CAN A SMART RING IMPROVE SLEEP? INVESTIGATING THE EFFECT OF A 4-WEEK OURA RING TRIAL ON SLEEP DURATION AND QUALITY

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ABSTRACT

Juliette Levet-Bourtayre: Can a Smart Ring Improve Sleep? Investigating the Effect of a 4-Week Oura Ring Trial on Sleep Duration and Quality
(Under the direction of Malia N.M. Blue)

This study evaluated the effects of a smart ring on sleep and cardiovascular health in middle-aged adults. Twenty-six individuals (57.7% female; age [Mean±SD]: 49.2±5.2 years) were given an Oura Ring and full access to its associated smartphone application for 4 weeks. Changes in objective sleep outcomes (duration, latency, efficiency), subjective sleep quality, arterial stiffness, and heart rate variability (HRV) were evaluated over the duration of the study. There were no significant changes in sleep duration ($p=0.427$), latency ($p=0.739$), efficiency ($p=0.990$), or quality ($p=0.923$) across the 4 weeks. Additionally, there were no significant changes in arterial stiffness ($p=0.691$) or HRV ($p=0.438$). These results suggest that in middle-aged adults, the standalone use of an Oura Ring for 4 weeks is not enough to elicit changes in sleep and subsequent changes in cardiovascular health. Future research should evaluate Oura Rings in conjunction with other intervention strategies to improve sleep and overall health.

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LIST OF ABBREVIATIONS

%fat	Body fat percentage
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
ANS	Autonomic nervous system
AS	Arterial stiffness
BMI	Body mass index
CBT-I	Cognitive behavioral therapy for insomnia
cfPWV	Carotid-femoral pulse wave velocity
CI	Confidence interval
cm	centimeters
CV	Cardiovascular
CVD	Cardiovascular disease
ECG	Electrocardiogram
HRV	Heart rate variability
hrs or h	Hours
kg/m^2	Kilograms per square meter
m/s	Meters per second
min	Minutes
ms	Milliseconds
MVPA	Moderate-to-vigorous physical activity
NREM	Non-rapid eye movement
NSF	National Sleep Foundation

PNS	Parasympathetic nervous system
PPG	Photoplethysmography
PROMIS	Patient-Reported Outcomes Measurement Information System
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
PWV	Pulse wave velocity
REM	Rapid eye movement
RMSSD	Root mean square of successive differences
RQ	Research question
SD	Standard deviation
SNS	Sympathetic nervous system
TT	Transit time
WHM	Wearable health monitor
wk	Week
yrs	Years

CHAPTER I: INTRODUCTION

Introduction to Topic

Sleep, which is vitally important for proper physiological function, is a multidimensional behavior consisting of components such as duration, latency, and efficiency (1). Specifically, sleep plays a crucial role in the function and health of cognitive, cardiovascular (CV), metabolic, and endocrine systems (2). Despite its importance, many individuals experience suboptimal sleep duration and poor sleep quality, which have been linked to negative health outcomes, including increased risk of cardiovascular disease (CVD), obesity, diabetes, and all-cause mortality (2–6). In the U.S., the majority of CVD diagnoses occur during middle-age (40 to 59 years old) (7,8). Additionally, in 2020, middle-aged adults had the highest prevalence of short sleep duration compared to other age groups which may play a role in the development of CVD (9–11). Due to the high prevalence of short sleep duration and CVD in middle-aged adults, developing effective ways of improving sleep, in an effort to decrease CVD risk, is essential in this population.

Influence of Sleep on the Cardiovascular System

Suboptimal sleep has been associated with a variety of CVDs including hypertension, coronary heart disease, and myocardial infarction (12,13). In 2022, healthy sleep was added as a component of CV health by the American Heart Association, highlighting the importance of sleep as a modifiable CVD risk factor (14). During optimal sleep, parasympathetic nervous system (PNS) activity is increased while sympathetic nervous system activity (SNS) is decreased (15). This change in autonomic balance leads to

reductions in heart rate, blood pressure, vascular resistance, and an overall decreased burden on the CV system which is essential for proper function (15). Previous research has found that suboptimal sleep is associated with increased inflammation and endothelial dysfunction which can lead to arterial stiffening, reduced heart rate variability (HRV), and atherosclerosis, all of which are associated with increased CVD risk (13,16–21). Given the significant global health and economic burdens associated with CVDs, finding effective ways to reduce CVD risk is imperative (22). Interventions that target sleep may offer a viable approach to reducing CVD risk. However, additional research is needed to identify feasible and effective sleep interventions.

Wearable Health Monitors as a Sleep Intervention Method

Interventions focused on improving sleep are important to support overall health. However, existing sleep interventions are often time-consuming and burdensome. They often involve highly skilled practitioners that create educational content and implement coaching sessions (23,24). Additionally, changes in sleep are commonly assessed with expensive technology and time-intensive laboratory visits (23,24). These barriers limit the feasibility and accessibility of sleep interventions and assessments, highlighting the need to explore other ways of improving sleep.

According to the Health Belief Model, "cues to action" may trigger changes in behaviors, therefore integrating "cues to action" into a sleep intervention may facilitate change (25,26). Wearable health monitors (WHMs) provide users with extensive feedback and "cues to action" about their health behaviors. For example, users may receive reminders to start winding down for sleep or to walk around during extended bouts of sedentary behavior. These cues may support the user's ability to self-regulate their sleep behaviors and

health (26,27). However, the existing literature investigating the effects of WHM use on sleep is limited. To our knowledge, a single study has shown that the standalone use of a wrist-worn WHM significantly improved perceptions of sleep quality in healthy adults (28). Although the use of a WHM may be a feasible way to intervene on sleep, there are potential limitations of using a wrist-worn device (29,30). A study found that only 1/3 of participants classified a wrist-worn actigraph as "comfortable" while sleeping, with most participants expressing discomfort due to the light and wristband of the device (29).

An alternative to traditional wrist-worn WHMs is the Oura Ring, a commercially-available smart ring. Oura Rings provide validated objective measures of sleep along with personalized recommendations and guidance which are delivered through a smartphone application (31–33). However, the effectiveness of this technology to change sleep behaviors remains unclear as existing research has not established whether receiving insights leads to meaningful improvements in sleep outcomes. Understanding if the use of an Oura Ring can improve sleep and sleep-associated CV health factors (e.g., arterial stiffness [AS] and HRV) may have important implications for future sleep interventions and recommendations.

Statement of Purpose

The overall purpose of this study was to investigate if sleep outcomes and cardiovascular health outcomes change during a 4-week Oura Ring trial in middle-aged adults.

Specific Aims

Aim 1A. To evaluate if objective sleep outcomes (duration, latency, and efficiency) change throughout a 4-week Oura Ring trial in adults between 40 and 59 years old.

Sleep duration, latency, and efficiency were assessed weekly (Week 1: Days 1-7, Week 2: Days 8-14, Week 3: Days 15-21, and Week 4: Days 22-28) by a 3rd

generation Oura Ring. For duration, participants were classified as short (<7 hours [hrs]), long (>9 hrs), or optimal (7-9 hrs) sleepers based on Week 1 data.

Aim 1B. To evaluate if subjective sleep quality changes following a 4-week Oura Ring trial in adults between 40 and 59 years old.

Sleep quality was assessed prior to and following the trial by the Pittsburgh Sleep Quality Index (PQSI) questionnaire.

Exploratory Aim. To evaluate if changes in sleep duration, latency, and efficiency impact arterial stiffness and heart rate variability following a 4-week Oura Ring trial in adults between 40 and 59 years old.

Arterial stiffness (AS) was measured by carotid-femoral pulse wave velocity (cfPWV) prior to and following the trial. Heart rate variability (HRV) was assessed by a 3rd generation Oura Ring at 2 timepoints: Week 1 (Days 1-7) and Week 4 (Days 22-28).

Research Questions (RQ)

Aim 1A:

- RQ_1: Does sleep duration measured by an Oura Ring change throughout a 4-week Oura Ring trial in adults between 40 and 59 years old?
- RQ_2: Does sleep latency measured by an Oura Ring change throughout a 4-week Oura Ring trial in adults between 40 and 59 years old?
- RQ_3: Does sleep efficiency measured by an Oura Ring change throughout a 4-week Oura Ring trial in adults between 40 and 59 years old?

Aim 1B:

- RQ_4: Does subjective sleep quality measured by the PSQI change following a 4-week Oura Ring trial in adults between 40 and 59 years old?

