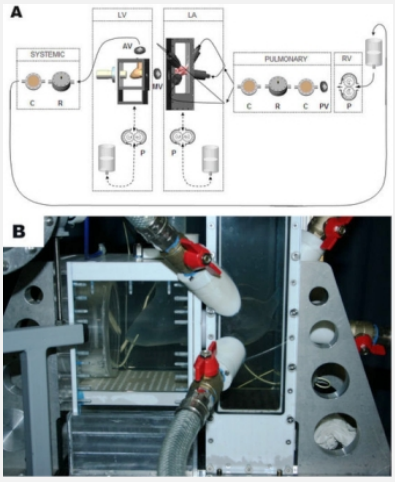
Using a Dual-Activation Cardiovascular Simulator for In Vitro Endocardiac Discharge Modeling



The Left Heart Simulator for Pulmonary and Systemic Circulation

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- Pr Régis RIEU, Aix-Marseille Université

The Challenge:
Hydrodynamically simulating a heart's left atrium and ventricle and systemic and pulmonary blood vessels to test and characterize prosthetic heart valves.

The Solution:
Using NI LabVIEW software, NI CompactRIO hardware, and a heart valve test bench to control contraction and relaxation of the simulated left ventricle and atrium in real time.

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Simulating the in vitro blood flow of the heart started when prosthetic heart valves were first developed and their minimum hydrodynamic performance was standardized. From the design stage of the valve replacement device to its first use by a surgeon, tests were conducted to ensure proper operation, safety, reliability, and durability of the prostheses. Therefore, this simulator can test various mechanical, biological, and percutaneous heart valves, but it is first and foremost a high-performance research and development tool for focusing on fluid mechanics, imaging, and cardiology.

From a Human Heart to a Simulator

The blood flow in the heart is a complex, 3D, dynamic phenomenon. The interest in modeling (whether in vitro or digital) lies in the opportunity to study the individual and combined impact of parameters on a variable by replicating physiological and pathological conditions that would be impossible to reproduce in vivo. Thus, the blood flow can be modeled with an equivalent mockup or experimentally. In the field of cardiovascular biomechanics, despite the latest advances in digital simulations, the complexity of the discharge makes it essential to use heart simulators.

Cardiovascular simulators help test prosthetic heart valves that replace faulty natural valves. Simulators also provide a better understanding of hemodynamic consequences from valve diseases, replacements, or repairs. Another advantage of the simulator is that researchers can use it to develop and validate methods for diagnosing valve pathologies and the impact on the cardiovascular system. These methods are then applied using diagnostic ultrasound or magnetic resonance imaging (MRI).

The goal of this simulator is to replicate the left atrium and ventricle of the heart as well as the systemic and pulmonary flows. The heart cavities are simulated with anatomically correct silicone models that are immersed into liquid-filled cages that contract and relax like a real heart, causing the blood-like fluid to pump and flow.

We chose hydraulic control, whereas previous simulators used hydro-pneumatic activation, because we wanted direct control of the volume in both cavities. By directly controlling both cavities, we can achieve transvalvular flow between the atrium and the ventricle without direct measurement, which gets both cavities closer to one another for a better anatomic configuration.

The pumps induce a pressure variation within the cages that simulates the periodical contractions/relaxations of both cavities in a synchronized manner. We use optimal control signal generation from a digital model to synchronize the pumps. This device prevents pressure variations between both cavities and replicates high-fidelity physiological or pathophysiological conditions in the test bench.

A Digital Model-Based Simulator

We implemented the digital model in LabVIEW. The control section of this simulator consists of four steps: test parameter definition, settings definition via the digital model, signal loading on the CompactRIO system, and data generation/acquisition. The simulator setup parameters are defined via a human machine interface (HMI) that we programmed in LabVIEW. For the settings signal definition, the user inputs the mitral and aortic valve and pulmonary vein circulation rates he or she wants to simulate. Ideally, these rates are provided using actual data from the ultrasound, MRI, or patient examinations.

In practice, the CompactRIO system controls the pump activation rates that are generated according to user-defined conditions. It then acquires data from various sensors including flowmeters and transducers. Following this data acquisition, the data specific to the valve that is useful in a clinical routine, such as effective orifice area (EOA) as well as pressure difference through the valve, can be calculated. Control signal generation and pressure and rate signal acquisition are performed in real time by the field-programmable gate array (FPGA) in CompactRIO. With this rugged embedded system, we can completely and securely control the simulator.

We validated our simulator by validating the digital model as well as measuring the various rates and comparing the measurements with those taken using the previous simulator. We also analyzed harmonics to check the validity of the simulator with the in vivo data available in the appropriate documentation. The pressure-volume trends from the atrium and the ventricle correspond to those obtained in vivo.

