

# Time-synchronization of interventional cardiovascular magnetic resonance data using a biomechanical model for pressure-volume loop analysis

Maria Gusseva, Daniel Castellanos, Joshua Greer, Mohamed Hussein, Keren Hasbani, Gerald Greil, Surendranath Reddy, Mohammad Hussain, Dominique Chapelle, Radomir Chabiniok

▶ **To cite this version:**

Maria Gusseva, Daniel Castellanos, Joshua Greer, Mohamed Hussein, Keren Hasbani, et al.. Time-synchronization of interventional cardiovascular magnetic resonance data using a biomechanical model for pressure-volume loop analysis. Journal of Magnetic Resonance Imaging, 2023, 57 (1), pp.320-323. 10.1002/jmri.28216 . hal-03651166

**HAL Id: hal-03651166**
**https://hal.science/hal-03651166**

Submitted on 25 Apr 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**Title**

Time-synchronization of interventional cardiovascular magnetic resonance data using a biomechanical model for pressure-volume loop analysis

**Authors**

Maria Gusseva, PhD[a,b]
Daniel A. Castellanos, MD[c]
Joshua S. Greer, PhD[d]
Mohamed Abdelghafar Hussein, MD[d,e]
Keren Hasbani, MD[f]
Gerald Greil, MD, PhD[d]
Surendranath R. Veeram Reddy, MD[d]
Mohammad Tarique Hussain, MD, PhD[d]
Dominique Chapelle, PhD[a,b]
Radomír Chabiniok, MD, PhD[a,b,d,g]

**Affiliations**

[a]Inria, Palaiseau, France
[b]LMS, Ecole Polytechnique, CNRS, Institut Polytechnique de Paris, Palaiseau, France
[c]Department of Cardiology, Boston Children's Hospital, Boston, MA, USA
[d]Division of Pediatric Cardiology, Department of Pediatrics, UT Southwestern Medical Center, Dallas, TX
[e]Pediatric department, Kafrelsheikh University, Kafr Elsheikh, Egypt
[f]Division of Pediatric Cardiology, Department of Pediatrics, Dell Medical School, UT Austin, TX
[g]Department of Mathematics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic

**Address for correspondence**

Radomír Chabiniok, MD, PhD
Address: Department of Pediatrics, UT Southwestern Medical Center, 5323 Harry Hines Blvd, Dallas, TX 75390, USA
Tel: +12144567311
E-mail: radomir.chabiniok@UTSouthwestern.edu

**Acknowledgement**

We would like to acknowledge Dr Philippe Moireau, Inria research team MΞDISIM, for the development of the cardiac simulation software CardiacLab used in this work.

**Grant Support**

This work was supported by the Inria-UTSW Associated Team TOFMOD. It was also funded from by the W. B. & Ellen Gordon Stuart Trust, The Communities Foundation of Texas and by the Pogue Family Distinguished Chair (award to Dr F. Gerald Greil in February, 2015). The work was in addition supported by the Ministry of Health of the Czech Republic [NV19-08-00071]. Research reported in this publication was supported by Children's Health$^{SM}$, but the content is solely the responsibility of the authors and does not necessarily represent the official views of Children's Health$^{SM}$.

**Ethics approval and consent to participate**

The data collections for single-ventricle patients were performed under the ethical approvals of the Institutional Review Boards of UT Southwestern Medical Center Dallas (STU 032017-061). The data collections for rTOF patients were performed under the ethical approvals of the Institutional Review Boards of UT Southwestern Medical Center Dallas (STU-2020-0023) and UT Austin (IRB 2020-06-0128). The IRBs waived the need for a consent to use the anonymized retrospective data.

**Running title**

Synchronization of pressure-volume data

## Introduction

Pressure-volume loops (*PV* loops) provide a meaningful insights into myocardial energetics (1, 2). Pressure-volume (*P*-*V*) data is often acquired by different modalities and subject to time-synchronization errors yielding skewed shapes of *PV* diagrams (Figure 1 (A)). A temporal dyssynchrony could be associated with cardiac magnetic resonance imaging (MRI) acquisition and reconstruction techniques: the temporal resolution of the scanner, the type of ECG trigger / gating (prospective vs. retrospective), averaging over cardiac cycles, and detection of R-peak from a wide QRS complex (3). In addition, some delays could arise from the inertia effect of the fluid-filled catheter that varies depending on the catheter type and size (4).