Exploratory Aim:

- RQ_5: If objective sleep duration changes throughout a 4-week Oura Ring trial, is this change associated with a change in AS in adults between 40 and 59 years old?
- RQ_6: If objective sleep latency changes throughout a 4-week Oura Ring trial, is this change associated with a change in AS in adults between 40 and 59 years old?
- RQ_7: If objective sleep efficiency changes throughout a 4-week Oura Ring trial, is this change associated with a change in AS in adults between 40 and 59 years old?
- RQ_8: If objective sleep duration changes throughout a 4-week Oura Ring trial, is this change associated with a change in HRV in adults between 40 and 59 years old?
- RQ_9: If objective sleep latency changes throughout a 4-week Oura Ring trial, is this change associated with a change in HRV in adults between 40 and 59 years old?
- RQ_{10}: If objective sleep efficiency changes throughout a 4-week Oura Ring trial, is this change associated with a change in HRV in adults between 40 and 59 years old?
- RQ_{11}: Does AS assessed by cfPWV change following a 4-week Oura Ring trial in adults between 40 and 59 years old?
- RQ_{12}: Does HRV measured by an Oura Ring change throughout a 4-week Oura Ring trial in adults between 40 and 59 years old?

Research Hypotheses

Aim 1A:

- H_1: Throughout the 4-week trial, there will be an improvement in sleep duration for short (< 7 hrs) and long sleepers (> 9 hrs). There will be no change in sleep duration for individuals within the optimal range of 7 to 9 hours. Significant increases in sleep duration will be seen for short sleepers and significant decreases will be seen for long sleepers.
- H_2: Throughout the 4-week trial, there will be significant decreases in sleep latency.
- H_3: Throughout the 4-week trial, there will be significant increases in sleep efficiency.

Aim 1B:

- H_4: Following the 4-week trial, there will be an improvement in subjective sleep quality. Post-trial PSQI scores will be significantly lower than pre-trial PSQI scores.

Exploratory Aim:

- H_5: For short sleepers, if significant increases in sleep duration are present throughout the 4-week trial, there will be a negative association between change in sleep duration and AS. Such as, increased sleep duration will be associated with decreased cfPWV. For long sleepers, if significant decreases in sleep duration are present throughout the 4-week trial, there will be a positive association between change in sleep duration and AS. Such as, decreased sleep duration will be associated with decreased cfPWV.
- H_6: If significant changes in sleep latency are present throughout the 4-week trial, there will be a positive association between change in sleep latency and AS. Decreased sleep latency will be associated with decreased cfPWV.

- H_7: If significant changes in sleep efficiency are present throughout the 4-week trial, there will be a negative association between change in sleep efficiency and AS. Increased sleep efficiency will be associated with decreased cfPWV.
- H_8: For short sleepers, if significant increases in sleep duration are present throughout the 4-week trial, there will be a positive association between change in sleep duration and HRV. Such as, increased sleep duration will be associated with increased HRV. For long sleepers, if significant decreases in sleep duration are present throughout the 4-week trial, there will be a negative association between change in sleep duration and HRV. Such as, decreased sleep duration will be associated with increased HRV.
- H_9: If significant changes in sleep latency are present throughout the 4-week trial, there will be a negative association between change in sleep latency and HRV. Decreased sleep latency will be associated with increased HRV.
- H_{10}: If significant changes in sleep efficiency are present throughout the 4-week trial, there will be a positive association between change in sleep efficiency and HRV. Increased sleep efficiency will be associated with increased HRV.
- H_{11}: Following the 4-week trial, there will be an improvement in AS. Post-trial cfPWV will be significantly lower than pre-trial cfPWV.
- H_{12}: Throughout the 4-week trial, there will be an improvement in HRV. Week 4 HRV will be significantly higher than Week 1 HRV.

Assumptions

Theoretical

- Participants provided accurate responses to questionnaires.
- Participants adhered to pre-assessment guidelines.

- Participants wore the Oura Ring as instructed.
- Participants reviewed sleep guidance and recommendations on the Oura Ring smartphone application.

Statistical

- The population from which the sample is drawn are normally distributed.
- For regression analyses, data have a linear relationship.
- For regression analyses, data are independent with minimal collinearity between variables.

Delimitations

- Participants were screened to confirm their age was between 40 and 59 years old and body mass index (BMI) was between 18.5 and 34.99 kg/m^2.
- Participants were screened to confirm they had no prior history of sleep disorders.
- AS measurements were collected in a quiet location following at least 10 minutes of rest.
- Sleep outcomes and HRV were collected by a validated, real-world method.

Limitations

- Recruitment of a specific population limits generalizability to other populations such as children, young adults, and elderly.
- Participants were recruited from the Raleigh-Durham-Chapel Hill area in North Carolina. Therefore, the study sample may not be representative of the entire U.S. population.
- The quasi-experimental study design did not include a control group for comparison.

Significance of Study

This study has the potential to identify the use of an Oura Ring and its associated smartphone application as an effective intervention for improving sleep. The results of this study could support the future development of sleep interventions using Oura Rings. This could provide a more feasible and accessible alternative to existing sleep interventions. Additionally, the exploratory aim of this study could identify specific relationships between sleep outcomes and CV health. With CVD being the leading cause of death in the U.S, the development of effective CVD prevention and intervention strategies is essential (22). Middle-aged adults have a high prevalence of CVD diagnoses and suboptimal sleep (7–11). Therefore, improving sleep may be an important strategy to decrease CVD risk in middle-aged adults.

CHAPTER II: LITERATURE REVIEW

Introduction

Sleep is a fundamental process that is essential for behavioral and physiological function (2,34,35). Specifically, sleep plays a key role in maintaining and improving cognitive function, mood, mental health, and physical health such as muscle recovery, autonomic balance, and immune function (2,34,35). Despite the importance of sleep, approximately 35% of middle-aged adults report short sleep durations, 15% report having trouble falling asleep (long sleep latency), and 22% report having trouble staying asleep (poor sleep efficiency) (9,11,36). Suboptimal sleep duration and poor sleep quality have been associated with negative health outcomes including CVD, obesity, diabetes, and all–cause mortality (8–11). The prevalence of CVD in middle-aged adults is 58% for males and 51% for females which emphasizes the need for effective CVD prevention and intervention strategies in this age group (22). Previous literature has shown that improving sleep through interventions can positively impact CV health outcomes such as blood pressure, and reduce CVD risk (23,24). However, the existing literature evaluating the effects of sleep interventions specifically on AS and HRV is limited. Additionally, many sleep interventions and assessments are time-intensive and expensive to implement. There is a need for the development of low-cost, accessible sleep interventions in which outcomes can be assessed in an ecologically valid manner.

WHMs may provide a more feasible alternative to traditional sleep interventions and assessments. As the market for wearable technology continues to grow, a wide variety of

devices including wrist-worn monitors and smart rings have become readily available to consumers. WHMs provide users with feedback on various aspects of their health and lifestyle habits (e.g., sleep, physical activity) as well as provide personalized lifestyle recommendations which may trigger changes in behavior (37). The existing literature provides extensive evidence that WHMs can promote healthier physical activity habits (37,38). Additionally, studies have shown that the use of a WHM coupled with coaching, positive reinforcement, and other intervention strategies can improve sleep outcomes (39–42). However, to the best of our knowledge, only a single study has investigated the effects of standalone WHM use on sleep outcomes, reporting that a 1-week WHM trial positively impacted subjective sleep quality (28).

While a wide variety of WHMs (e.g., Fitbit, Apple Watch, Garmin, and WHOOP) track sleep metrics, these are typically worn on the wrist. The Oura Ring differs from these devices in that it is worn on the finger which may affect user experiences. Oura Rings are commercially available smart rings that are used in conjunction with a smartphone application. By tracking physiological metrics such as heart rate, HRV, temperature, and breathing frequency, Oura Rings are able to detect sleep with 96% accuracy and provide insights on physical activity and readiness (43). This information is displayed in the Oura application and allows for an integrated overview of the user's health and habits. Additionally, the Oura application provides users with educational resources that define each metric and provide recommendations on how to optimize their health.

Given the association between suboptimal sleep and CVD risk, there is a need to better understand the influence of sleep on CV health. Therefore, this study: 1) investigated if sleep outcomes change throughout a 4-week Oura Ring trial, and 2) explored if changes in

sleep are associated with changes in CV health outcomes (AS and HRV) in middle-aged adults. The long-term goal of this research is to design a sleep intervention using Oura Rings to improve overall health and decrease CVD risk.

