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Computational Study of Sleep Apnea

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Sleep Apnea is a serious sleep disorder in which the breathing repeatedly starts and stops during asleep. The present work is to explore the use of the cardiopulmonary parameters to diagnose Sleep Apnea. In quite breathing, negative pleural pressure (Ppl) in inspiration phase slightly increases right ventricle stroke volume and pulmonary flow but decreases left ventricle stroke volume. This paper analyzed the effect of sleep apnea using the intra-pleural pressure change during inspiration and expiration and generating a waveform. For this, the breathing pattern of the sleep apnea is introduced ex vivo by varying the pleural pressure from the range -2mmHg to -5mmHg in a hybrid cardiopulmonary electrical analogous model based on clinically obtained healthy controls with a breathing frequency of 13Hz. The results can be used to study the cardiopulmonary effects in sleep apnea. The culmination of this study offers valuable insights into the intricate interplay between cardiopulmonary factors and sleep apnea. By examining the generated waveforms under varying pleural pressures, a deeper understanding of the effects of sleep apnea on the cardiovascular and pulmonary systems is achieved. The results derived from this analysis have the potential to significantly contribute to the comprehensive study of the physiological ramifications of sleep apnea on the cardiovascular and pulmonary systems. These findings hold promise for advancing both the diagnostic techniques and the overall management strategies for sleep apnea, ultimately improving the quality of life for those affected by this disorder.

Keywords: Cardiopulmonary parameters, Sleep Apnea, Intra-pleural pressure.

I. INTRODUCTION

Sleep apnea, a prevalent sleep disorder affecting millions globally, poses significant health risks if left untreated. Conventional diagnostic methods and treatment approaches have inherent limitations, necessitating innovative solutions to improve patient outcomes. In recent years, the computational study of sleep apnea has emerged as a transformative avenue to address these challenges comprehensively. This study explores the multifaceted motivations driving the proposed work in the computational study of sleep apnea, emphasizing its potential to revolutionize sleep medicine, enhance patient care, and contribute to the broader understanding of sleep disorders.

The primary motivation behind the proposed work is to revolutionize sleep apnea diagnosis. Traditional diagnostic procedures, such as polysomnography (PSG), are labor-intensive, costly, and often inaccessible to large segments of the population.

Computational models, harnessing machine learning algorithms and big data analysis, offer an opportunity to process vast amounts of sleep-related physiological signals efficiently. This leads to more accurate and timely diagnoses, allowing for early intervention and preventing the progression of sleep apnea-related complications. Sleep is a complex phenomenon, involving intricate interactions between various physiological systems. The computational study of sleep apnea seeks to unravel the underlying complexities of sleep physiology. By employing sophisticated mathematical models and simulations, researchers can explore the dynamics of respiratory control, airway anatomy, and neural responses during sleep. These insights offer a deeper understanding of the pathophysiology of sleep apnea, paving the way for targeted therapeutic interventions.

Sleep apnea manifests differently across individuals due to varying anatomical, genetic, and lifestyle factors. The proposed work aims to leverage computational models to implement personalized medicine in sleep apnea management. Integrating patient-specific characteristics into the models allows for tailored treatment plans that address the unique needs of each individual. This approach not only enhances treatment effectiveness but also improves patient compliance and overall satisfaction with therapy. Treatment optimization is another driving motivation of the proposed work. Computational simulations can simulate the effects of different treatment options, from continuous positive airway pressure (CPAP) therapy to oral appliances and surgical interventions. By comparing treatment outcomes across a diverse range of patient profiles, researchers can identify the most effective and efficient interventions for specific subgroups, ensuring more precise and targeted treatment recommendations. The integration of computational algorithms with wearable devices holds immense promise for sleep apnea management. The proposed work may lead to the development of advanced wearable sensors that monitor sleep patterns and respiratory events in real-time.

Such devices facilitate remote monitoring, enabling telemedicine consultations and empowering patients to actively participate in their care. The seamless data collection and analysis provide healthcare providers with crucial insights, leading to prompt adjustments in treatment plans as needed. Its association with cardiovascular diseases, hypertension, diabetes, and cognitive impairments necessitates urgent solutions. The proposed work, through its potential to enhance diagnosis, treatment, and management, has the capacity to positively impact public health. Timely and effective sleep apnea management can reduce the incidence of related comorbidities, alleviate the burden on healthcare systems, and improve overall quality of life for millions.

