. The contractions in each of the four chambers lead to pressure differences that cause mechanical valves in the heart to open or close and allow blood to flow in and out of each chamber and through the arteries and veins of the human body. This cycle is repeated for every heart beat (each time the pacemaker sends a signal), and it results in pressure waveforms that have been recorded and are readily available in literature.

Our simple model uses an analogy between mechanical systems and electrical systems so that mature circuit techniques available to electrical engineers can be used to analyze the heart [1]. If measurements of the electrocardiogram (ECG), phonocardiogram (PCG), or photoplethysmogram (PPG) are input into such a model, then consistency between these measurements and the model and time delays between the various signals may be useful in monitoring parameters related to blood pressure via analysis-by-synthesis techniques [1, 2]. An example of an analysis-by-synthesis technique is to use vocal-tract models for robust speech recognition in noise [3]. Our motivation, unlike those in previous modeling efforts, which are theoretical and best suited to the computer, is to create as simple a model as possible that is suitable for low-power integrated-circuit implementations but that nevertheless reproduces important features of heart function. Future medical tags on the heart can then use such a chip as part of an analysis-by-synthesis system for estimating cardiovascular parameters robustly.

Fig. 1 shows an analysis-by-synthesis block diagram that creates what we term a *"heart locked loop" (HLL)* in analogy with phase locked loops (PLL) used in other communication systems [3]. The heart signal processor transforms ECG, PCG, and PPG information to cardiac waveforms that can be compared to those from our chip or to another model via the feature comparator. Errors produced by the comparator are processed by the heart-controller block to update the heart model in a feedback fashion such that it is consistent with the observed data. Eventually, the HLL locks to the input heart signal with optimal cardiovascular parameters output by the controller like a PLL locks to its input. The feature comparator in a HLL is analogous to the phase detector in a PLL, the heart controller in the HLL is analogous to the loop filter in the PLL, and the heart model in the HLL is analogous to the voltage controlled oscillator in the PLL. In this paper we shall only describe our electronic heart model. We have presented the concept of the HLL to provide background motivation for its use.

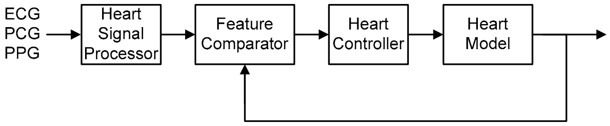

Figure 1. Concept of heart locked loop.

II. MODEL OF THE CARDIOVASCULAR SYSTEM

An electronic model of the heart, using an analogy between mechanical and electronic systems, is derived by making pressure analogous to voltage, fluid volume velocity

J. Bohorquez, W. Sanchez, L. Turicchia, and R. Sarpeshkar, "An Integrated-Circuit Switched-Capacitor Model and Implementation of the Heart," Proceedings of the First International Symposium on Applied Sciences on Biomedical and Communication Technologies, ISABEL 2008, pp. 1-5, 25-28 October 2008. Digital Object Identifier 10.1109/ISABEL.2008.4712624

analogous to current, and fluid volume analogous to charge. Compliance, inertance, and mechanical damping are then analogous to capacitance, inductance, and electrical resistance.

By converting typical mechanical parameters to electrical parameters, the model shown in Fig. 2 is created. The transmission line comprised of resistors, inductors, and capacitors represents the distributed impedance of the circulatory system. The four valves in the heart are modeled as ideal diodes in parallel with capacitors.

A. Mechanical- to-Electrical Conversion Factors

The first step in creating a model of the heart is to choose appropriate mechanical-to-electrical conversion factors. Since typical pressure values for the heart are on the order of 100 mmHg, and convenient voltage ranges of operation for components in our process scale with 100mV, we set $1\text{mmHg} \equiv 1\text{mV}$. A choice for volume velocity or flow of $1\text{ml/s} = 1\text{nA}$ yields $1\text{mmHg}/(1\text{ml/s}) \equiv 1\text{M}\Omega$. Since the typical period of a heart beat is 1s, the capacitance values in our circuit are near $(1\text{s}/(1\text{M}\Omega)) = 1\mu\text{F}$. Table I lists the conversion factors that result from our choice of pressure-to-voltage, flow-to-current, and time-to-time (1:1) factors.