Introduction to Sleep Outcomes

Sleep duration and sleep quality are both fundamental components of sleep and can be used to assess sleep health (44–47). Sleep duration is defined as the total amount of time spent asleep (45,46). The National Sleep Foundation (NSF) recommends that adults get 7 to 9 hours of sleep every night (45,46). Sleep quality is often determined by a combination of sleep outcomes including sleep latency, sleep disturbances, sleep efficiency, wake after sleep onset, and sleep duration (44,46). Sleep latency is the time it takes for an individual to fall asleep (44,46). For adults, the NSF states that falling asleep in less than 30 minutes indicates good sleep quality while poor sleep quality is indicated by a sleep latency greater than 45 minutes (44,46). Sleep efficiency is defined as the ratio of total time spent asleep to total time in bed (44,46). According to the NSF, a sleep efficiency of 85% or more is considered ideal in adults (44,46). Sleep efficiencies less than or equal to 74% are indicative of poor sleep quality in adults (44,46). Wake after sleep onset is defined as the amount of time, in minutes, spent awake between the initial onset of sleep and final awakening (44). This study investigated changes in sleep duration, sleep latency, sleep efficiency, and overall sleep quality.

Introduction to Cardiovascular Outcomes

Arterial Stiffness

AS is characterized by a reduced ability of an artery to respond to changes in pressure and a decreased elasticity of the arterial wall (48,49). Arterial stiffening can occur due to

aging, metabolic diseases, poor CV health, sleep disturbances, and other factors (49). AS has been established as a strong predictor of CVD and all-cause mortality, making it an important clinical outcome and target for therapeutic interventions (49,50). Furthermore, several studies, have suggested that AS may precede hypertension and that measures of AS may be better predictors of CVD risk than traditionally used measures such as blood pressure (51–54).

Heart Rate Variability

HRV is defined as the change in the time intervals between adjacent heartbeats (55,56). HRV is a measure of neurocardiac function, autonomic balance, and regulatory capacity (55–57). Autonomic balance is the coordination between the two branches of the autonomic nervous system (ANS), the PNS and the SNS (55). HRV has been established as a predictor of all-cause mortality and has been associated with coronary atherosclerosis and inflammation, making it an important indicator of CV health (55,58–61). Reduced HRV signifies a decreased ability to respond to physiological demands which can increase the risk of diseases such as CVD and diabetes (55,57,61,62).

Physiological Link Between Sleep and Cardiovascular Health

Suboptimal sleep durations and sleep quality have been associated with poor CV health. For example, short sleep durations have been associated with multiple CVD risk factors including hypertension, type II diabetes mellitus, and obesity (6,13,63–65). Data evaluating the mechanisms to understand the association between poor sleep quality and CVD risk is limited (13). However, a recent review suggests that the association between short sleep and CVD risk may be explained by a variety of pathways including inflammatory, endocrine, and genetic mechanisms (13).

Sleep is made up of different stages that can be classified into rapid eye movement (REM) sleep and non-rapid eye movement (NREM) sleep (15). NREM sleep is characterized by higher levels of PNS activity while REM sleep is characterized by higher levels of SNS activity (15). The higher levels of PNS activity and simultaneous lower levels of SNS activity during NREM sleep lead to a decreased cardiovascular burden (15). During normal sleep, blood pressure and heart rate decrease (13,18). This phenomenon is known as "nocturnal dipping" (18). It has been proposed that short sleep durations do not allow nocturnal dipping to occur which can lead to elevated blood pressure for extended durations of time, causing increased inflammation in the blood vessels (13,18). Short sleep durations have been associated with increased levels of interleukin-6, C-reactive protein, and other inflammatory markers (13,66). Additionally, lack of adequate sleep has been associated with increased lipid circulation and the progression of obesity, both of which may contribute to increased inflammatory markers (13,17,67). The presence of these inflammatory markers causes a reduction in the function of nitric oxide, an important vasodilatory molecule, and increases endothelin-1, a strong vasoconstrictor molecule; together this impairs endothelial function which leads to arterial stiffening (68). Additionally, increased levels of inflammatory markers have been associated with reduced HRV (69). The association between short sleep durations and increased CVD risk may be partially explained by this inflammatory mechanism (68). It is possible that a similar physiological response also occurs with poor quality sleep.

Sleep and Arterial Stiffness

Several studies have explored the association between sleep parameters (duration and quality) and AS (19,20). A recent meta-analysis, encompassing studies with mean ages

ranging from 41 to 70 years, found a U-shaped association between sleep duration and AS (19). Both short (<7 hrs) and long (>9 hrs) sleep durations were associated with increased AS, as measured by pulse wave velocity (PWV) (19). However, another meta-analysis conducted by Saz-Lara et al. (2022), with a similar mean age range (42 to 70 years), found a J-shaped association between sleep duration and AS when sleep duration was categorized as short (<6 hrs) and long (>8 hrs) with the reference group having sleep durations between 6 to 8 hours (20). Only long (>8 hrs) sleep durations were associated with greater AS, as measured by PWV (20). Furthermore, when sleep duration was treated as a continuous variable, Saz-Lara et al. (2022) did not find an association between increased sleep duration and AS (20). The findings of these two recent meta-analyses demonstrate inconsistencies in the existing literature regarding the relationship between short sleep duration and AS, indicating the need for further research. Additionally, many of the studies included in these two meta-analyses used subjective assessments of sleep duration. Only 1 out of 11 studies used objective measures of sleep duration which highlights a lack of objective sleep assessments in the existing literature (19,20).

In addition to exploring the relationship between sleep duration and AS, Saz-Lara et al. (2022) also explored the relationship between sleep quality and AS (20). Poor sleep quality was associated with increased AS (20). Additional studies have supported these results with long sleep latency and poor sleep efficiency being associated with increased AS (70,71). Altogether, the literature suggests that long sleep duration, poor sleep quality, and potentially short sleep duration contribute to elevated AS, thereby increasing the risk of CVD. However, the effects of sleep interventions on AS have not been well investigated. The

current study evaluated if objective changes in sleep duration, latency, and efficiency throughout a 4-week Oura Ring trial are associated with change in AS.

Sleep and Heart Rate Variability

Previous literature has explored the relationship between HRV and sleep duration and quality (21,72–77). In a cross-sectional study conducted in Iranian hospital staff (age: 39±13 years [yrs]), no relationship was observed between sleep duration and HRV, however, poor sleep quality, measured by PSQI, was associated with adverse HRV measures (77). Studies have shown that in physically active young adults (age: 22±2 yrs), healthy adults (age: 26±4 yrs) and healthy males (age: 31±2 yrs), experimentally manipulated sleep deprivation has been shown to decrease PNS activity and increase SNS activity, overall negatively impacting HRV (21,72,73). However, other sleep deprivation studies have shown that sleep deprivation impacted HRV outcomes in the opposite direction, increasing or not affecting PNS activity and decreasing SNS activity in healthy adults (age: 23±2 yrs), healthy and physically active cadets (age: 26±3 yrs), and healthy males (age: 25±3 yrs) (74–76). Therefore, the relationship between sleep duration and HRV is unclear and requires further investigation.

Similarly, the relationship between sleep quality and HRV is inconsistent and limited. Previous research has predominately evaluated individuals with a known sleep disorder such as insomnia or sleep apnea (78,79). Specifically, a recent review did not find significant differences in HRV in patients with insomnia when compared to healthy controls, however, another review found significantly lower levels of PNS activity in patients with obstructive sleep apnea (78,79). The existing literature investigating the association between sleep quality and HRV in populations without sleeping disorders is limited. Additionally, there is limited evidence if improving sleep through interventions also improves HRV.

