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Insight into Local and Global Short Term Predictability of Human Photoplethysmogram

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Abstract– The photoplethysmography is one of the widely used techniques in medical settings and sports equipment to measure biological signals produced by cardiovascular system (CVS). It is recognized that the photoplethysmogram (PPG), which can be defined as the continuous recording of the light intensity scattered from a given source by the tissues and collected by a suitable photodetector, can provide valuable information about CVS performance, however, PPG dynamics is not yet fully understood [1]. This study sought to investigate properties of local (in chosen region on reconstructed trajectory) and global (overall trajectory) short-term prediction performance of the PPG. The results demonstrated certain similarities between global prediction performance of the PPG and noise induced Duffing's forced oscillator; and that local and global predictability may differ considerably, that may explain fluctuations observed in the global prediction performance and give insight into local properties of the PPG.

1. Introduction

Photoplethysmogram (PPG) is one of the widely used in applications biological signal produced by the cardiovascular system (CVS). In our previous studies it was shown that PPG dynamics is consistent with chaotic motion definition and deterministic nonlinear prediction (DNP) is one of nonlinear time series analysis methods that can provide important information about chaotic characteristics of the PPG [2].

Previously PPG predictability was compared with Rössler's single band chaos and chaotic Lorenz models; and results explicitly demonstrated that long-term prediction is impossible [2]. However, as it can be seen in Fig. 1 the correlation coefficient (CC) declining trend of their short-term DNP was considerably different, which gave rise to new questions concerning PPG predictability properties. One of them is related to the rapid decline of predictability performance in the very short range. As shown in Fig. 1, the short-term DNP's performance for Lorenz and Rössler remains high significantly longer than for PPG data. Although this difference does not put into question the existence of short-term prediction, this indicates that in very short-term evolution, Rössler's single band chaos and the PPG underlying processes have considerable differences. Therefore, one question originating from results of comparison of the PPG prediction performance with Rössler's and Lorenz predictability is what type of dynamics exhibits similar to the PPG prediction properties. Since, as seen from results shown in Fig. 1, chaotic Lorenz and Rössler's models do not possess short-term prediction properties that resemble those of the PPG, different types of chaotic models should be chosen for comparative study of the PPG's short-term prediction characteristics. As both Lorenz and Rössler's models belong to autonomous systems [3], in this study the PPG predictability is compared with a non-autonomous chaotic system. Therefore, one of the goals in this study is investigation of the PPG dynamics' short-term predictability characteristics in comparison with a well-known chaotic non-autonomous system.

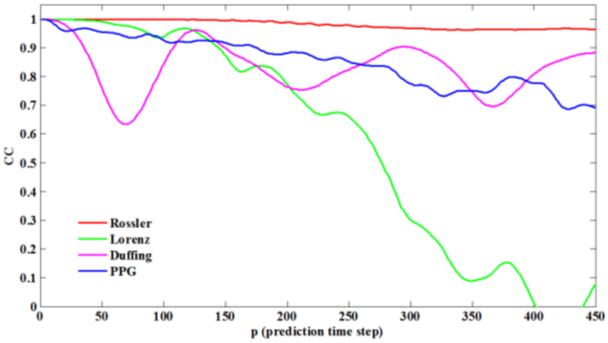


FIG. 1 CC curves for DNP of Rössler's single band chaos, chaotic Lorenz, chaotic Duffing's forced oscillator and the PPG.

Another question that inevitably arises from the DNP results of the previous studies is related to the wide fluctuation of prediction performance that can be observed in DNP's CC curve, as seen in Fig. 1. As variations in these fluctuations might be meaningful, what causes this phenomenon is another question under investigation in this study. Therefore, here particularly careful attention is paid to the short-term prediction properties of the PPG.