A complete synchronization of the *P*-*V* signals is possible when using an intraventricular conductance catheter. In other settings, a manual delineation of the isovolumic phases may be performed. However, such an approach can be suboptimal, e.g. in patients with valvular regurgitation due to the absence of clear isovolumic phases. We aim to develop a time-synchronization technique that is independent of the data acquisition methods or patients' pathophysiology by using patient-specific biomechanical model derived waveforms to detect *P*-*V* offsets in the measured data. Our previous pilot study demonstrated the potential of such an approach on *P*-*V* data acquired sequentially (volumetric data during cardiac MRI followed by pressure data during cardiac catheterization) without valvular regurgitation (3). In the present study we aim to extend the method for simultaneously acquired *P*-*V* data (i.e. during interventional cardiac MRI) and for patients with pulmonary regurgitation (i.e. right ventricles of patients with repaired tetralogy of Fallot, rTOF).

## Methods

*2.1 Data*

Datasets from two groups of patients were included in the study. The first group contained 10 patients with single-ventricle physiology undergoing interventional cardiac MRI within the pre-Fontan assessment. *P-V* were acquired simultaneously at baseline and immediately after fluid administration providing 24 *P-V* datasets. Fluid boluses were administered either as a single 5 ml/kg bolus or as two 2.5 ml/kg boluses. A highly-accelerated prospective ECG-triggered cine bSSFP sequence (kt-BLAST factor 5, partial Fourier 0.625, slice thickness 10 mm, spatial resolution 2.4 x 2.4 x 10 mm) was used. Another group contained patients with rTOF with 17 left and 20 right ventricular *P-V* datasets (rTOF-LV and rTOF-RV, respectively). A retrospective ECG-gated cine bSSFP sequence (SENSE 2, spatial resolution 2 x 2 x 10 mm) was used. Catheter pressures were sequentially acquired during pulmonary valve replacement therapy. Temporal resolution was ~30 ms in both groups and all acquisitions. A motion tracking algorithm (5) was used to obtain time-vs.-volume signals from cardiac MRI.

*2.2. Biomechanical heart model*

We employed a biomechanical heart model of a single heart cavity where the geometry and kinematics of the ventricle are represented by sphere (6) with constitutive mechanical laws describing active (contractile) and passive (viscoelastic) behavior of the myocardium. To model a cardiac cycle in patient-specific manner model parameters were tuned such that simulated waveforms corresponded to the maximum and minimum pressure and volume for a given patient (see e.g. (7)).

*2.3 Time synchronization*

The model was used as a template for temporal synchronization of original *P-V* data. We assumed that synchronicity of simulated *P-V* traces is given by the biophysical and physiological formulation of the model. We minimized the distance

between data and model waveforms (Figure 1 (B)) to detect the corresponding time offsets for $t_{offset}^{pressure}$ and $t_{offset}^{volume}$:

$$\min_{t_{offset}} \int_0^{t_{end}} (f(t) - g(t - t_{offsel}))^2 \, dt, \quad (1)$$

where $\mathrm{f(t)}$ and $\mathrm{g(t)}$ are the simulated and original ventricular pressure or volume, respectively; $\mathrm{t_{end}}$ is the end of the cardiac cycle in the original data. Total *P-V* time offset was given by:

$$t_{offset}^{P-V} = abs(t_{offset}^{pressure} - t_{offset}^{volume}). \quad (2)$$