Sleep Interventions

In the existing literature, there are many types of non-pharmacological interventions focused on improving sleep health. Previous studies have investigated the effects of sleep education, behavior change methods, relaxation techniques, physical exercise, mind-body exercise, aromatherapy/massages, psychotherapy, environmental interventions, and later school start times in a variety of populations (80). Non-pharmacological sleep interventions are often multi-faceted consisting of various intervention techniques and delivery methods including face-to-face meetings, group meetings, online courses, and educational brochures (80,81). A study which aimed to improve blood pressure by increasing sleep duration asked participants to attend weekly online training sessions for 6-8 weeks provided by an animated virtual therapist and attend a 30-minute CVD risk factor education session delivered by trained nurses (82). Participants demonstrated improved sleep quality and decreased blood pressure following the intervention (82). However, this intervention method required trained professionals for successful implementation, was time-consuming, and likely expensive to implement which decreases the accessibility and feasibility of this intervention (82). Another study investigated the effects of a sleep intervention on blood pressure as well as inflammatory, sympatho-adrenal, and metabolic markers (23). The study consisted of two overnight laboratory visits separated by a 6-week intervention period in which participants were given sleep hygiene resources and told to either maintain or increase their sleep duration based on group assignment (23). During the two visits, blood pressure was continuously monitored throughout a 24-hour period and blood samples were obtained 1.5 hours after waking up (23). Although the study shows promising results with blood pressure being significantly decreased in the sleep extension group, the methods used are not practical

due to the burden on participants and researchers (23). Additionally, studies that assess sleep through overnight laboratory visits fail to capture participants in their free-living environment which may limit the ecological validity of the results. Further development of sleep interventions is needed to broaden their use and implementation in a variety of populations.

Wearable Health Monitor Interventions on Lifestyle Behaviors

Using WHMs could simplify access to or implementation of sleep interventions by reducing barriers. Specifically, WHMs may provide a lower-cost alternative; they often have associated smartphone applications that incorporate behavior change methods such as goal setting and self-monitoring which do not require trained professionals or regularly scheduled educational sessions to be implemented (37). Instead, WHMs provide individualized feedback through customized algorithms. However, these algorithms often require 1 to 2 weeks of consistent data before producing personalized recommendations, warranting longer interventions (11,58). The feedback and educational material provided by the associated smartphone applications may act as "cues to action," a component of the Health Belief Model (Figure 1) (25,37,83). The "cues to action" provided by a WHM can facilitate changes in behaviors directly or alter individual beliefs such as perceived benefits and perceived barriers (Figure 1) (25,37,83). For example, the use of WHMs has been shown to have an overall positive effect on physical activity participation by sending reminders to break up sedentary bouts, giving users daily activity goals, and reminding users of the benefits of

being active (38). However, the existing literature investigating their effects on sleep is limited.

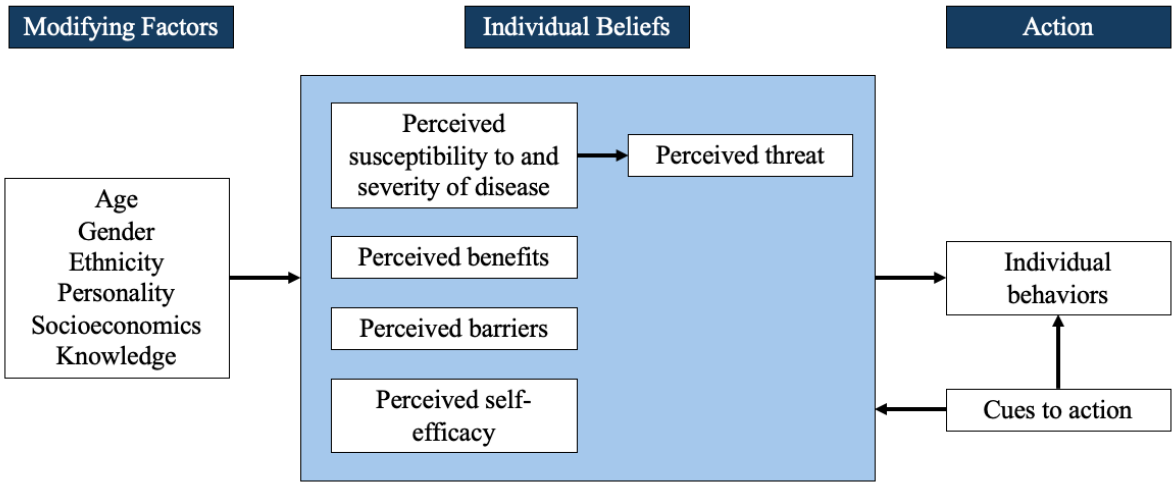

Figure 1. Components of Health Belief Model (25).

A review published in 2020 by Cajita et al., analyzed the use of WHMs in interventions targeting physical activity, sedentary behavior, and sleep (84). Of the 65 studies included in the review, only 4 studies investigated the effects of WHM-based interventions on sleep with only 1 focusing specifically on sleep (84). The other 3 interventions targeted multiple behaviors simultaneously (84). These intervention studies involved the use of WHMs coupled with weekly emails containing general health tips, reminders to use the device and application, encouragement, challenges, and rewards (40,85). One of the studies also included counseling, group education and exercise sessions, and access to a fitness center (86). Another study utilized an application specifically designed for research purposes that is inaccessible to the public (41). This application included personalized sleep prescriptions, educational videos, access to objective sleep metrics from a WHM, and suggestions for good sleep (41).

These studies highlight the potential of WHMs to be used to intervene on sleep behaviors, however, they also demonstrate that current research has not fully evaluated the

standalone use of WHMs as a way to intervene on sleep. To our knowledge, a single randomized crossover trial has investigated the isolated effects of using a WHM and its associated smartphone application on sleep quality and sleep quantity in healthy individuals (n=32) (28). The intervention consisted of wearing the WHOOP Strap 2.0, a wrist-worn WHM, and using its associated smartphone application for 7 days (28). Subjective sleep quality was improved in the intervention condition compared to the control condition; however, there were no significant differences in sleep quantity, wake after sleep onset, time spent napping, and total sleep over a 24-hour period (28). This study suggests that the standalone use of WHMs can improve sleep quality while highlighting a gap in the existing literature; additional research evaluating different WHMs, longer interventions, and objective sleep outcomes is needed (28).

Methodological Considerations

Methods to Assess Sleep

Sleep can be evaluated by both objective and subjective assessments using a wide array of techniques (43,87,88). Sleep can be objectively assessed through actigraphy, in-laboratory polysomnography (PSG), in-home PSG, and WHMs (43,87). In-laboratory PSG is considered the "gold standard" for evaluating sleep; however, it requires trained professionals, expensive equipment, and it fails to monitor participants in their free-living environment (43,87,88). WHMs utilize accelerometry and physiological measures of ANS activity to objectively assess sleep (43). WHMs are relatively inexpensive, readily accessible, and allow data to be collected in a non-laboratory setting (31,33,89–92). Subjective sleep assessments including the PSQI and other questionnaires are commonly used due to their low cost and ease of administration (87,93). Subjective methods of assessing sleep can collect

additional information about sleep habits and perceived sleep that cannot be obtained through objective assessments (93). Using both objective and subjective methods may allow for a more comprehensive assessment of sleep. Therefore, this study used the 3rd generation Oura Ring to objectively assess sleep and the PSQI to subjectively assess sleep.

Methods to Assess Arterial Stiffness

AS can be assessed through both invasive and non-invasive techniques. Invasive techniques such as coronary arteriography are not practical for clinical or research purposes as they are challenging, time-consuming, and may place patients and participants at risk of adverse events (94,95). Non-invasive measurements can be obtained through methods such as applanation tonometry, piezoelectric mechanotransducer, cuff-based oscillometry, ultrasound, and magnetic resonance imaging (96–98). The most commonly used measurement of AS is PWV which is measured in meters per second (m/s) (99,100). Higher PWV values signify higher AS (96,98). cfPWV is considered the gold standard non-invasive measurement of AS, but other sites such as brachial-femoral, carotid-radial, and brachial-ankle PWV can also be used (96,98).

Devices such as the SphygmoCor XCEL and VICORDER® are commonly used to obtain valid and reliable measures of cfPWV (99). The SphygmoCor XCEL utilizes both applanation tonometry and cuff-based oscillometry to obtain measures of cfPWV and is often used as the reference standard (99,101,102). However, the SphygmoCor XCEL requires a trained operator which limits its use in clinical and research settings. The VICORDER® is an automated device that utilized cuff-based oscillometry to obtain measures of cfPWV (99) The VICORDER® has been shown to have high intra-rater reliability (ICC=0.92, CV=6%) and high test-retest reliability (CV=2.8%) (101,102). The VICORDER® has been shown to

have good agreement with the SphygmoCor XCEL for cfPWV measures and is generally easier to use than the SphygmoCor XCEL (101,102). Therefore, this study used cfPWV, as measured by the VICORDER®, as an assessment of AS and CVD risk.