The motivation behind the proposed work in the computational study of sleep apnea is driven by a profound

commitment to advancing sleep medicine and transforming patient care. By harnessing the power of computational methods, researchers endeavor to refine diagnosis, uncover the intricacies of sleep physiology, and develop personalized treatment strategies. The potential to optimize therapies, create innovative wearable devices, and positively influence public health underscores the ground-breaking nature of this work.

II. Literature Review

Experimental analysis of sleep apnea diagnosis has been conducted using various methods. One study focused on the analysis of heart rate variability features using frequency, time, and time-frequency methods to diagnose obstructive sleep apnea (OSA) from electrocardiogram (ECG) signals [1]. Another study utilized the Koopman spectral analysis method to characterize the intermittent transition between apneic and non-apneic episodes in OSA patients [2]. Synchronization between different EEG channels was investigated using continuous wavelet transform in order to identify biomarkers in the electrical activity of the brain during sleep associated with OSA [3]. Additionally, a study evaluated the reliability of cardiopulmonary coupling (CPC) analysis, an ECG-based technique, for the detection of OSA and found that CPC analysis yielded acceptable results compared to polysomnography [4]. These experimental analyses provide insights into the pathophysiological processes and potential diagnostic approaches for sleep apnea.

Also, Experimental analysis carried out in diagnosing sleep apnea includes the evaluation of cardiopulmonary coupling (CPC) analysis [6], the development of an automated fuzzy entropy-based method for detecting apnea/hypopnea using single-lead electroencephalogram signals [7], the measurement of the severity of OSA using various methods such as apnea-hypopnea index (AHI), oxygen desaturation, and daytime sleepiness [8], the use of deep learning algorithms for sleep apnea detection and quantification using statistical features of ECG signals [9], and the study of electrical activity of the brain using Electroencephalogram (EEG). These experimental approaches aim to improve the accuracy, convenience, and cost-effectiveness of sleep apnea diagnosis, providing potential applications in sleep medicine.

Computational studies on sleep apnea have also been conducted to improve the diagnosis and treatment of the disorder. Researchers have used computer simulations to analyze airflow and soft tissue dynamics in order to identify optimal patient interventions. These studies have correlated computer-derived biomechanical variables with clinical measures of sleep apnea severity, such as the apnea-hypopnea index (AHI) [10]. Anatomic and physiologic variables, including airspace cross-sectional areas, volumes, and airflow resistance, have been found to correlate with sleep apnea severity. However, no studies have yet correlated computer-derived dynamic measures of upper airway mechanical stability to sleep apnea severity. The use of computational fluid dynamics has also allowed for the assessment of airflow characteristics and functional evaluation of the upper airway, providing valuable information for diagnosis and treatment planning.

It marks the first instance of a segment-based assessment of heart rate variability (HRV) that encompasses sleep stages and apneic events in children. Furthermore, it introduces the progression of HRV metrics within paediatric obstructive sleep apnea (OSA)-specific frequency ranges across different sleep stages.

III.METHODOLOGY

Normally, the diagnosis of sleep apnea has relied on conventional methods, with polysomnography (PSG) being the gold standard. However, this project seeks to explore an alternative approach by focusing on intra-pleural pressure change (Ppl) as a diagnostic parameter. The aim is to develop a simplified and cost-effective method for diagnosing sleep apnea, leveraging Matlab for numerical simulations. The project employs Matlab to conduct numerical simulations for diagnosing sleep apnea. The intra-pleural pressure changes during sleep, is imported into Matlab for analysis. This data represents both normal and apnea conditions. The imported data is initially examined within Matlab, providing insight into the raw information and its characteristics. Matlab's signal processing functions are applied to ensure the reliability of subsequent analyses. Further preprocessing steps are performed to optimize the data for simulation and analysis. A developed mathematical cardiovascular model is used which closely mimicks the physiological responses during sleep, including the effects of sleep apnea. Model parameters are fine-tuned based on case studies. After the cardiovascular model is tuned, it is used to extract critical parameters from the simulated data. Key parameters, such as time and amplitude, are meticulously analyzed to identify the most suitable parameter for the diagnosis of sleep apnea.

