STUDY OF SIX MODELS OF THE INSTANTANEOUS PRESSURE-VOLUME RELATIONSHIP

[1]A. Lucas, [2]J.-W. Lankhaar, [2]P. Steendijk, [1]Ph. Kolh, [1]Th. Desaive and [1]P.C. Dauby
[1] Cardiovascular Research Center, University of Liège, Liège, Belgium; email: alucas@ulg.ac.be,
[2]Institute for Cardiovascular Research, VU University Medical Center, Amsterdam, The Netherlands

SUMMARY

Models and simulations are very useful to study interactions between anatomic structures and physical cardiac phenomena. In this work, we are interested in models describing the instantaneous pressure-volume relationship, i.e. isochrone models. More precisely, we concentrate on the 6 models considered by Lankhaar *et al.* [1]. We propose a critical analysis of the work of these authors. In this view, a test made up of several steps is applied to each model. When the test is not positive, we suggest some improvement of their procedure.

INTRODUCTION

Pressure-volume loops are a common modeling tool of the cardiovascular system. They are very useful because they characterize the global function of the cardiac pump. They can also be analyzed by considering the various phases of the cardiac cycle and marking each point of a cycle with the corresponding time. When several loops are considered, the points corresponding to the same time *t* in each loop can be joined to define a curve named isochrone. This concept does not have to be mixed up with the theoretical concept of isophase. The latter is a curve that links the points corresponding to the same **relative** time of a considered cardiac phase in the different loops, such as the start or the end of filling, the start or the end of ejection. Of course, these points do not necessarily occur at the same time in the different cycles.

For example, the ESPVR (end-systolic P-V relationship) is classically defined as the curve that links points marking the end systole, namely the upper left corners of the loops (in pink on Figure 1), and is thus an isophase. The end-systolic isochrone can be defined as the curve that links the closest points to those of the ESPVR and occurring at the same time in the cycles (in green on Figure 1). If we observe Figure 1, we see clearly that these two sets of points do not coincide.

METHODS

Lankhaar *et al.* [1] have estimated the parameters characterizing six different isochrones models from experimental data measured in five sheep. To evaluate their accuracy, these models were used in a mathematical model of a ventricle coupled with an arterial system.

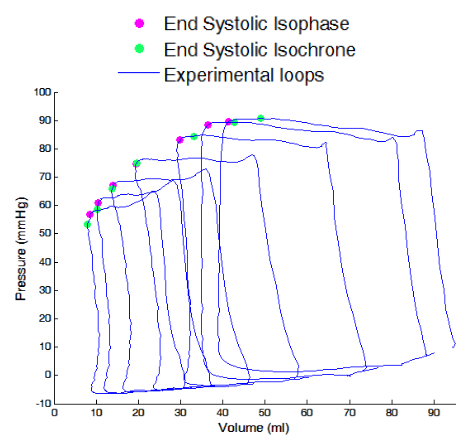

Figure 1: Illustration of the difference between the ESPVR and the end-systolic isochrone.

To test the procedure developed in [1] to identify the parameters and to criticize the models definition, we perform on each model the following procedure (Figure 2). First, we estimate model parameters but this time from the loops resulting from the simulations done by Lankhaar *et al.*. Second, we compare our new parameters values with those found by these researchers from the original experimental data. Finally, if these two sets of parameters are equal, we conclude that the procedure is consistent. If not, we try to identify the possible origins of this inconsistency.

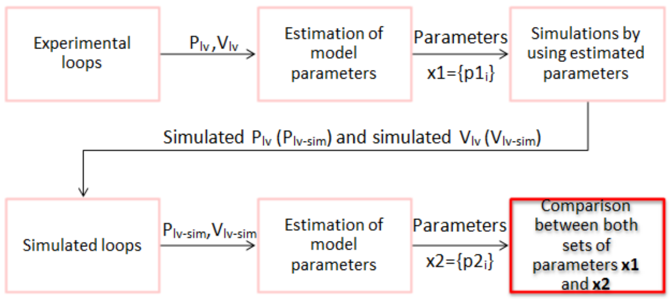

Figure 2: Test realized in order to verify the consistency of the procedure.