Methods to Assess Heart Rate Variability

HRV can be assessed through time-domain, frequency-domain, and non-linear measurements (56). Frequency-domain measures provide more detailed information than time-domain measures however, time-domain measures are easier to analyze and are more commonly used (103,104). These measurements can be obtained over varying durations including 24 hours, short-term (about 5 minutes), and ultra-short-term (<5 minutes) (105). Time-domain measures of HRV have traditionally been obtained using electrocardiograms (ECGs) which are considered the gold-standard methodology (103,106). However, ECGs require the use of various electrodes and a complicated setup which limits their use for long-term and remote monitoring (103,106). Photoplethysmography (PPG) is an alternative to ECGs which utilizes light and sensors to measure changes in the skin's blood flow (106,107). PPG sensors have been incorporated into WHMs and allow for continuous monitoring of HRV. The Oura Ring utilizes PPG sensors to compute the root mean square of successive differences (RMSSD) between normal heartbeats (108). RMSSD is one of the recommended HRV measures due to its statistical properties (104). The Oura Ring's nightly average HRV, which was used for analysis in this study, has shown very high agreement when compared to gold-standard ECG ($r^2 = 0.980$) (109). The current study assessed HRV, as measured by RMSSD, through a 3rd generation Oura Ring.

CHAPTER III: METHODS

Participants

G*Power Software version 3.1.9.7 was used to calculate sample size requirements for the current study. Previous literature evaluating the effect of a WHM on sleep quality demonstrated a moderate effect size (28). For a repeated measure analysis of variance (ANOVA) with 1 group, 4 measurement timepoints, an estimated correlation of 0.5 among repeated measures, a nonsphericity correction ϵ of 1, an estimated an effect size of 0.25 and an alpha level of 0.05, a sample size of 24 participants was needed to be sufficiently powered at 80%. We aimed to recruit 28 participants to account for a potential 15% drop out rate.

Twenty-seven adults between the ages of 40 and 59 years old from the Raleigh-Durham-Chapel Hill area in North Carolina were enrolled. A convenience sample for this study was obtained by research personnel using several techniques including: 1) Research for Me, 2) research flyers posted in libraries, recreational facilities, and commonly visited campus buildings, 3) emails to community and campus organizations, and 4) posts on local Facebook groups. Research for Me is a database dedicated to connecting people with research opportunities at UNC Chapel Hill, UNC Health and across North Carolina. All recruitment techniques included the inclusion criteria, a description of the study's purpose, and a link or QR code to an online screening survey. The screening survey was administered electronically using Qualtrics software. Participants initially eligible based on self-reported height, weight, and age were contacted by a research assistant for further telephone screening to verify their eligibility.

The full inclusion criteria for eligibility in this study were: 1) between the ages of 40 to 59, 2) BMI between 18.5 and 34.99 kg/m^2, 3) able to read and communicate in English, and 4) able and willing to use smartphone application. Subjects were excluded if they: 1) had a pre-existing sleep disorder, 2) had used an Oura Ring in the 30 days prior to enrollment, 3) were pregnant or planned to become pregnant, 4) had an occupation or lifestyle that regularly disrupts sleep (i.e., shiftwork, newborn), 5) had other significant chronic medical or psychiatric illness that, in the investigators' opinion, would prevent participation in the study.

Experimental Design

For this quasi-experimental study, eligible participants were asked to complete a total of 3 in-person laboratory visits (Figure 2). At the initial visit, participants provided written informed consent and completed questionnaires about their health history, sleep (PSQI), and physical activity (International Physical Activity Questionnaire – Short Form). Height and weight were measured using a stadiometer and digital scale (seca 770, Mount Pleasant, SC, USA). Participants were given 1-2 sizing rings and instructed to wear them for 24-48 hours to determine the appropriate Oura Ring size. This visit lasted approximately 30 minutes.

Prior to the second visit, participants were asked to fast for 4-6 hours (i.e., no food or fluid intake other than water), avoid strenuous exercise for 24 hours, and refrain from alcohol, tobacco, and caffeine for 12 hours. At visit 2, participants were given the appropriate size Oura Ring based on their experience with the sizing rings and manufacturer recommendations. Participants downloaded the Oura application, created an account, and familiarized themselves with the application with assistance from the research team. Body fat percentage (%fat) was assessed using dual-energy x-ray absorptiometry (Horizon A DXA System, Hologic Inc., Marlborough, MA, USA). Measures of pre-trial AS were collected.

This visit lasted approximately 60 minutes and occurred within 1-3 days of visit 1. Starting on the same day as visit 2, participants were instructed to wear the Oura Ring on their index, middle, or ring finger of the non-dominant hand for 4 weeks (28 days). During the 4-week trial, participants were asked to complete electronic surveys assessing Oura application usage at the end of Weeks 1-3. These surveys were administered using RedCap and participants received secure links over email.

Visit 3 took place within 3(±2) days of completing the 28-day trial. For this third visit, participants were asked to follow the same pre-assessment guidelines as visit 2. Participants returned their Oura Rings to the research team and completed questionnaires assessing their sleep, Week 4 Oura application usage, and physical activity. Post-trial AS measurements were collected. This visit lasted approximately 45 minutes. All data obtained in the research laboratory setting and by the Oura Ring was collected and reduced by trained research staff.

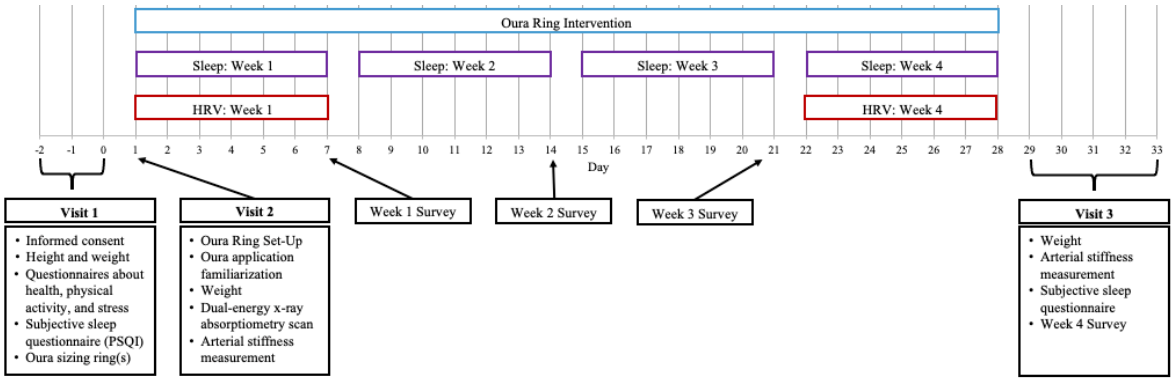

Figure 2. Experimental Design and Procedures Timeline.

The research conducted for this study was carried out in full compliance with the ethical standard set forth by the University's Institutional Review Board, adhering strictly to the principles outlined in the Declaration of Helsinki. All participants completed a written informed consent approved by the University's Institutional Review Board prior to their participation in the study.

Measures

Objective Sleep Outcomes

Objective measures of sleep duration, latency, and efficiency were collected from a 3rd generation Oura Ring (Oura Health, Elektroniikkatie 10, 90590 Oulu, Finland). The smart ring defines sleep duration as the total amount of time spent asleep, sleep latency as the time it takes to fall asleep, and sleep efficiency as the percentage of time spent asleep (32). Data from the ring was transmitted to and downloaded from Oura Teams, a cloud platform. Average values of sleep duration, latency, and efficiency were calculated for each week (Week 1: Days 1-7, Week 2: Days 8-14, Week 3: Days 15-21, and Week 4: Days 22-28).

Subjective Sleep Outcomes

Subjective sleep outcomes were assessed using the validated PSQI (110). The PSQI was designed to assess sleep over the previous month and takes 5 to 10 minutes to complete (110). Participants were asked 19 questions about 7 sleep components: 1) subjective sleep quality, 2) sleep latency, 3) sleep duration, 4) habitual sleep efficiency, 5) sleep disturbances, 6) use of sleeping medication, and 7) daytime dysfunction (110). Each of these components was scored on a scale from 0 to 3 (110). The scores of these 7 components were summed to calculate a global PSQI score which has a range of 0 to 21 (110). A higher score indicates poorer sleep quality; a score of 5 or less indicates optimal sleep (110).