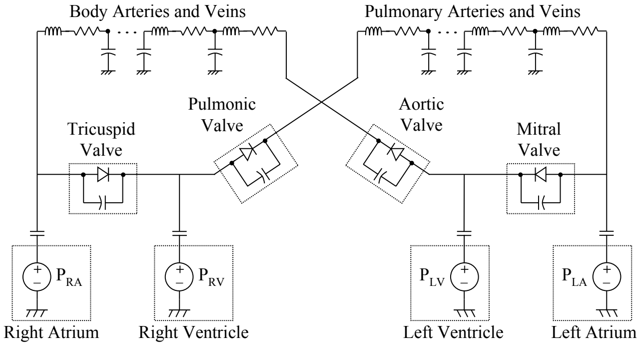

Figure 2. Electrical model of the human heart. Valves are modeled as zero-threshold diodes, and the voltage sources in series with capacitances represent Thevennized equivalents for the four chambers. Note that the left chambers are drawn on the right in keeping with the convention of having the heart positioned as it would be in a human facing the reader.

Mechanical Parameter	**Electrical Parameter**	**Mechanical Units**	**Electrical Units**	**Typical Mechanical Value**	**Typical Electrical Value**
Pressure	Voltage	1 mmHg	1 mV	100 mmHg	100 mV
Volume	Charge	1 ml	1 nA·s	5000 ml	5 uA·s
Flow	Current	1 ml/s	1 nA	90 ml/s	90 nA
Compliance	Capacitance	1 ml/mmHg	1 uF	60ml/120mmHg	0.5 uF
Resistance	Resistance	1 mmHg·s/ml	1 MOhm	1 mmHg/ml	1 MOhm
Inertia	Inductance	1 mmHg·s^2/ml	1MH		

Table I: Mechanical to electrical parameter conversion table.

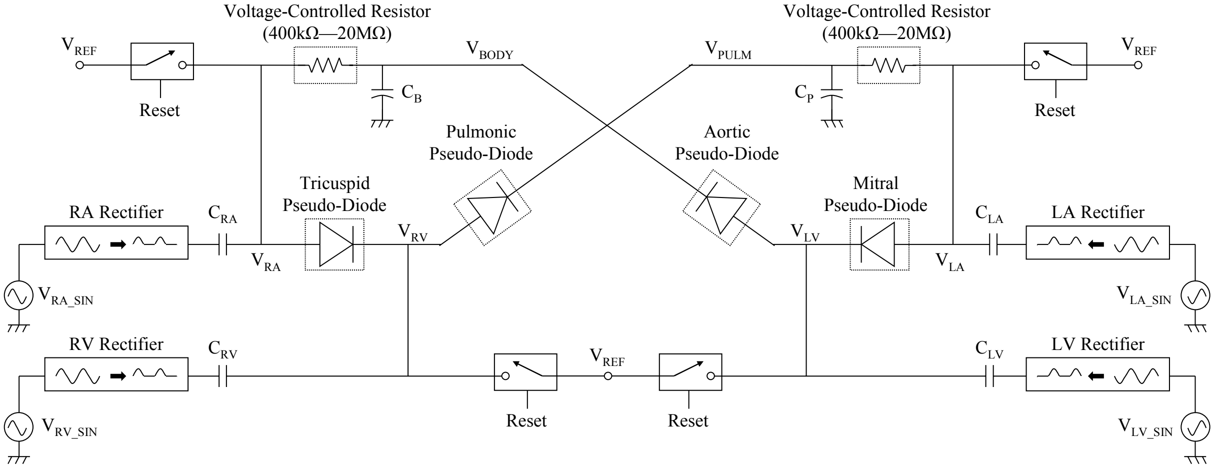

Figure 3. System schematic for simplified model of the human heart.

It is important to choose conversion factors such that an integrated-circuit implementation with a few discretes is possible. Our choice is only one of many. For example, smaller electrical capacitances would result from choosing higher resistance values, i.e., by picking larger voltages to represent pressure and/or smaller currents to represent flow. Large and tunable resistances are efficiently implemented with transconductors built with low-power subthreshold operational transconductance amplifiers (OTAs). We have used such transconductors in our current integrated-circuit implementation.