RESULTS AND DISCUSSION

When we perform the test described in Figure 2, we emphasize inconsistencies for some of the six models. The two sets of parameters were different. Geometrically, when we plot the isochrones using parameters values estimated from simulated loops (constructed from fitted isochrone models), they do not intercept isochrone points of these loops. This shows that parameters we estimate from simulated loops are different from those used to construct them. A zoom of an isochrone occurring in the ejection phase is represented in Figure 3.

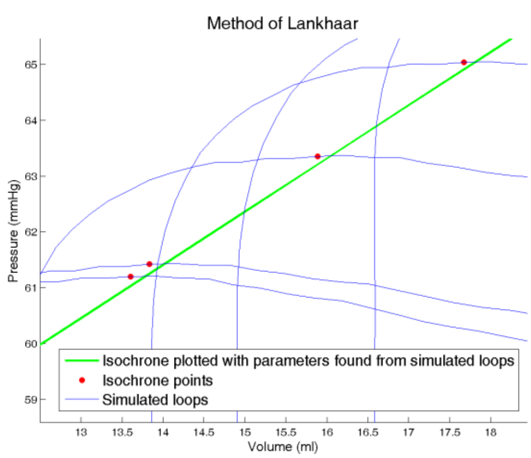

Figure 3: Zoom of an isochrone occurring in the ejection phase with the method of Lankhaar *et al.*.

The main cause of the discrepancies is the repeated use of the ESPVR in the models definition. This curve is, as usual, defined as an isophase, and not as an isochrone (Figure 1). Thus, including an isophase to estimate some parameters of an isochrone model induces inconsistencies.

In order to correct this, we replace end-systolic isophases (ESPVRs) by end-systolic isochrones in the models definition. After this modification, we observe that the two sets of parameters are equal. Furthermore, we see geometrically on Figure 4 that the isochrone plotted using parameters estimated from simulated loops intercept isochrone points.

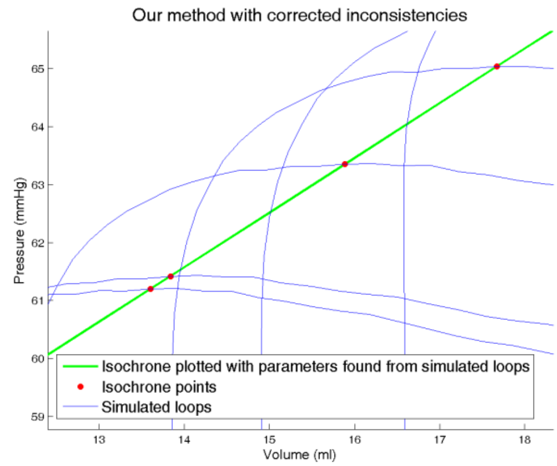

Figure 4: Zoom of an isochrone occurring in the ejection phase with our corrected method.

Another problem in [1] is the lack of precision in the determination of important landmarks of the cycles, and the lack of uniformity between the methods used for parameters estimation and those used for loops simulation. More precisely, important landmarks, such as the start of ejection, the start of filling and the end systole, are determined either differently in the two parts of the work, or with not enough precision in relation to their strict definition in the models. So, when necessary, we determine these landmarks paying attention to the uniformity and according to the definition of the models.

CONCLUSIONS

The ESPVR commonly defined as an isophase is not adapted in isochrone models. We think it is better to define an end-systolic isochrone, namely the closest isochrone to the ESPVR. Furthermore, the determination of important landmarks in the cycles requests a particular attention.

Finally, thanks to our modifications, parameters found from simulated loops are similar to those estimated from experimental data. So, the procedure seems more consistent and the models definition more precise.

ACKNOWLEDGEMENTS

This work was financially supported by the French Community of Belgium (Actions de Recherches Concertées – Académie Wallonie-Europe).

REFERENCES

1. Lankhaar J.-W. et al. Modeling the Instantaneous Pressure–Volume Relation of the Left Ventricle: A Comparison of Six Models. *Annals of Biomedical Engineering*, Volume **37**, Number 9, 1710-1726, 2009