*PV* loops were constructed for original and time-synchronized (t-syn) data. Quantitative evaluation of t-syn traces was derived from time-varying elastance (TVE). TVE (8), defined as $E(t) = P(t)/V(t)$, was computed from original and t-syn data, where $P(t)$ and $V(t)$ are ventricular pressures and volumes, respectively. According to TVE the isovolumic phase could be described as (9, 10):

$$\max(dP/dt) = \max(dE/dt) * EDV, \quad (3)$$

where $\max(dP/dt)$ and $\max(dE/dt)$ are maximum time derivatives of ventricular pressure and elastance, respectively, end-diastolic volume (*EDV)* is assumed to be constant during isovolumic contraction. We confronted $\max(dE/dt)$ derived from original and t-syn data ($\max(E_{orig}/dt)$ and $\max(E_{t-syn}/dt)$, respectively) with respect to the $\max(dP/dt)$ of the original pressure waveforms via linear regression analysis. Note that $\max(dP/dt)$ does not change with time-synchronization.

Finally, the original, t-syn and model-derived values of maximum TVE (i.e. $\mathrm{E_{max}}$= max$[P(t)/V(t)]$), and stroke work (i.e. area encompassed within the PV loop) were computed for each patient and statistically compared with Wilcoxon signed rank test at $\mathrm{p} < 0.05$.

**Results**

Figure 1 (D-F) shows t-syn *PV* loops for selected patients from all groups. The slope coefficients of linear regressions models (Coef) of max($dE_{orig}/dt$) vs. max($dE_{t-syn}/dt$) in single-ventricle patients were 1.279 vs. 1.040; in rTOF LVs 1.795 vs. 1.126; and in rTOF RVs 1.615 vs. 1.180 (Figure 2).

Mean (± SD) model-derived *P-V* offsets of single-ventricle patients were 0.059 (± 0.022) s; of rTOF-LVs and rTOF-RVs 0.110 (± 0.039) s and 0.116 (± 0.032) s, respectively.

T-syn vs. original $E_{max}$ (p=0.000) and stroke work (p=0.000) were significantly lower in all patients. The difference for model-derived vs. time-synchronized (1) $E_{max}$ was not significant in all three groups (p>0.050 in all patients), (2) stroke work was not significant for single-ventricle and rTOF LV (p>0.050 in both groups) and significant for rTOF RV patients (p=0.000), Figure 3.

**Discussion**

We developed a biomechanical model-assisted time-synchronization technique for clinical *P-V* data. Time-synchronization qualitatively improves the shapes of *PV* loops in all patients. Quantitative improvement of t-syn data was demonstrated via stronger TVE relationship during isovolumic phase. In addition to that t-syn values of $E_{max}$ and stroke work were significantly different from the non-synchronized ones. Therefore, time-synchronization of *P-V* data is crucial to derive meaningful values for ventricular energetics.

This model can replace noisy data traces, thus overcoming errors associated with data acquisition and/or processing protocols (e.g. missing part of the cardiac cycle, noise in the data, or non-physiological over-/undershoot in pressure measurements).

**References**

1. Wong J, Pushparajah K, de Vecchi A, et al.: Pressure–volume loop-derived cardiac indices during dobutamine stress: a step towards understanding limitations in cardiac output in children with hypoplastic left heart syndrome. *International Journal of Cardiology* 2017; 230:439–446.

2. Veeram Reddy SR, Arar Y, Zahr RA, et al.: Invasive cardiovascular magnetic resonance (iCMR) for diagnostic right and left heart catheterization using an MR-conditional guidewire and passive visualization in congenital heart disease. *Journal of Cardiovascular Magnetic Resonance* 2020; 22:20.

3. Gusseva M, Greer JS, Castellanos DA, et al.: Model-Assisted Time-Synchronization of Cardiac MR Image and Catheter Pressure Data. In *Functional Imaging and Modeling of the Heart*. Edited by Ennis DB, Perotti LE, Wang VY. Cham: Springer International Publishing; 2021:362–372. [*Lecture Notes in Computer Science*]

4. de Vecchi A, Clough RE, Gaddum NR, et al.: Catheter-induced errors in pressure measurements in vessels: an in-vitro and numerical study. *IEEE Trans Biomed Eng* 2014; 61:1844–1850.

5. Castellanos DA, Škardová K, Bhattaru A, et al.: Left Ventricular Torsion Obtained Using Equilibrated Warping in Patients with Repaired Tetralogy of Fallot. *Pediatr Cardiol* 2021; 42:1275–1283.