Arterial Stiffness

AS was assessed through cfPWV. The VICORDER® (SMT Medical, Skidmore Medical Ltd., Bristol, UK) device was used to measure cfPWV (99,101,102,111). Participants were asked to lie supine on an examination table and a cuff was placed around their upper thigh as close to the inguinal crease as possible to capture the femoral artery. The

carotid pulse was located and marked with a pen. The distance in centimeters between the carotid pulse and the top of the thigh cuff was measured. This measured distance was then mathematically adjusted to calculate arterial path length using the following formula: Arterial Path Length = [Distance from Carotid Pulse to Cuff + 5.6 cm] x 0.8 (112). Participant height, weight, sex, date of birth, and arterial path length were entered into the VICORDER® software (112). Participants were asked to rest quietly in a Semi-Fowler's position (upper body elevated at 30°) for 10 minutes. Following rest, an oscillometric cuff was placed around the carotid artery and semi-automated measurements of cfPWV were obtained in duplicate using the VICORDER®. The waveforms from the proximal (carotid) and distal (femoral) arterial segments were generated and displayed in the VICORDER® software (Figure 3) (112).

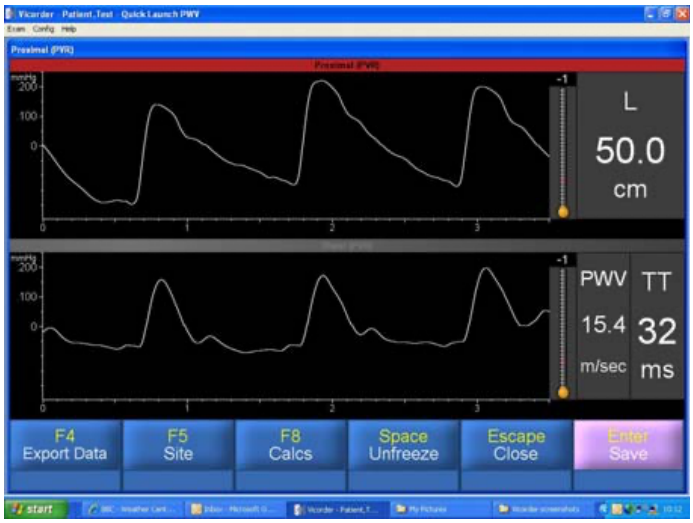

Figure 3. cfPWV measurement on VICORDER® software (112). Top display is the pressure waveform from the proximal (carotid) arterial segment. Bottom display is the pressure waveform from distal (femoral) arterial segment. Measurement was terminated when waveforms appeared uniform in height and in width. L: arterial path length (cm), PWV: pulse wave velocity (m/s), TT: transit time (ms).

The measurements were terminated and cfPWV was recorded once waveforms were consistent for a minimum of three cycles. cfPWV was calculated by dividing arterial path length by transit time (112). Transit time, the time between the foot of the proximal (carotid) pressure waveform and the foot of the distal (femoral) pressure waveform, was automatically obtained by the VICORDER® (112). If the difference in heart rate between trials was greater than 5 beats per minute, an additional third measure was completed. The two closest measures of cfPWV were averaged.

Heart Rate Variability

HRV was obtained from a 3rd generation Oura Ring (Oura Health, Elektroniikkatie 10, 90590 Oulu, Finland). The Oura Ring collects measurements of HRV every 5 minutes during sleep using RMSSD between normal heartbeats (Figure 4). Nightly HRV data was downloaded from Oura Teams and weekly averages for Week 1 and Week 4 were calculated.

Figure 4. Average HRV for one night displayed in Oura smartphone application. HRV: heart rate variability (ms).

Oura Ring Intervention

During the 4-week Oura Ring trial, participants were given full access to their data through the Oura application. The "Sleep" tab in the Oura application displayed the following sleep metrics: 1) total sleep (sleep duration), 2) time in bed, 3) sleep efficiency, 4) Oura-derived sleep score, 5) restfulness, 6) REM sleep, 7) deep sleep, 8) latency, and 9) timing (Figure 5). Users could learn more about these by clicking on individual metrics. The application provided definitions, recommended values, and tips for improvement on each metric (Figure 6). After recording 1-2 weeks of consistent sleep data, personalized "Bedtime Guidance" could be found on the "Home" tab in the Oura smartphone application. Users could view their ideal bedtime as well as information on bedtime and wake-up windows (Figure 7).

Figure 5. Sleep metrics displayed in "Sleep" tab in Oura application.

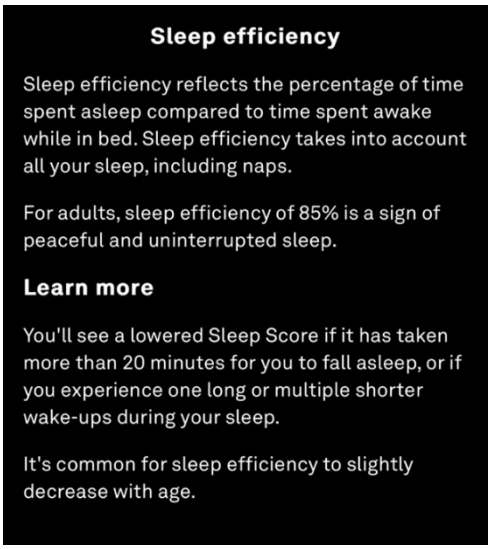

Figure 6. Example of sleep metric information displayed in Oura application. This figure shows the definitions and recommended value for sleep efficiency. Similar information can be obtained for each sleep metric in the application.

Additionally, the application provided users with educational resources on sleep hygiene in the “Learn” section of the “Explore” tab. These resources presented information about how alcohol, caffeine, light, meditation, and other factors influence sleep. Alongside this information, recommendations such as “avoid drinking within a few hours of bedtime” were provided (Figure 8). The application also provided guided meditations and stories focused on managing stress and relaxing before sleep (Figure 9). To assess the use of these features, participants were asked to complete an electronic survey at the end of each week. This survey allowed users to select which features they used and provide information on how frequently they used them (e.g., 1x/week, 2-3x/week, daily, etc.).

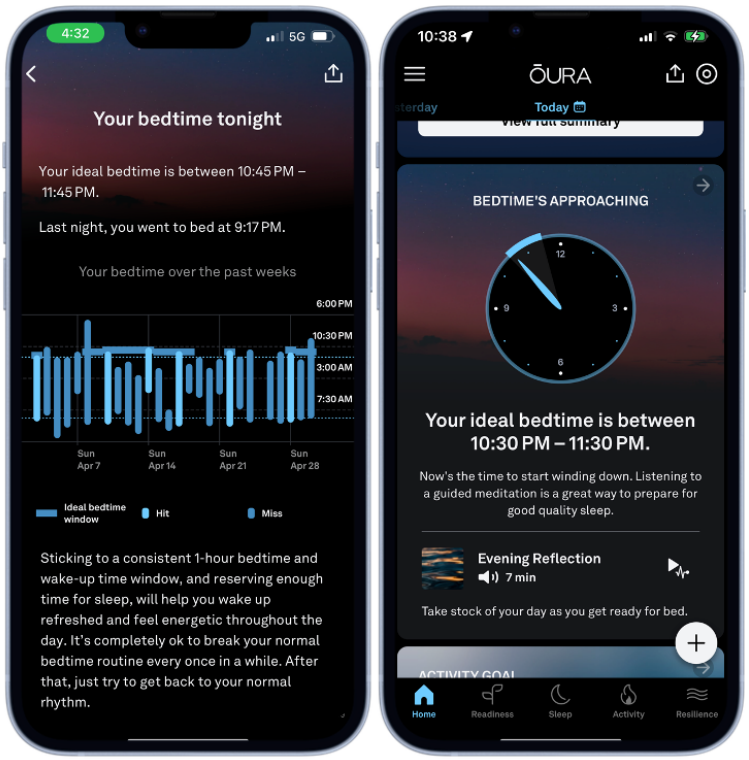

Figure 7. “Bedtime Guidance” presented in the Oura application. This was found on the “Home” tab and provided ideal bedtimes based on previous data and habits.