Conventionally the results of DNP's CC and relative root mean squared error (RRMSE) are averaged over the

PPG reconstructed trajectory and therefore correspond to the reconstructed trajectory overall. Results representing the properties of PPG dynamics obtained from whole reconstructed trajectory will be referred to herein as global scale results or properties; thus conventional prediction results shown in Fig. 1 will be called global prediction. As seen from the Poincaré sections (Fig. 2), trajectories expansion and density depend on the local region along the reconstructed attractor and therefore it can be assumed that prediction performance might differ locally on each part of the reconstructed trajectory. This possible variation of dynamical properties among different parts or regions along the reconstructed trajectory might be able to explain the considerable fluctuations observed in global prediction performance. At the same time, by itself, investigation of local dynamics properties might provide one with a deeper understanding of the PPG dynamics and as a result promote further development of PPG applications, since every region along the reconstructed attractor can be associated with the cardiac cycle's phases.

In contrast with global prediction, prediction calculated on a fixed region of the reconstructed trajectory will be called local prediction. Therefore, for a better understanding of PPG dynamics, in addition to the comparative study of global short-term prediction, this study also aims to investigate local short-term prediction.

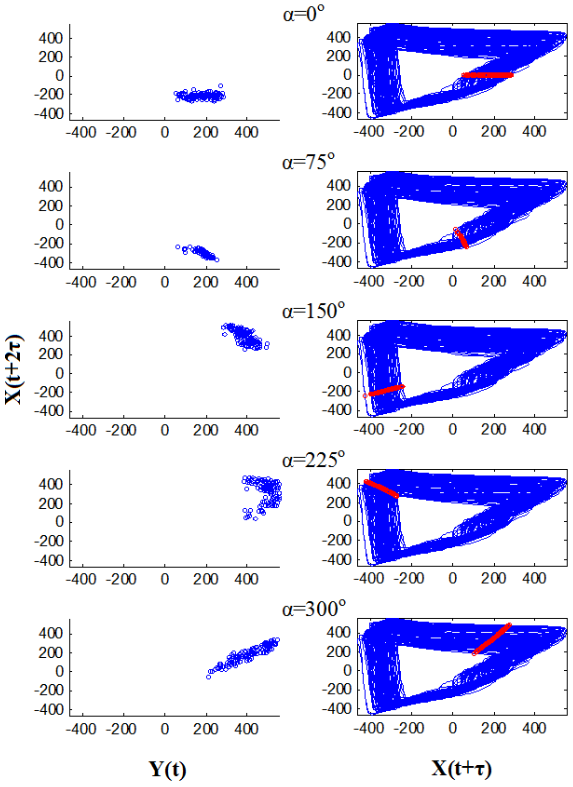


FIG. 2 Poincaré section for the PPG (left), where Y(t) = $\sqrt{x(t)^2 + x(t+\tau)^2}$ *; and the reconstructed trajectory sliced by the rotating plane for the PPG (right).*

2. Methods and Materials

2.1 Data collection

The PPG signal was recorded using a finger PPG recorder by detecting the near infrared light reflected by vascular tissue following illumination with a LED. Data were collected from nine healthy 19- to 27-year old volunteers among Tokyo University of Agriculture and Technology (TUAT) students. Experimental data collection was approved by TUAT authorities. Written informed consent was given to participants prior the experiment. At the time of the study all subjects were healthy non-smokers, physically active to similar levels, were not taking any medication, and all of them declare no history of heart disease.

For each subject five measurement repeats were done. The measured period was 5 min with 5 msec sampling steps. For all data collection sessions, a BACS (Computer Convenience, Inc.) PPG sensor was located on the right forefinger. Every measurement was preceded by a blood pressure check and was done with the subject in a relaxed sitting position in a room with temperature, noise and vibration control. Each test subject was asked to rest for 5 min under quiet conditions in the laboratory room in the same sitting position in which the recordings were obtained, and with the test site uncovered. An example of a 30-second long portion of the obtained PPG signal is shown in Fig. 3.