The project aims to distinguish sleep apnea from normal breathing patterns by simulating intra-pleural pressure changes and utilizing the computational cardiovascular model. This analysis focuses on identifying varying sleep apnea waveforms compared to normal breathing patterns, primarily focusing on changes in amplitude. The study also explores different degrees of apnea severity, ranging from mild to severe, to analyze cardiovascular parameter changes. However, it's important to note that this analysis may lack validation. The project mainly focuses on: Investigating the feasibility of using intra-pleural pressure change as a novel parameter for diagnosing sleep apnea, offering a simplified and cost-effective alternative to conventional methods like PSG. Identifying and validating specific parameters, such as changes in amplitude, to effectively differentiate sleep apnea from normal breathing patterns. Exploring the potential of the model to distinguish varying degrees of apnea severity, although validation for this aspect is not included in the study.

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This project report investigates a method for diagnosing sleep apnea with the goal of numerically characterizing the cardiovascular systems by developing a detailed hybrid cardiopulmonary (CP) model.

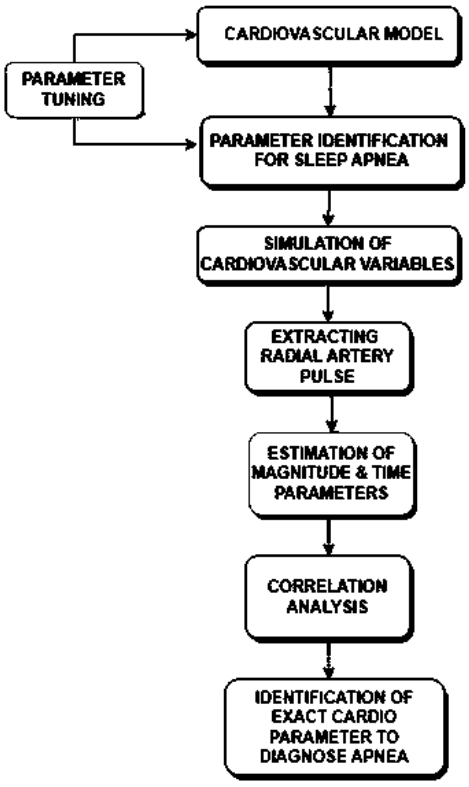

Fig 3.1. Methodology flow chart

IV.MATHEMATICAL MODELLING

This chapter explains the hybrid cardiopulmonary mathematical model rooted in the physiological principles. Amidst various modeling approaches, the current model amalgamates the advantages inherent in lumped parameter modeling and distributed parameter modeling. Lumped parameter modeling offers numerous benefits, particularly in simulating the overall dynamics of cardiopulmonary system components, with the exception of the hemodynamics of the arterial tree system. On the other hand, the distributed modeling approach excels in elucidating the wave propagation phenomena within the arterial tree system. Consequently, the current model harnesses the strengths of both modeling approaches mentioned above. The cardiovascular model consists of sub models for the mechanics of the atrium and ventricles, the cardiac valves, the direct ventricular interaction through the septum, the systemic and pulmonary circulation, the venous system, and the effect of the pericardium on heart pumping efficiency. Among the many models described in the literature, the circulation model used in this research is an adaptation of Sun et al (1997). They used a thorough depiction of the heart and valves in their model. To effectively simulate CP physiology, the aforementioned model did not consider the following critical elements: the physiology of the respiratory system; intrathoracic pressure; and the influence of respiration on CVS. It also included an abstract model of the baroreflex, which only regulates cardiac duration.

Consequently, this model captures the direct pressure interplay between the RV and LV through the interventricular septum.

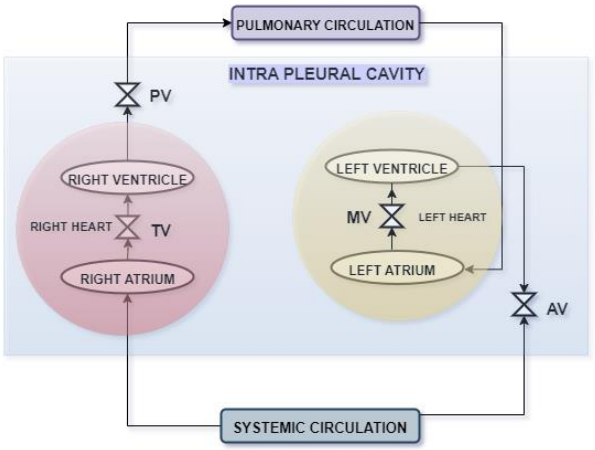

Fig 4.1. Schematic diagram of cardiovascular system model (TV- Tricuspid valve, PV- Pulmonary valve, MV- Mitral calve and AV-aortic valve) Courtesy: Hemalatha et al

