Spectral analysis of the beat-to-beat variability of arterial compliance

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***Abstract*—Arterial compliance is an important parameter influencing ventricular-arterial coupling, depending on structural and functional mechanics of arteries. In this study, the spontaneous beat-to-beat variability of arterial compliance was investigated in time and frequency domains in thirty-nine young and healthy subjects monitored in the supine resting state and during head-up tilt. Spectral decomposition was applied to retrieve the spectral content of the time series associated to low (LF) and high frequency (HF) oscillatory components. Our results highlight: *(i)* a decrease of arterial compliance with tilt, in agreement with previous studies; *(ii)* an increase of the LF power content concurrent with a decrease of the HF power, potentially reflecting changes in vasomotor tone, blood pressure and heart rate variability associated with higher sympathetic activity and vagal withdrawal occurring with tilt.**

I. Introduction

Arterial compliance (C) is an important cardiovascular parameter characterizing mechanical and structural properties of the arteries and strongly influencing the cardiac load. Defined as the magnitude of change in the arterial volume due to a given change in arterial pressure, a decreased value of C has been associated with numerous physiological states and pathological processes [1]. Despite the great deal of effort made to include the assessment of C into routine cardiovascular examination and to interpret it as a clinically important index of vascular stiffening [2], very little is known about the short-term-variability nature of this parameter. To fill this gap, the present study aims at investigating the short-term variability of arterial compliance in both time and frequency domains. To this end, beat-to-beat time series of C measured in young healthy subjects undergoing a head-up tilt procedure using a recently developed noninvasive methodology [3] were analyzed computing standard time domain parameters as well as frequency-domain measures derived from the method of spectral decomposition [4], [5]. In particular, the use of spectral decomposition allows to retrieve the power content associated to specific oscillations with central frequency in the low frequency (LF, $0.04-0.15$ Hz) and high frequency (HF, $0.15-0.4$ Hz) bands of the spectrum. In this work, it is exploited to investigate with fine detail the presence and importance of LF oscillations within the beat-to-beat variability of C.

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II. Materials and methods

The arterial compliance time series analyzed in this study are taken from a larger database recently collected [3]. Stationary segments of 300 consecutive beats were extracted from the original recordings in the resting supine position (REST) and in the upright position reached after passive head-up tilt (TILT). In this work, only 39 subjects were selected for further analysis after visual inspection of the time series. We refer the reader to [3] for further information about the database.

Each arterial compliance time series C was taken as a realization of a stochastic process which was first characterized in the time-domain computing the first-order statistics, i.e. the mean μ_c and the variance σ_c^2. Then, the process was described using a linear autoregressive (AR) model as:

$$Y(n) = \sum_{k=1}^{p} a(k)Y(n-k) + U(n), \tag{1}$$

where p is the model order, $U(n)$ is a scalar zero-mean white process with variance σ_U^2, and $a(k)$ is the coefficient describing the interaction from $Y(n-k)$ to $Y(n)$ at lag k. Model identification was performed via the ordinary least-squares approach. Since the use of the Akaike Information Criterion sometimes led to duplicate peaks or negative power as a result of spectral decomposition [5], the model order was manually adjusted so as to detect a single component with positive power in each spectral band of interest. Representing the model coefficients in the Z domain yields the transfer function $H(z) = [1 - \sum_{k=1}^{p} a(k)z^{-k}]^{-1} = \bar{a}(z)^{-1}$. Then, applying the residue theorem, the transfer function was expressed as $H(z) = \frac{1}{\prod_k (z - z_k)}$, evidencing the poles z_k, $k = 1, \ldots, q = p/2$, i.e. the roots of $\bar{a}(z)$. The power spectral density (PSD) of the process, which can be written in the Z-domain as $S(z) = H(z)\sigma_U^2 H^*(\frac{1}{z^*})$, was expanded exploiting Heaviside decomposition with simple fractions relevant to all the poles (i.e., the poles z_k and their reciprocals $\bar{z}(k) = z^{-1}(k)$), which are fractions weighted by the relevant residuals of $S(z)$ (i.e., $r_k z_k$ and $-r_k \bar{z}_k$), to get:

$$S(z) = \sum_{k=1}^{q} S^{(k)}(z) = \sum_{k=1}^{q} [\frac{r_k z_k}{z - z_k} - \frac{r_k \bar{z}_k}{z - \bar{z}_k}]. \tag{2}$$