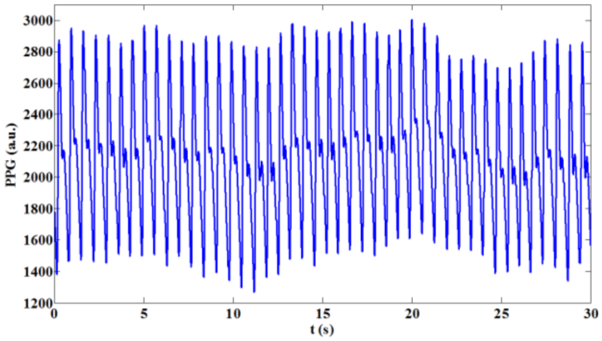


FIG. 3 *Example of 30-second long portion of the healthy young subject PPG signal.*

2.2. Comparative study of global short-term DNP

As mentioned above, in this study a non-autonomous chaotic system is used for comparative investigation of the PPG's short-term predictability. One of the well-known examples of non-autonomous systems is the chaotic Duffing's forced oscillator, which is utilized in this study. Duffing's forced oscillator is described by the following equation:

$$\ddot{x} + k\dot{x} + x^3 = B\cos(\omega t), \qquad (1)$$

where the system coefficients were chosen as $k=0.05$, $B=7.5$, $\omega=1$, which corresponds to a chaotic regime [3]. Numerical simulation was done by the 4th order Runge-Kutta method with time step 0.01.

DNP CC for Duffing's forced oscillator in comparison with Rössler, Lorenz and PPG DNP are shown in Fig. 1, where it is seen that the short-term CC curve corresponding to Duffing's data has a significantly faster drop, compared with Rössler's and Lorenz's curves.

2.3 Local DNP

In order to estimate local short-term predictability of the PPG in a fixed region on the reconstructed trajectory, CC and REMSE need to be calculated over this local region. Let t_1^i and t_2^i be starting and ending points of the i^{th} region on the reconstructed trajectory, then formulas for global prediction CC and RRMSE can be rewritten as

$$CC_i(p) = \frac{\sum_{t=t_1^i}^{t_2^i}(Z(t+p)-\bar{Z}(t+p))\big(Z^*(t+p)-\overline{Z^*}(t+p)\big)}{\sqrt{\sum_{t=t_1^i}^{t_2^i}(Z(t+p)-\bar{Z}(t+p))^2}\sqrt{\sum_{t=t_1^i}^{t_2^i}\big(Z^*(t+p)-\overline{Z^*}(t+p)\big)^2}},$$

$$RRMSE_i(p) = \sqrt{\frac{\sum_{t=t_1^i}^{t_2^i}\big(Z(t+p)-Z^*(t+p)\big)^2}{\sum_{t=t_1^i}^{t_2^i}(Z(t+p)-\bar{Z}(t+p))^2}}.$$

CC_i and $RRMSE_i$ defined by these formulas are the local correlation coefficient and relative root mean square error corresponding to the i^{th} region.