6. Caruel M, Chabiniok R, Moireau P, Lecarpentier Y, Chapelle D: Dimensional reductions of a cardiac model for effective validation and calibration. *Biomechanics and Modeling in Mechanobiology* 2014; 13:897–914.

7. Ruijsink B, Zugaj K, Wong J, et al.: Dobutamine stress testing in patients with Fontan circulation augmented by biomechanical modeling. *PLOS ONE* 2020; 15:e0229015.

8. Suga H, Sagawa K, Shoukas AA: Load Independence of the Instantaneous Pressure-Volume Ratio of the Canine Left Ventricle and Effects of Epinephrine and Heart Rate on the Ratio. *Circulation Research* 1973; 32:314–322.

9. Little WC: The left ventricular dP/dtmax-end-diastolic volume relation in closed-chest dogs. *Circulation Research* 1985; 56:808–815.

10. Sunagawa K, Sagawa K: Models of ventricular contraction based on time-varying elastance. *Crit Rev Biomed Eng* 1982; 7:193–228.

**List of abbreviations**

| | |
|---|---|
| MRI | magnetic resonance imaging |
| ECG | electrocardiogram |
| LV | left ventricle |
| P-V | pressure-volume |
| QRS | QRS complex |
| rTOF | repaired tetralogy of Fallot |
| RV | right ventricle |
| TVE | time-varying elastance |

## Declarations

### Availability of data and materials

The datasets used in this study are available from the corresponding author on reasonable request.

### Competing interests

The authors declare that they have no competing interests.

## Figures

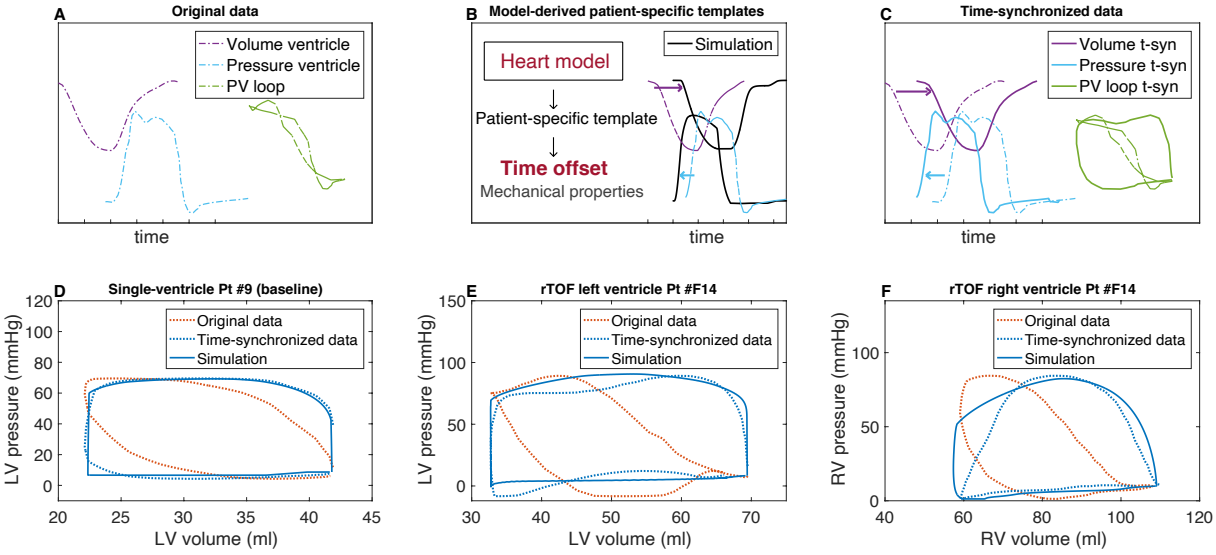



**Figure 1:** Model-assisted time-synchronization of clinical pressure-volume data. A: Distorted pressure-volume loop (PV loop) due to the time offset between the acquired pressure and volume data illustrated on rTOF left ventricle Pt #AF24 from our study. B: Detection of the time offset by using patient-specific biomechanical model, simulating synchronous pressure and volume waveforms. C: Corrected PV loop (solid line) reconstructed from the time-synchronized (t-syn) data D: Pressure-volume loops for single-ventricle patient #9 at baseline (cine MRI is prospectively ECG-triggered). E-F: Pressure-volume loops for rTOF patient left and right ventricles (rTOF-LV and -RV, respectively), rTOF-RV Pt #F14 contains 11% and 30% of tricuspid and pulmonary regurgitation, respectively.