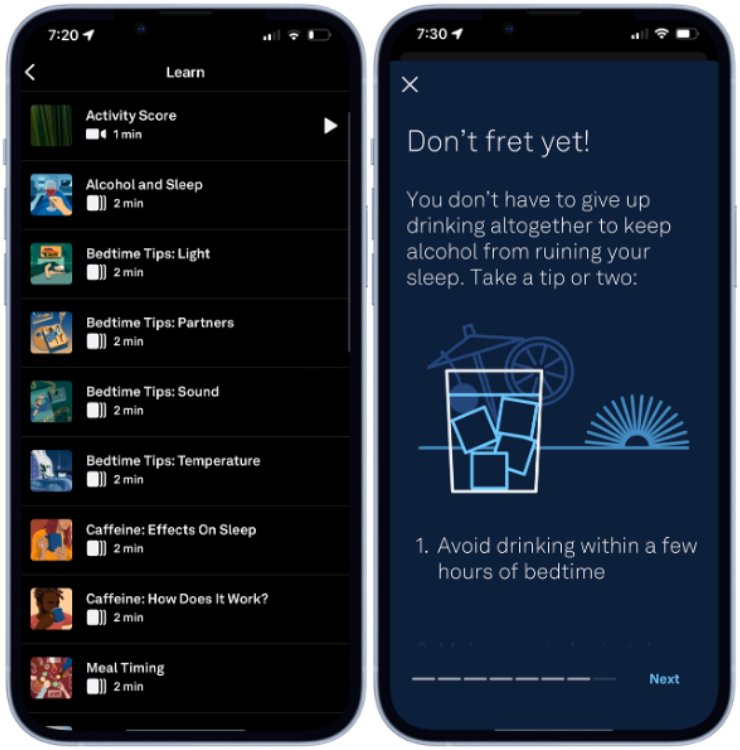

Figure 8. Educational resources on sleep hygiene found in the "Learn" section of the "Explore" tab of the Oura application. Left is list of resources provided. Right is from the "Alcohol and Sleep" resource.

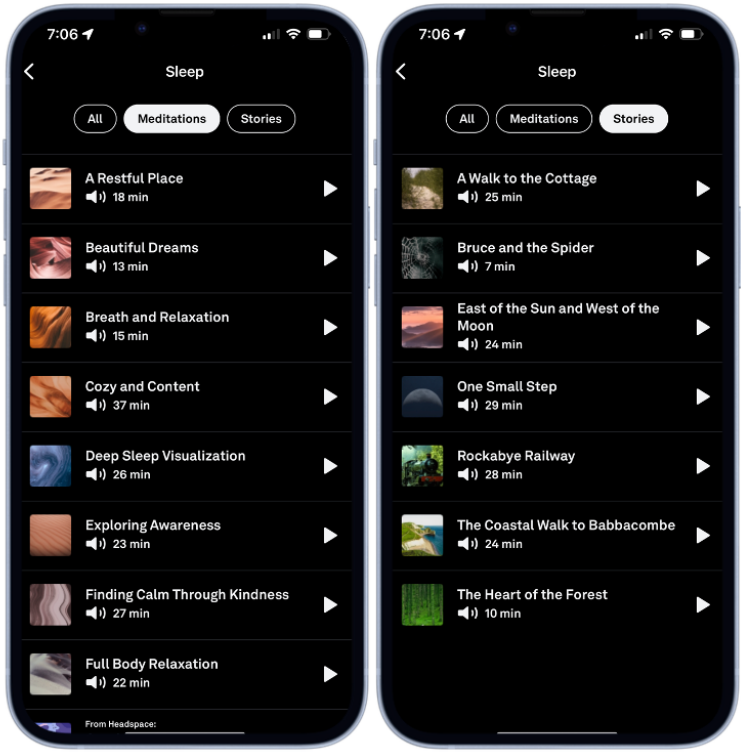

Figure 9. Examples of guided meditations (left) and stories (right) provided by the Oura application.

Statistical Analyses

Mean, standard deviation (SD), and range were calculated for all normally distributed continuous variables. Frequencies expressed as a percentage were reported for categorical variables. All statistical analyses were performed using Jamovi (Version 2.4.7.0, IBM, Somers, NY, USA). An alpha level of $p \leq 0.05$ was set a priori for all analyses.

Aim 1A:

Separate repeated measures ANOVAs with post-hoc analyses were used to evaluate changes in sleep duration, latency, and efficiency throughout the 4-week Oura Ring trial. Each sleep outcome was analyzed at 4 timepoints: 1) Week 1, 2) Week 2, 3) Week 3, and 4) Week 4. Additionally, 3 separate repeated measures analysis of covariance (ANCOVAs) evaluated changes in sleep duration, latency, and efficiency over time while controlling for age and sex.

For duration, participants were classified as short (<7 hrs), long (>9 hrs), or optimal (7-9 hrs) sleepers based on Week 1 data. If warranted, these groups were analyzed separately to account for the possibility that improvements in sleep duration might occur in different directions.

Aim 1B:

To assess change in subjective sleep quality, a paired samples t-test was performed. The mean difference between pre-trial and post-trial PSQI score was calculated. Additionally, a repeated measures ANCOVA evaluated change in PSQI score over time while controlling for age and sex.

Exploratory Aim:

If significant changes in sleep duration, latency, or efficiency were present, additional analyses were conducted as follows: four separate multiple linear regression analyses with change in AS as the dependent variable and change in 1) sleep efficiency, 2) sleep latency, 3) sleep duration – short sleepers, and 4) sleep duration – long sleepers as the independent variables while controlling for age and sex. If warranted, four additional analyses were completed utilizing the same linear regression analyses plan with change in HRV as the dependent variable. Change in AS was defined as the difference between pre-trial and post-trial cfPWV. Change in HRV was defined as the difference between Week 1 and Week 4 HRV.

To assess change in AS, a paired samples t-test was performed. The mean difference between pre-trial and post-trial cfPWV was calculated. Additionally, a repeated measures ANCOVA evaluated change in cfPWV over time while controlling for age and sex.

To assess change in HRV, a paired samples t-test was performed. The mean difference between Week 1 and Week 4 HRV was calculated. Additionally, a repeated measures ANCOVA evaluated change in HRV over time while controlling for age and sex.

CHAPTER IV: MANUSCRIPT FOR AIMS 1A AND 1B

Introduction

Sleep is essential for proper cognitive and physiological function (2,34,35). Specifically, sleep plays a key role in maintaining and improving mood, muscle recovery, immune function, and cardiovascular health (2,34,35). Despite its importance, approximately 35% of middle-aged adults (40 to 59 years old) report short sleep durations, 15% report having trouble falling asleep (long sleep latency), and 22% report having trouble staying asleep (poor sleep efficiency) (9,11,36). Middle-aged adults have the highest prevalence of short sleep duration compared to all other age groups (9–11). In addition to being associated with all-cause mortality, suboptimal sleep is a potential contributing factor to the development of cardiovascular disease, obesity, and diabetes (2–6).

Interventions targeting sleep may be a viable approach to improve overall health and decrease disease risk. However, existing sleep interventions and assessments can be time-intensive and require trained personnel and expensive resources for individualized coaching and educational sessions. There is a need for the development of accessible and ecologically valid sleep interventions. Wearable health monitors (WHMs) may provide a more feasible alternative to traditional sleep interventions and assessments as they provide users with detailed information about their health behaviors such as physical activity and sleep. The educational content, personalized recommendations, cues, and nudges provided by WHMs and their associated smartphone applications may trigger behavior changes. These

components of a WHM may help users self-regulate their lifestyle in attempt to achieve normal, healthy values for metrics such as sleep duration, latency, and efficiency (26,27).

Previous research has shown that multi-faceted interventions involving the use of a WHM in addition to traditional sleep intervention strategies (e.g., coaching, education) can improve sleep duration (39,42,113), latency (114), efficiency (39,115), and overall sleep quality (39,42,115). However, the existing literature investigating the standalone effects of a WHM on sleep outcomes is limited. A singular study has shown that the standalone use of a wrist-worn WHM significantly improved perceptions of sleep quality in healthy adults (28). Although the use of a WHM may be a feasible and effective way to intervene on sleep, there are potential limitations to using a wrist-worn device (29,30). A study reported that the majority of participants found a wrist-worn device uncomfortable while sleeping due to the light and wristband of the device (29). Evaluating the effects of alternative WHMs such as Oura Rings may be important to support the development of feasible sleep interventions. Oura Rings are commercially available smart rings that are used in conjunction with a smartphone application. By tracking physiological metrics such as heart rate, heart rate variability, temperature, and breathing frequency, Oura Rings are able to detect sleep with 96% accuracy and provide insights on physical activity and readiness (43). This information is displayed in the Oura application and allows for an integrated overview of the user's health and habits. Oura Rings have the potential to improve sleep behaviors and outcomes; however, these effects have not yet been investigated. Therefore, the purpose of this study was to evaluate if objective sleep outcomes (duration, latency, efficiency) and subjective sleep quality change during a 4-week Oura Ring trial in middle-aged adults.