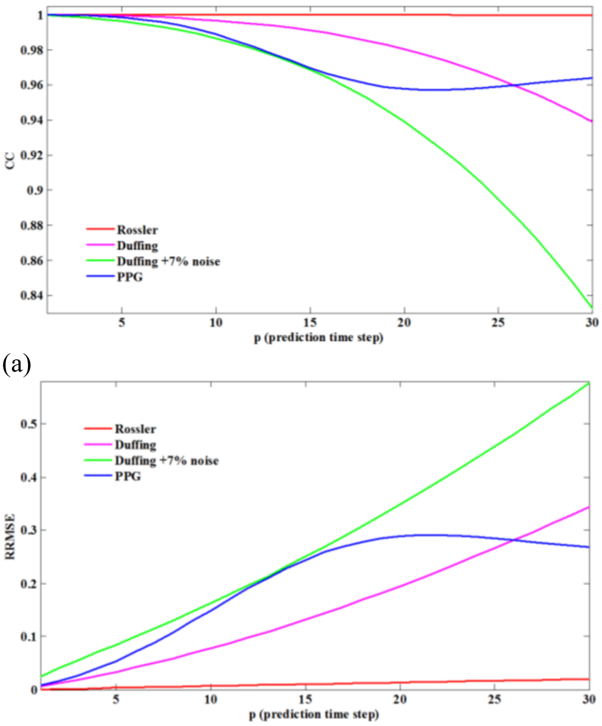
3. Results

3.1. Global short-term prediction

DNP was applied to the collected PPG data sets. Duffing's chaotic forced oscillator (1) was chosen as the model for comparison instead of Rössler and Lorenz models.

Fig. 4 (a) and (b) demonstrate short-term prediction's CC and RRMSE, respectively, for the PPG, chaotic Duffing's time series and Duffing's time series with 7% noise induction. Results for Rössler's single band chaos prediction were added to illustrate differences in prediction performance. As seen from Fig. 4, even a short-term prediction performance for both Rössler and Duffing's time series shows considerable differences, and while the CC curve for Rössler's time series does not demonstrate any noticeable decline for short-term (30 time steps forward) prediction, the CC curve corresponding to Duffing's time series has a distinguishable decline. Noise induction on the Duffing's data preserves the CC's curve declining trend and results in a decrease in the prediction performance. As is clearly seen in Fig. 4 (a), PPG short-term prediction's CC has significant similarity with 7% noise induced Duffing's forced oscillator over a range from 1 to 16 steps forward prediction; what is significant is that for both, the PPG and noise induced Duffing's data show a similar trend of a relatively rapid CC curve decline. Differences between prediction performance for the PPG and Duffing with Rössler are even more enhanced in RRMSE plots. The RRMSE for Duffing and the PPG have a rapid increase unlike the RRMSE for Rössler, which curve remains close to zero and almost flat. Additionally, DNP performance for Duffing's data and the PPG have similar high fluctuations of CC and RRMSE curves as seen in Fig. 1.

Therefore, the PPG short-term predictability has some similarity with the predictability of noise induced Duffing's forced oscillator's data rather than with Rössler.



(a)

(b)

FIG. 4 *(a) CC and (b) RRMSE curves for DNP of Rössler's single band chaos, chaotic Duffing's forced oscillator, chaotic Duffing's forced oscillator data with 7% additive noise and the PPG.*

3.2. Local regional short-term prediction

In order to achieve a better understanding of local PPG dynamics by utilizing short-term prediction, 4 regions on the reconstructed trajectory (Fig. 5, upper plot) were chosen empirically for conducting local short-term prediction.

The middle and bottom plots in Fig. 5 show the local CC and RRMSE, respectively, over the four chosen regions and global short-term DNP (blue lines). As seen in Fig. 5 in the range of 1-5 steps forward prediction there is almost no observable difference in the prediction performance between different regions on the reconstructed trajectory for the CC, while more clear differences can be seen in the RRMSE; and for predictions longer than 5 steps considerable differences in both local CC and RRMSE curve shape can be observed.

Fig. 5 demonstrates examples of local components that contribute to global short-term prediction performance after averaging along the reconstructed trajectory. With the same prediction step length, but different predictee, the predicted value may appear in a region with higher or lower averaged prediction performance, i.e. global CC or RRMSE values might be affected by local predictability. Therefore, predictability differences on the local level might be able contribute to understanding of significant fluctuations observed in global short-term predictions (Fig. 1).