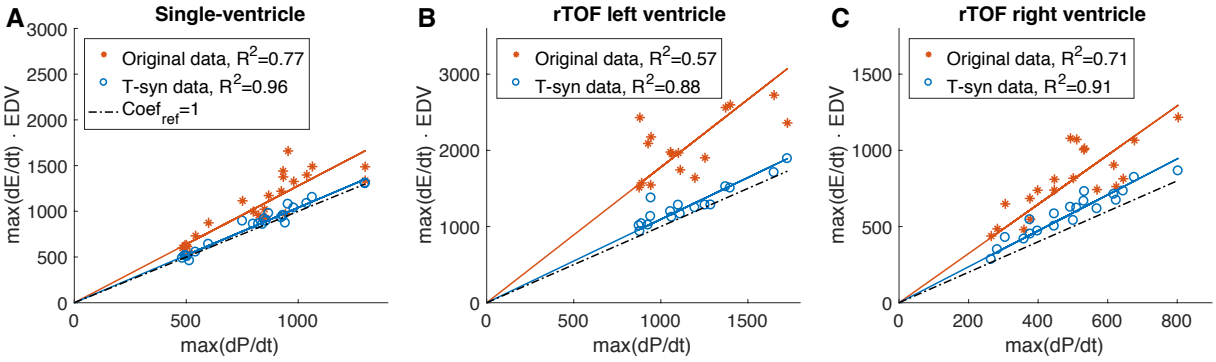



**Figure 2.** Linear regression models for original and time-synchronized (t-syn) data for single-ventricle patients (A), rTOF left ventricle (rTOF-LV) (B), and rTOF right ventricle (rTOF-RV) (C). Dotted black line is a reference linear model with slope ($Coef_{ref}$) equal to 1. $R^2$: coefficients of determination of linear regression models.

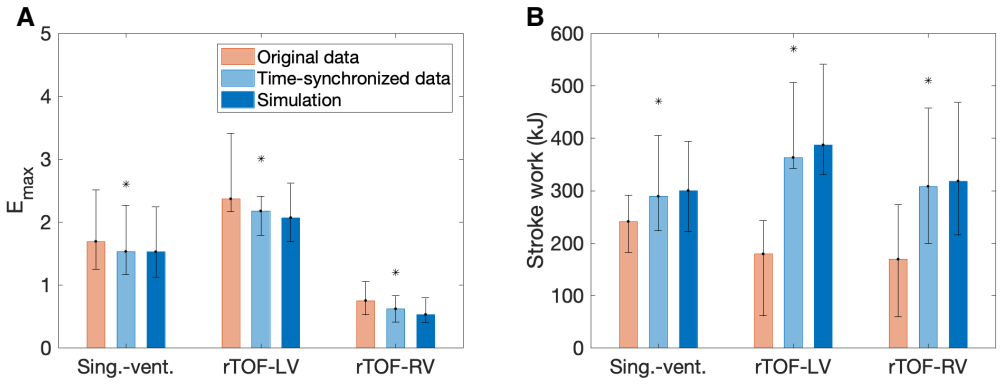



**Figure 3.** Boxplot of original and time-synchronized indices of myocardial function in each patient group. A: maximum values of time-varying elastance ($E_{max}$). B: stroke work (area encompassed within the pressure-volume loop). Bars correspond to the medians, upper and lower error bars are 75$^{th}$ and 25$^{th}$ percentiles, respectively. Asterisks show significant difference of time-synchronized data with respect to the original at $p < 0.05$. rTOF-LV/-RV: repaired tetralogy of Fallot left/right ventricle patients, respectively.