Prosthetic Heart Valve Testing

Replacing a native valve because of a disease depends on a clinical diagnosis, the patient's age, and several parameters related to his/her health state. The native valve is replaced with a mechanical or biological prosthetic heart valve during an open-heart operation. The surgeon must choose the right device in accordance with the patient's hemodynamic profile, clinical recommendations, and device-specific data provided by the manufacturer. Current standards such as ISO 5840 aim at ensuring the correct and lasting operation of the prosthetic heart valve once it is implanted. Thus, in vitro tests both on animals and patients are necessary for device approval before it is released to the market.

For in vitro tests, hydrodynamic performance in pulsed conditions is one of the key tests. Several hydrodynamic conditions including heart rate, cardiac output, and average aortic pressure are implemented on the prosthesis to test its behavior. The standard requires a minimum performance defined by quantitative criteria. This simulator allows complete tests that can quantify the criteria required by the standard while using the prosthetic heart valve in an optimal manner. Recently developed percutaneous valves, which can be placed without an open-heart operation, evolve the standard while taking into account clinical issues related to this new technology.

Search Tool

The discharges into the ventricle and atrium may be studied through two-component/stereoscopic, multiplane particle image velocimetry (PIV). The models and cages are translucent, so we can acquire this type of data and then process and analyze it in terms of fluid dynamics. The PIV acquisitions are also controlled by the LabVIEW program, which can synchronize the heart cycle with the images captured. Ultrasound measurements can also be processed in different locations, either directly in the ventricle or through the aortic and mitral valves, so the user can acquire parameters usually obtained during an ultrasound cardiographical examination. Thus, the simulator makes it possible to understand complex blood flows within the heart cavities to establish new clinical criteria.

Research Example

The simulator was used in research to study the impact of different types of mitral valves and bioprosthesis or mechanical valve replacement devices on pulmonary hypertension and thromboembolic events. Depending on the type of valve replacement device, acquiring the intravalvular flow in vitro and simulating this flow in pathological circumstances can isolate and seize the complex links between device selection and recovery and/or regression of related valve and secondary diseases.

Evolution Prospects

Synchronizing and activating the volume of both heart cavities in real time, their anatomical shapes, simulating the pulmonary network, controlling the mitral flow, and the repeatability and reliability of acquisition make this one of the highest performance simulators to date. Developing percutaneous prosthetic heart valves can lead to further improvements of this simulator to test these new devices in a simulated context or during procedures. These evolutions can meet the clinician's needs, including the ability to simulate percutaneous procedures or highlight appropriate criteria to diagnose or quantify disease severity. The current simulator's performance is due to National Instruments hardware and the expertise of their support engineers, and we will continue using NI to build future evolutions of this simulator.

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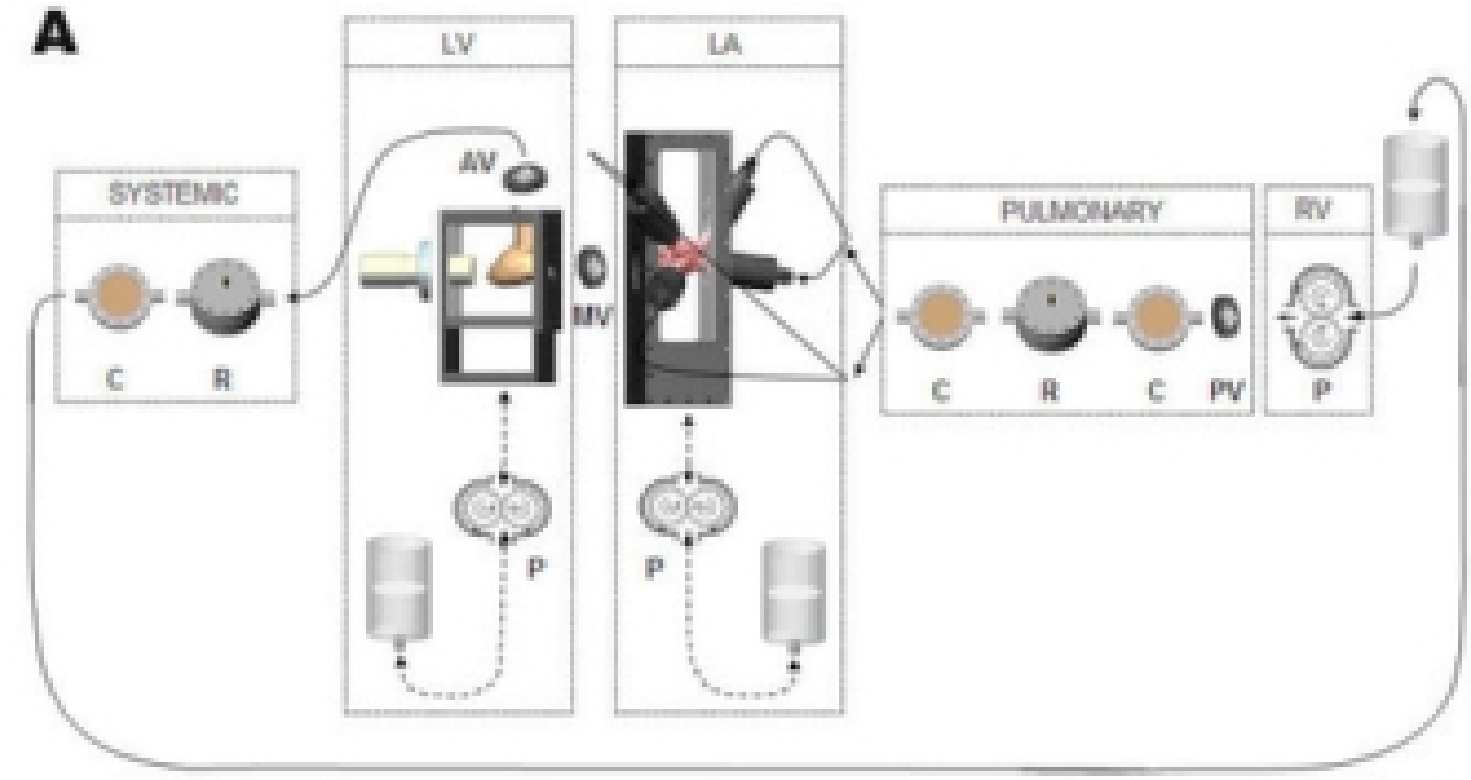