For simplicity, the model of Figure 2 was further simplified to the extremely simple one in Figure 3. We chose not to model inductances since good accuracy in a heart model is obtained without their use [1]. The latter reference also contains an extensive bibliography on more complex heart models. Complications such as the change in compliance of the heart from being stiff doing systole (pumping phase) to being compliant during diastole (relaxation phase) could be included in future versions of our model but are not present in this version.

III. OVERALL SYSTEM DESIGN

There are four basic component types that make up the heart model of Figure 3: pseudo-diodes, rectifiers, voltage-controlled large resistors, and capacitors.

The pseudo-diodes function as the four valves in the heart by turning on (allowing current flow through them) when the voltage potential across them is greater than zero and turning off (stopping current flow through them) when the voltage potential across them is less than zero. This scheme simulates the function of heart valves which open (allowing blood flow through them) when the pressure potential across them is greater than zero, and close (stopping blood flow through them) when the pressure potential across them is less than zero. Unlike actual diodes, the pseudo-diode circuits used in Fig. 3 need to have a zero-volt turn-on threshold voltage. The low turn-on voltage is necessary to ensure that the electrical model is faithful to mechanical behavior.

The rectifiers are used to convert sinusoidal input signals to clipped-sine-wave signals that resemble the pressure waves generated in the ventricles and atria of the heart.

The voltage-controlled resistors are used to model mechanical resistance to blood flow resulting primarily from viscosity in the veins and capillaries of the human body. Our goal of integrating as much of the system as possible and allowing for tunability, which is important in an analysis-by-synthesis scheme, led us to design a pseudo-resistor that was small in size, large in value, and controllable through an external voltage signal.

The six capacitors shown in Fig. 2 are off-chip tantalum chip capacitors ranging from 0.5 μF—5 μF. The capacitances $C_B, C_{RA}, C_{RV}, C_P, C_{LA}, \text{and } C_{LV}$ model an effective compliance of the body veins and capillaries, right atrium, right ventricle, pulmonary veins and arteries, left atrium, and left ventricle respectively.

The reset switches shown in Fig. 2 are not part of the heart-model itself, but are used to create an initial condition in the system that allows all of the components to function properly. Since the total charge in our system needs to be constant, just as total blood volume in the cardiovascular system is typically constant, the initial amount of charge needs to be set such that the voltage values at different nodes in the system are within the input and output range of its components. To accomplish this goal, four CMOS switches connect a reference voltage (V_{REF}) to four nodes ($V_{RA}, V_{RV}, V_{LA}, V_{LV}$) in the system. The value of V_{REF} corresponds to the average pressure in the cardiovascular system plus an arbitrary offset used so that all components operate within their acceptable common-mode voltage range.

A. *Pseudo-Diode Circuit*

Fig. 4 shows the pseudo-diode circuit used to model heart valves. Fig. 4(b) shows a functional diagram of the circuit composed of a comparator and a CMOS transmission-gate switch. The CMOS switch has an "on" resistance when the switch is closed which is modeled by the two resistors labeled $1/2 \times R_{ON}$. If the voltage on the "anode" (labeled A) is greater than that on the "cathode" (labeled C), the comparator output turns the CMOS switch on and a conduction path is created from A to C. However, if the voltage on node C becomes larger than the voltage on node A, a small amount of current begins to flow from C to A creating a voltage across R_{ON} that causes the CMOS switch to turn off so that no more current flows through it.

B. *Rectifier Circuit*

The rectifier circuit shown in Fig. 5 is used to convert sinusoidal input waveforms into clipped sine waves that resemble the pressure waves created in the ventricles and atria of the heart. The rectifier circuit comprises a pseudo-diode circuit, a resistor, and a voltage follower. The voltage V_T is set externally to the same value as V_{REF} and V_{IN} is set by an external sine wave generator. The amplitude and DC-offset of V_{IN} are used to shape the signal V_{OUT}. DC offsets larger than V_T result in narrower clipped sine wave signals.