After deriving the PSD via the computation of (2) on the unit circle in the complex plane, the spectral profiles of the LF and HF components $S^{(\mathrm{LF})}(f)$, $S^{(\mathrm{HF})}(f)$ were computed from the poles with central frequency located in the ranges $0.04-0.15$ Hz and $0.15-0.4$ Hz, respectively, and the related variance $\sigma^2_{c,\mathrm{LF}}$ and $\sigma^2_{c,\mathrm{HF}}$ was obtained from the pole residuals.

Finally, normalized values of the spectral power were obtained dividing the variance associated to the LF and HF poles by the total variance, i.e. $P_{\mathrm{LF}} = \sigma^2_{c,\mathrm{LF}}/\sigma^2_c$ and $P_{\mathrm{HF}} = \sigma^2_{c,\mathrm{HF}}/\sigma^2_c$.

An example of spectral decomposition is shown in *Fig. 1(a)*.

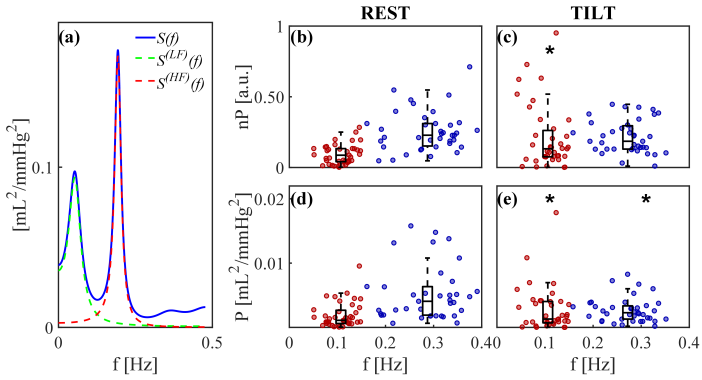

Fig. 1. Spectral analysis of the arterial compliance time series. **(a)** Example of spectral decomposition of the arterial compliance C for a representative subject monitored during tilt. The PSD of C, $S(f)$, is decomposed into components $S^{(\mathrm{LF})}(f)$ and $S^{(\mathrm{HF})}(f)$ with associated frequency f_{LF}, f_{HF} and power $\sigma^2_{c,\mathrm{LF}}$, $\sigma^2_{c,\mathrm{HF}}$. **(b)-(e)** Normalized power (nP, (b,c)) and absolute power (P, (d,e)) of C computed at rest (b,d) and during tilt (c,e); powers are depicted as boxplot distribution and individual values with coordinates $(f_{\mathrm{LF}}, \sigma^2_{c,\mathrm{LF}})$(red circles) and $(f_{\mathrm{HF}}, \sigma^2_{c,\mathrm{HF}})$(blue circles). Statistically significant differences assessed by the Student t-test for paired data: *, p<0.05 REST vs. TILT.

III. Results

The time-domain analysis (*Table 1*) revealed that both the mean μ_c and the variance σ^2_c of the arterial compliance time series decreased significantly with head-up tilt.

The results of spectral decomposition and analysis are reported in *Fig. 1(b)-(e)*, showing the boxplot distributions of the normalized (*Fig. 1(b,c)*) and absolute (*Fig. 1(d,e)*) power values of C computed within the LF (red circles) and HF (blue circles) bands, and depicted in a way such that subject-specific information relevant to the frequency location of the LF and HF spectral peaks is also provided. Statistically significant differences are detected between the two experimental conditions for both normalized and absolute LF power values, and for absolute HF power values. While the tendency of the LF power is towards an increase moving from rest to tilt (with p-values of 0.003 for normalized and 0.049 for absolute values), the HF power tends to decrease during tilt ($p > 0.05$ for normalized values, $p = 0.003$ for absolute values) Differences between absolute and normalized values might be due to between-subject variability of the arterial compliance .