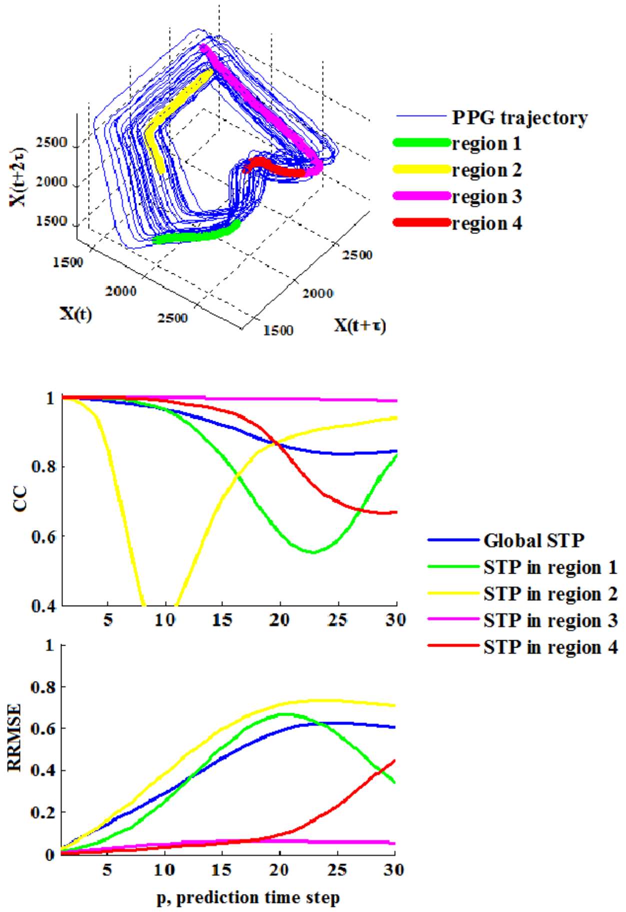


Fig. 5 *Four local regions on part of reconstructed PPG trajectory in which local short-term prediction was conducted (upper plot); CC (middle plot) and RRMSE (bottom plot) curves for local short-term deterministic nonlinear prediction in 4 regions of reconstructed PPG trajectory.*

4. Discussion

The objective of this study was to provide additional insight into the short-term predictability of the PPG as it may uncover new characteristics of PPG dynamics. Previously only the existence of short-term prediction was proven [2], while its characteristics were of no interest. Besides that, none of the numerous studies dealing with conventional or nonlinear time series analysis of the PPG have investigated the behavior of short-term predictability. However short-term prediction itself can provide useful and valuable information about the features of PPG dynamics. Thus, the performance of global short-term prediction showing rapid decline, which was not observed in the Rössler and Lorenz models, was found to be similar to short-term prediction properties of 7% noise induced Duffing's forced oscillator. Besides that, similarities in CC and RRMSE fluctuations could be observed in the PPG time series and noise induced chaotic Duffing's forced oscillator prediction performance. As Duffing's chaotic forced oscillator is classified as a non-autonomous system, these results reveal the possibility that PPG dynamics is a non-autonomous system, although further detailed investigation of the similarities between non-autonomous systems and the PPG is required.

An additional investigation of local predictability (Fig. 5) showed that depending on the region along the reconstructed trajectory, DNP performance can significantly differ from forming a slowly growing RRMSE curve to its quick rise. These differences emphasize the importance of studying local dynamics behavior. Predictability differences between local regions might be one of the reasons leading to significant fluctuations in the global CC and RRMSE curves.

5. Conclusion

In this study careful attention was paid to the performance of global as well as the local short-term DNP. Global short-term prediction was investigated by comparisons with Duffing's forced oscillator in the chaotic regime. Results of a comparative study of the PPG signal demonstrated certain similarities between global prediction performance of the PPG and 7% noise induced Duffing's forced oscillator. Based on these results it is expected that further comparative investigation of the PPG and non-autonomous systems might be beneficial for revealing the PPG dynamics properties.

Additional analysis of local predictability demonstrated that local regions along the reconstructed attractor have considerably different predictability. Since different areas on the PPG attractor refers to different phases of blood pulsation information of local, differences between regions on the reconstructed PPG trajectory might provide useful data for new application studies and a deeper understanding of the PPG dynamics. However, further investigation of the local characteristics of the reconstructed dynamics is required.

Acknowledgments

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