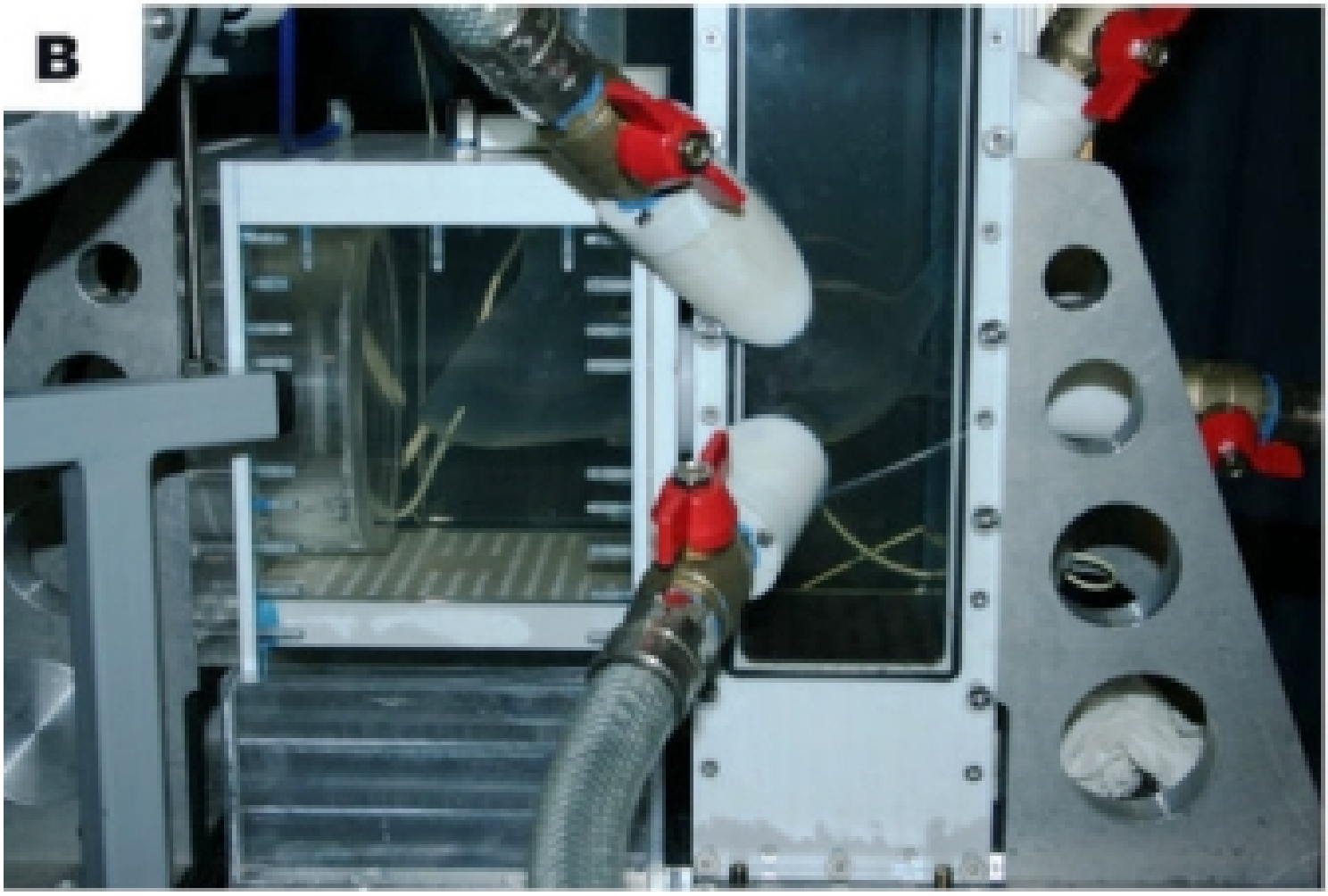

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