Equation to simulate the waveform for sleep apnea:

$$P_{pl} = \begin{cases} -2.17\sin(2\pi f1\, t) - 5.6 & 0 \le t \le 120 \\ -5.5 & 120 < t < 144 \\ -2.17\sin(2\,\pi\, f1\, t) - 5.6 & 124 < t < 264 \end{cases}$$

Where,

f = 15 Hz, f1 = f/60, t = 264 seconds

V. RESULTS AND DISCUSSION

The right ventricle and right atrium elastance are formulated and the simulated elastance plot is shown in figure 5.1

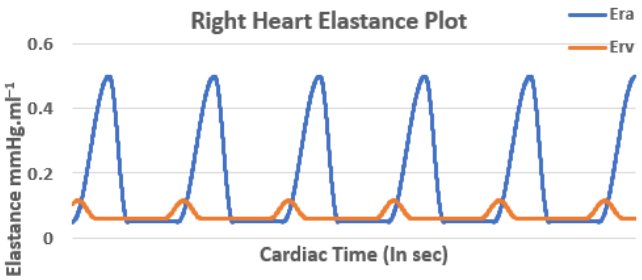

Fig 5.1. Right Heart Elastance plot

The change is identified by finding original peak and apnea peak using the apnea waveform.

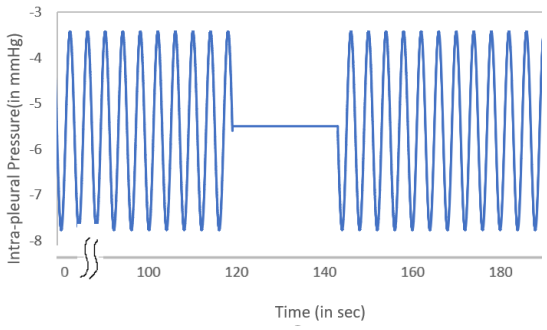

Fig.5.2 Sleep Apnea waveform

Figure 5.2 illustrates the breathing pattern observed during episodes of sleep apnea, characterized by the temporary cessation of breath in the course of regular respiration. The graph is constructed by tracking alterations in intra-pleural pressure during both normal respiration and apneic episodes. The graph demonstrates typical breathing in a sinusoidal pattern up to the 120th second, followed by a 24-second pause with no variation in intra-pleural pressure, signifying a severe apnea episode. Subsequently, normal breathing patterns resume. These intra-pleural pressure changes serve as essential input values in our cardiovascular model, which yields the subsequent findings.

Differences in cardiovascular parameters between normal and apnea conditions were assessed, with a focus on identifying the most significant parameter that displayed substantial disparities between the two. Graphs depicting cardiovascular parameters were plotted, and the contrasts in values during normal and apnea respiration is observed.

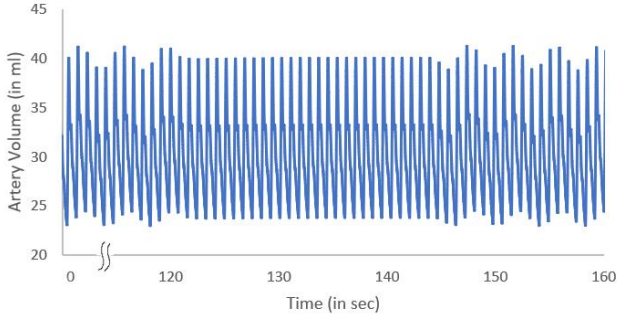

Fig 5.3. Artery Volume

Figure 5.3 provides a visual representation of variations in artery volume throughout sleep apnea episodes. This figure highlights how there is a fluctuation in artery volume during these apnea episodes, which is distinctive from the stable artery volume observed during normal conditions.

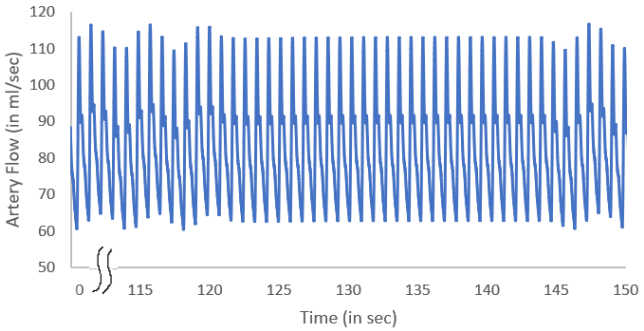

Fig 5.4. Artery Flow

Figure 5.4 depicts alterations in artery flow associated with sleep apnea, demonstrating a reduction in flow rate during apnea and a return to normal levels during regular conditions.