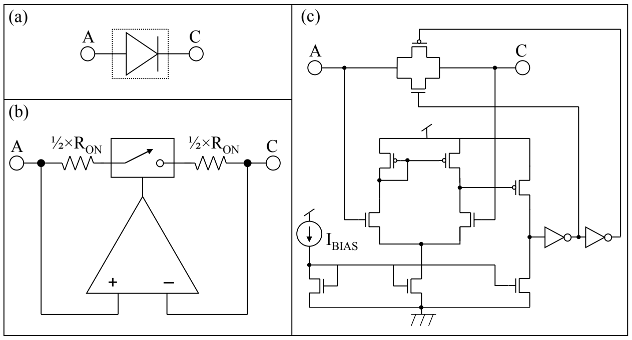

Figure 4. Pseudo-diode circuit (a) symbol, (b) functional diagram, and (c) schematic. The pseudo-diode circuit functions like a diode with zero-volt threshold; positive voltage (forward bias) closes a switch and allows flow, while negative voltage (reverse bias) opens a switch and limits flow.

C. Current-Controlled Large Resistor Circuit

Fig. 6 shows the current-controlled large-resistor circuit (CCLR). The circuit is composed of two back-to-back operational transconductance amplifiers (OTA) which individually output a current equal to the voltage across them divided by their transconductance G_m. Two OTAs were used such that bidirectional current flow through a resistance could be modeled. The circuit thus implements an effective resistance of value $1/G_m$. The effective resistance of the CCLR is set by I_{BIAS} (see Fig. 4(c)). The current value of I_{BIAS} is set through a separate transconductor (not shown) that converts an external tuning voltage to a current voltage. This scheme transforms the CCLR to a voltage-controlled large resistor (VCLR).

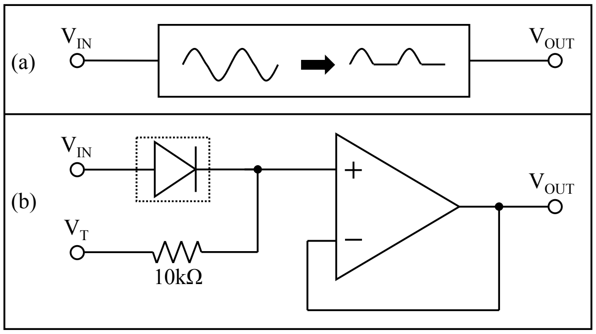

Figure 5. Rectifier circuit (a) symbol and (b) schematic. This circuit converts sine waves to clipped sine waves resembling pressure waves in the heart's ventricles and atria. The amplitude and DC offset of V_{IN} relative to V_T are adjusted to modify the shape of V_{OUT}.

IV. MEASUREMENT RESULTS

A 2.2 mm x 2.2 mm chip implementing the circuits that we have discussed was fabricated in an AMI 0.5μm process via the MOSIS prototyping service.

A. Sub-Circuit Characterization

Fig. 7 shows a characterization of the rectifier circuit. V_T is set to 2.5V and a sine wave with 2.5V DC offset is applied to V_{IN}. As shown in the figure, when V_{IN} rises above V_T the pseudo-diode turns on and V_{OUT} tracks V_{IN} with a small offset. The offset is a result of the voltage division between the $10k\Omega$ resistor and the "on" resistance of the pseudo-diode. This plot also confirms that the pseudo-diode works.

B. System-Level Results

Fig. 8 shows measured results from the entire chip. All of the pseudo-diode circuits function properly and the overall signals closely resemble the pressure waves in the heart and circulatory system in spite of the simplicity of our model. The signals shown in Fig. 8 were taken from the output of op-amps external to the chip which were used to remove the 2.5V reference voltage and to provide some voltage gain. The right y-axis in Figure 8 shows equivalent pressure values if an effective conversion gain of 5mV/mmHg is used.

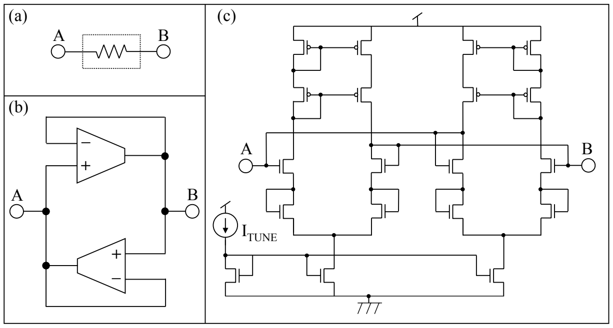

Figure 6. Current-controlled large resistor circuit (a) symbol, (b) functional diagram, and (c) schematic. The effective resistance is $R=1/(50 \times I_{TUNE})$.

