Chapter 6

Conclusions and Future Perspectives

Periodic blood volume change underneath a person's skin induces subtle color variations in the skin area. These subtle changes can be captured by a noninvasive and low-cost optical technique called photoplethysmography (PPG). The methods of PPG measurement have evolved in the past decades from using contact-based devices (e.g., fingertip PPG from the pulse oximeters) to using contactless devices (e.g., remote PPG from the RGB cameras). In this dissertation, we studied the modeling of contact-based and contact-free PPG signals to facilitate its promising applications in cardiovascular signal and vital sign sensing and learning for digital smart health.

In the first part of the dissertation (Ch. 2), we explored the potential of user-friendly and continuous electrocardiogram (ECG) monitoring with the help of contact-based PPG sensors. ECG is a clinical gold standard for non-invasive cardiac monitoring. Given that continuous ECG monitoring in consumer products is challenging, PPG provides a low-cost alternative, though it provides less clinical knowledge compared to ECG. How to leverage the advantages of these two measurement modalities for better and easier healthcare? We approached this problem by first studying the physiological and signal relationship between PPG and ECG signals, and then inferring the waveform of ECG via the PPG signals based on their relationship. To address this cardiovascular inverse problem, joint dictionary learning frameworks were proposed to learn the mapping that relates the sparse domain coefficients of each PPG cycle to those of the corresponding ECG cycle. This line of research has the potential to fully utilize the easy measurability of PPG and the rich clinical knowledge of ECG for better preventive healthcare.

In the second part of the dissertation (Ch. 3), we developed a physiological digital twin for personalized continuous cardiac monitoring. Digital twins are emerging as a promising framework for realizing precision health for their ability to represent an individual's health status. Using our proposed dictionary learning based algorithm in Ch. 2 as the backbone model, this chapter of the dissertation focused on the problem of inferring ECG signals from PPG signals for continuous precision cardiac monitoring under realistic conditions in which available ECG data is scarce. By performing transfer learning, a generic digital twin model learned from a large portion of paired ECG and PPG data was fine-tuned to precisely infer the ECG from the PPG of a target participant whose available ECG data are scarce. Experimental results showed that the proposed transfer learning method yielded the best ECG reconstruction accuracy compared to other baseline comparison models, which suggested that it could be used as a reliable digital twin for precision continuous cardiac monitoring. In parallel, convolutional neural network based backbone model designs were also proposed based on the underlying physiological process of ECG generation for better explainability.

In the third part of the dissertation (Ch. 4 and Ch. 5), we presented a noncontact method of blood oxygen saturation (SpO_2) monitoring from remote PPG signals captured by smartphone cameras. SpO_2 is an important indicator of pulmonary and respiratory functionalities. Recent works have investigated how ubiquitous smartphone cameras can be used to infer SpO_2. Most of these works are contact-based, requiring users to cover a phone's camera and its nearby light source with a finger to capture reemitted light from the illuminated tissue. Contact-based methods may lead to skin irritation and cross contamination, especially during a pandemic. Thus, we aimed for contactless methods for SpO_2 monitoring using hand videos acquired by regular RGB cameras of smartphones. Both principled signal processing based method and data-driven neural network based method were proposed for SpO_2 estimation by either explicitly or implicitly extracting features from multi-channel skin color signals with color channel mixing and temporal analysis. Experimental results showed that our proposed methods could achieve better accuracy of blood oxygen estimates compared to traditional methods using only two color channels and prior arts.