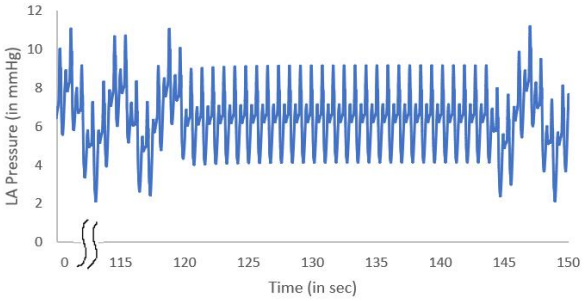

Fig 5.5. LA Pressure

Figure 5.5 offers a visual representation of changes in left arterial pressure during sleep apnea. This figure demonstrates the shift in left atrial pressure patterns in response to sleep apnea, in contrast to the stable pressure levels observed under normal conditions.

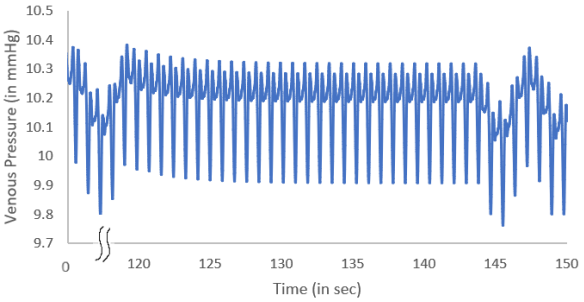

Fig 5.6. Venous Pressure

Figure 5.6 presents a graphical depiction of variations in venous pressure during sleep apnea. This figure highlights the alterations in venous pressure as a response to sleep apnea.

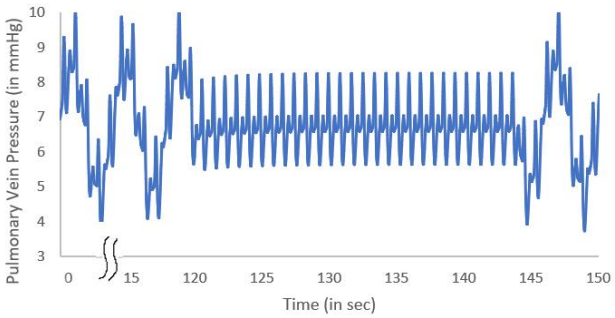

Fig 5.7. Pulmonary Vein Pressure

Figure 5.7 displays the alterations in pulmonary vein pressure during sleep apnea

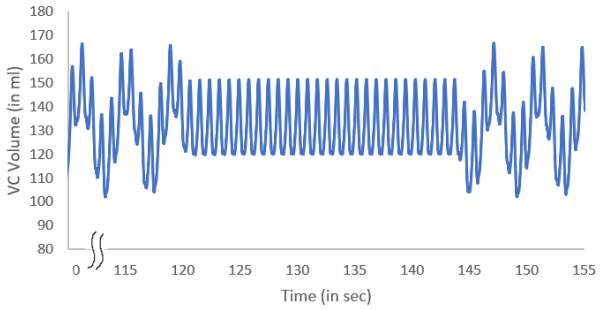

Fig 5.8. VC Volume

Figure 5.8 portrays variations in VC (venous compliance) volume during sleep apnea. This figure underscores the fluctuations in VC volume associated with sleep apnea, which contrast with the regular volume levels observed during normal condition.

VI. CONCLUSION

In conclusion, this project demonstrates a novel approach to diagnosing sleep apnea using cardiopulmonary parameters and a hybrid cardiopulmonary electrical analogous model. The traditional methods for diagnosing sleep apnea suffer from inconveniences, high costs, and limited availability, often requiring overnight stays in specialized facilities. By exploring the use of intra-pleural pressure and its impact on cardiovascular parameters, this study offers a promising alternative. The results highlight specific parameters, such as VC Volume, as strong diagnostic markers for identifying apneic conditions, providing a non-invasive and patient-friendly means of assessment. The integration of MATLAB through numerical simulation concept in this research further underscores its value in advancing medical science and enhancing our understanding of complex health conditions.

The potential for collecting patient-specific data opens doors for further advancements in this field, offering a more personalized approach to diagnosis and treatment. Ultimately, these findings have the potential to revolutionize both diagnostic techniques and overall management strategies for sleep apnea. This, in turn, can significantly improve the quality of life for those affected by this disruptive sleep disorder.

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