TABLE I
Time domain indexes

	REST	TILT
$\mu_c[\frac{mL}{mmHg}]$	1.76 ± 0.41	1.42 ± 0.28*
$\sigma^2_c[\frac{mL^2}{mmHg^2}]$	0.022 ± 0.015	0.015 ± 0.008*

Student t-test for paired data: *, p<0.05 REST vs. TILT.

IV. Discussion and conclusion

In this study, we characterized in both time and frequency domains the short-term beat-to-beat variability of noninvasive estimates of arterial compliance. The method of spectral decomposition was applied to the AR model transfer function to retrieve spectral components with specific frequency and power. In comparison with classical methods where a spectral profile is integrated within the frequency band of interest, spectral decomposition avoids spurious contributions due to broadband oscillations, thereby allowing a more precise location of the central frequency and power content of the oscillations within a given frequency band [5].

Our results document that orthostasis challenges arterial compliance by causing a significant decrease of its mean values and variability (*Table 1*). This is in accordance with previous findings [3], [6] and suggests that, when higher sympathetic activity is assumed, the well-known changes of heart rate and total peripheral resistance via fast baroreflex mechanisms occurs together with a concomitant increase of arterial stiffness. Furthermore, it was demonstrated that vasomotion has an important influence on the arterial compliance [3]. The significant increase of LF and the decrease of HF power with tilt (*Fig. 1 (b)-(e)*) could then be ascribed to the simultaneous action of all these external influences, which mostly arise during the orthostatic stress and can be considered as an expression of the symphatetic modulation of the arterial compliance [7].

Future studies should be focused on the use of bivariate or multivariate parametric models, analyzed in the time and/or spectral domains, to investigate the coupling between arterial compliance and the variables mostly analyzed in cardiovascular variability analysis, i.e. arterial pressure, heart rate and respiration.

References

[1] N. Westerhof, N. Stergiopulos, M. I. Noble, and B. E. Westerhof, *Snapshots of hemodynamics: an aid for clinical research and graduate education*. Springer, 2010, vol. 7.

[2] D. Švec and M. Javorka, "Noninvasive arterial compliance estimation," *Physiological Research*, vol. 70, no. Suppl4, pp. S483–S494, 2021.

[3] D. Švec, B. Czippelova, J. C. Krohova, N. Mazgutova, R. Wiszt, Z. Turianikova, L. Matuskova, and M. Javorka, "Short-term arterial compliance changes in the context of systolic blood pressure influence," *Physiological Research*, vol. 70, no. Suppl 3, p. S339, 2021.

[4] G. Baselli, A. Porta, O. Rimoldi, M. Pagani, and S. Cerutti, "Spectral decomposition in multichannel recordings based on multivariate parametric identification," *IEEE transactions on biomedical engineering*, vol. 44, no. 11, pp. 1092–1101, 1997.

[5] R. Pernice, L. Sparacino, G. Nollo, S. Stivala, A. Busacca, and L. Faes, "Comparison of frequency domain measures based on spectral decomposition for spontaneous baroreflex sensitivity assessment after acute myocardial infarction," *Biomedical Signal Processing and Control*, vol. 68, p. 102680, 2021.

[6] M. Hasegawa and S. Rodbard, "Effect of posture on arterial pressures, timing of the arterial sounds and pulse wave velocities in the extremities," *Cardiology*, vol. 64, no. 2, pp. 122–132, 1979.

[7] B. Czippelova, Z. Turianikova, J. Krohova, R. Wiszt, Z. Lazarova, K. Pozorciakova, M. Ciljakova, and M. Javorka, "Arterial stiffness and endothelial function in young obese patients-vascular resistance matters," *Journal of Atherosclerosis and Thrombosis*, p. 47530, 2019.