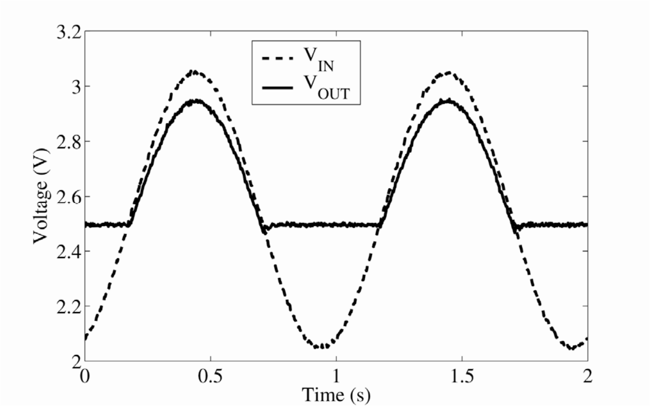

Figure 7. Measured voltage waveforms for rectifier circuit with sinusoidal input.

One undesirable feature of our circuit that we observed experimentally results from the pseudo resistor of Figure 6 not being precisely charge balanced in both directions of current flow due to asymmetric D.C. offsets in the transconductors. Such charge imbalance leads to slow accumulation of d.c. charge and consequently, a slow drift in the common-mode voltage of the circuit that necessiates a reset. Future work should therefore use a pseudo resistor that is guaranteed to have zero current at zero voltage across the pseudo resistor. Such pseudo resistors have been built, successfully tested, and reported by us in a recent publication [4], but were not incorporated into this version of our chip. Future work could also alter capacitances in a switching fashion to model the abrupt changes in compliance of the heart from diastole to systole. Finally, future work could include active gyrator-based inductors to capture small but discernible effects due to inductance seen during aortic valve closings. However, our simple chip may already suffice to be useful as part of an analysis-by-synthesis system in a heart tag that uses our chip and other sensors to robustly extract and monitor important cardiovascular parameters.

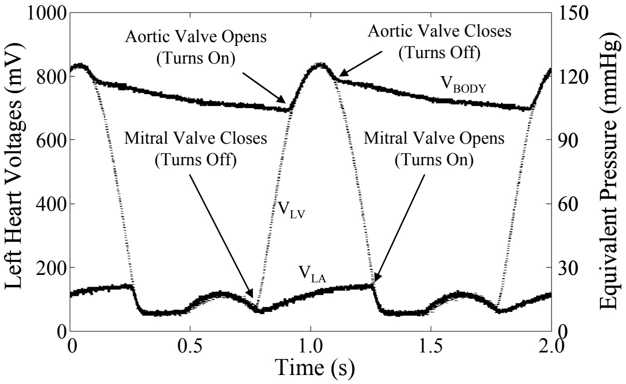

Figure 8. Measured voltage waveforms for the left half of the heart and equivalent pressure values.

V. CONCLUSION

The human heart and circulatory system were modeled on an electronic chip using novel circuit techniques to emulate the valves, arteries, ventricles, atria, and other mechanical systems in our simple integrated circuit. The analog model of the heart is intended for use with heart signal processors in a feedback *heart locked loop (HLL)*. The HLL has the potential to estimate cardiovascular parameters robustly. We discussed how future improvements to our chip could lead to more complex heart models.

REFERENCES

[1] T. A. Parlikar, "Modeling and Monitoring of Cardiovascular Dynamics for Patients in Critical Care," PhD Thesis, Electrical Engineering, Massachusetts Institute of Technology, 2007

[2] J. C. Bramwell and A. V. Hill, "The Velocity of the Pulse Wave in Man," *Proc. Royal Society of London. Series B*, vol. 93, no. 652, pp. 298–306, Apr. 1922.

[3] K. H. Wee, L. Turicchia, and R. Sarpeshkar, "An Analog VLSI Vocal Tract," *IEEE Transactions on Biomedical Circuits and Systems,* in press, 2008.

[4] K. H. Wee and R. Sarpeshkar, "An Electronically Tunable Linear or Nonlinear MOS Resistor," *IEEE Transactions on Circuits and Systems I,* in press, 2008.