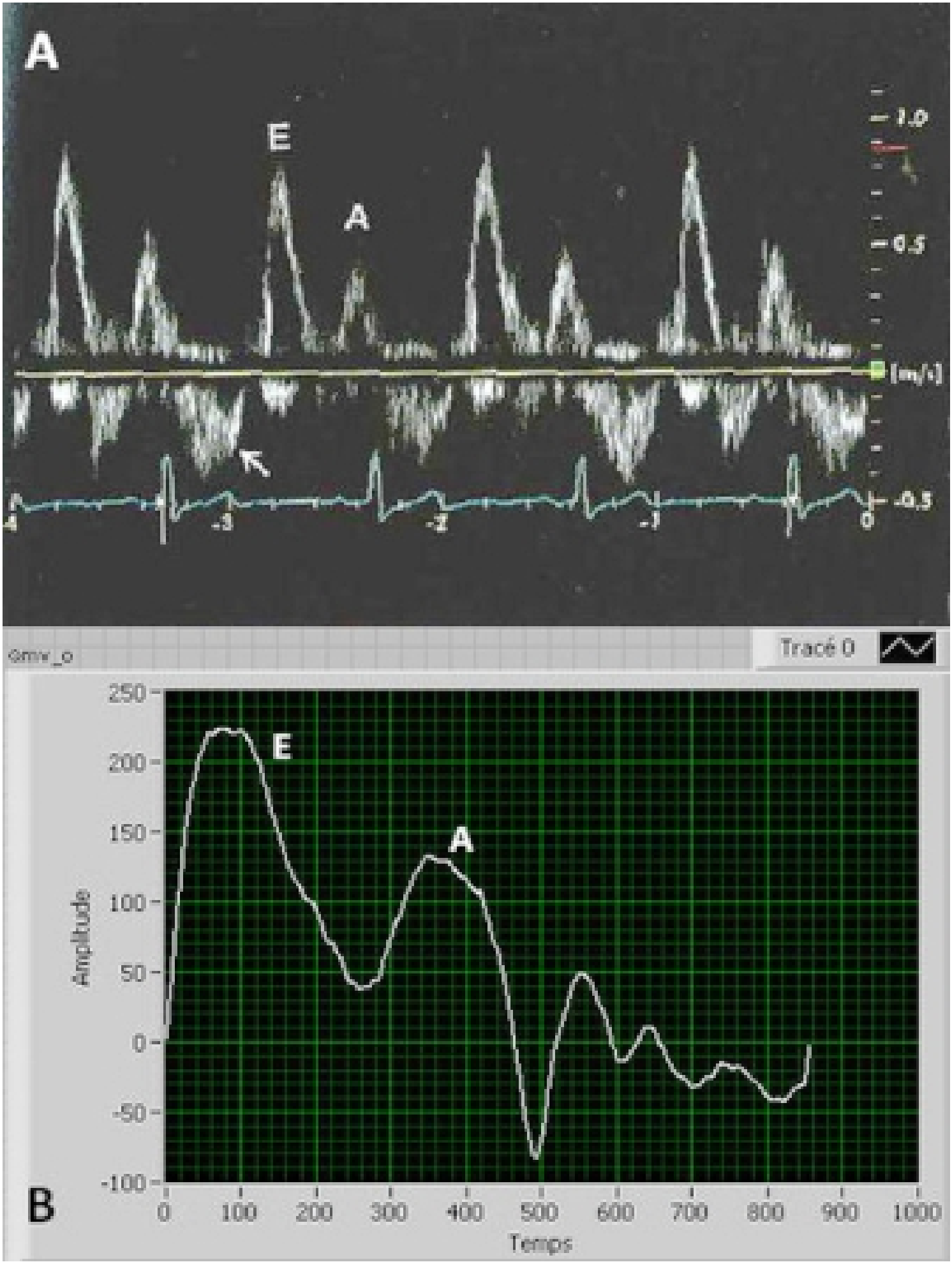
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