Methods

Subjects

Two hundred and forty-nine people expressed interest in the study; 34 individuals were screened for eligibility (Figure 10). Twenty-seven middle-aged adults were enrolled; of those, 1 was removed due to recent changes in medications, which may have influenced outcomes (Figure 10). Therefore, 26 adults (57.7% female; age[Mean±SD]: 49.2±5.2 years; Body Mass Index [BMI]: 24.9±3.6 kg/m^2; %fat: 28.1±6.8) were evaluated in this study (Table 1).

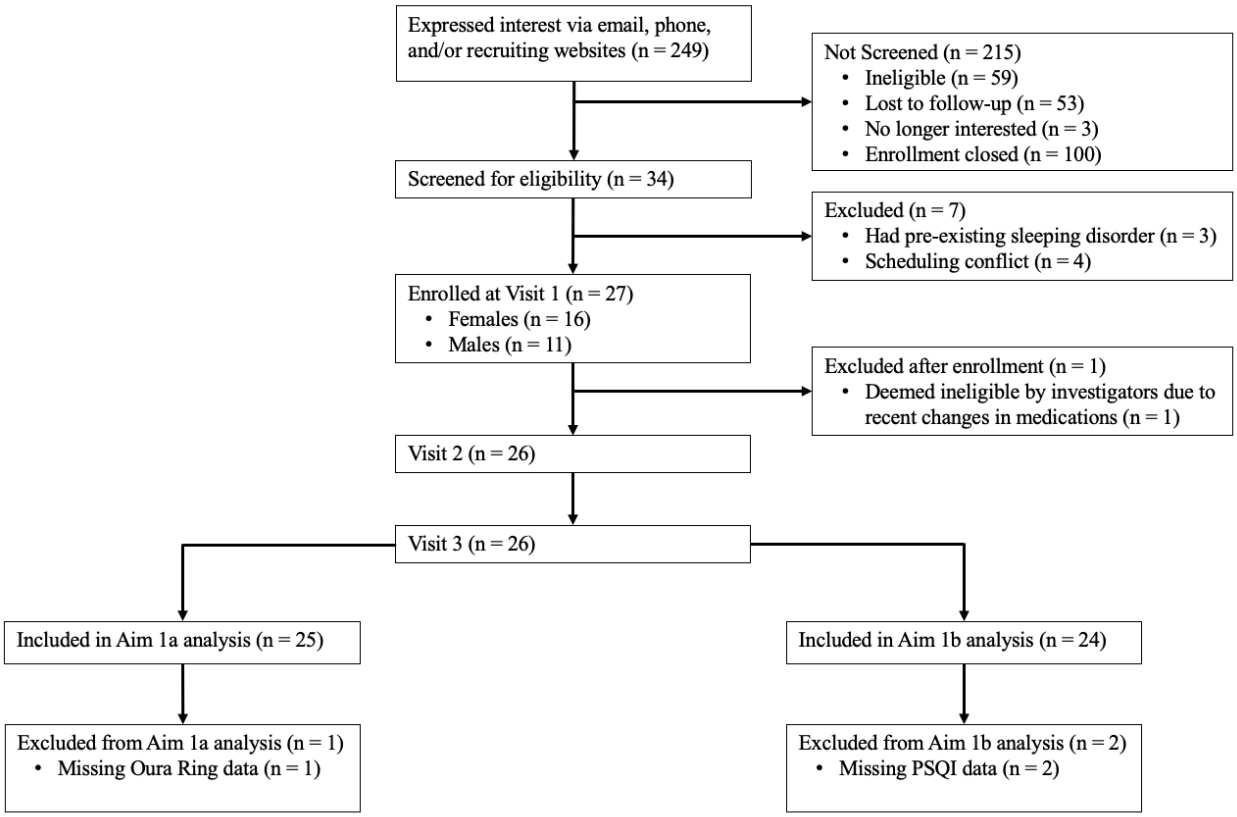

Figure 10. CONSORT Diagram. PSQI: Pittsburgh Sleep Quality Index

All subjects were between the ages of 40 and 59 and had a BMI between 18.5 and 34.99 kg/m^2. Subjects were excluded from the study if they had a pre-existing sleep disorder, had used an Oura Ring in the 30 days prior to enrollment, were pregnant or planned to

become pregnant, had an occupation or lifestyle that regularly disrupts sleep (i.e., shiftwork, newborn), or had other significant chronic medical or psychiatric illness that, in the investigators opinion, would prevent participation in the study. All participants completed a written informed consent approved by the University's Institutional Review Board prior to their participation in the study.

Experimental Design

All subjects completed a total of 3 in-person laboratory visits. At the initial visit, participants provided written informed consent and completed questionnaires about their health history, sleep (Pittsburgh Sleep Quality Index [PSQI]), and physical activity (International Physical Activity Questionnaire – Short Form). Height was measured using a stadiometer and weight was measured using a digital scale (seca 770, Mount Pleasant, SC, USA). Participants were given 1-2 sizing rings and instructed to wear them for 24-48 hours to determine the appropriate Oura Ring size.

Visit 2 occurred within 1-3 days of visit 1. Body fat percentage (%fat) was assessed using dual-energy x-ray absorptiometry (Horizon A DXA System, Hologic Inc., Marlborough, MA, USA). Participants were given the appropriate size Oura Ring based on their experience with the sizing rings and manufacturer recommendations. Participants downloaded the Oura application, created an account, and familiarized themselves with the application with assistance from the research team. Participants were instructed to wear the Oura Ring on their index, middle, or ring finger of the non-dominant hand for 4 weeks (28 days) starting on the same day as visit 2. During the 4-week trial, participants were asked to complete electronic surveys assessing Oura application usage at the end of Weeks 1-3. These surveys were administered using RedCap and participants received secure links over email.

Visit 3 took place within 3(±2) days of completing the 28-day trial. Participants returned their Oura Rings to the research team and completed questionnaires assessing their sleep and Week 4 Oura application usage.

Objective Sleep Outcomes

Objective measures of sleep duration, latency, and efficiency were collected from a 3rd generation Oura Ring (Oura Health, Elektroniikkatie 10, 90590 Oulu, Finland). The smart ring defines sleep duration as the total amount of time spent asleep, sleep latency as the time it takes to fall asleep, and sleep efficiency as the percentage of time spent asleep (32). Data from the ring was transmitted to and downloaded from Oura Teams, a cloud platform. Average values of sleep duration, efficiency, and latency were calculated for each week (Week 1: Days 1-7, Week 2: Days 8-14, Week 3: Days 15-21, and Week 4: Days 22-28).

Subjective Sleep Quality

Subjective sleep outcomes were assessed using the validated PSQI (110). The PSQI was designed to assess sleep over the previous month and takes 5 to 10 minutes to complete (110). Participants were asked 19 questions about 7 sleep components: 1) subjective sleep quality, 2) sleep latency, 3) sleep duration, 4) habitual sleep efficiency, 5) sleep disturbances, 6) use of sleeping medication, and 7) daytime dysfunction (110). Each of these components was scored on a scale from 0 to 3 (110). The scores of these 7 components were summed to calculate a global PSQI score which has a range of 0 to 21 (110). A higher score indicates poorer sleep quality; a score of 5 or less indicates optimal sleep (110).

Statistical Analyses

Mean, standard deviation (SD), and range were calculated for all normally distributed continuous variables. Frequencies expressed as a percentage were reported for categorical variables. All statistical analyses were performed using Jamovi (Version 2.4.7.0, IBM, Somers, NY, USA). An alpha level of $p \leq 0.05$ was set a priori for all analyses.

Separate repeated measures analysis of variance (ANOVAs) with post-hoc analyses were used to evaluate changes in sleep duration, latency, and efficiency throughout the 4-week Oura Ring trial. Each sleep outcome was analyzed at 4 timepoints: 1) Week 1, 2) Week 2, 3) Week 3, and 4) Week 4. Additionally, 3 separate repeated measures analysis of covariance (ANCOVAs) evaluated changes in sleep duration, latency, and efficiency over time while controlling for age and sex. For duration, participants were classified as short (<7 hrs), long (>9 hrs), or optimal (7-9 hrs) sleepers based on Week 1 data. If warranted, these groups were analyzed separately to account for the possibility that improvements in sleep duration might occur in different directions.

To assess change in subjective sleep quality, a paired samples t-test was performed. A repeated measures ANCOVA evaluated change in PSQI score over time while controlling for age and sex.

Results

Descriptive characteristics and demographics are presented in Table 1 and Table 2 respectively.

Table 1. Mean ± standard deviation (SD) of participant characteristics. yrs: years, BMI: body mass index, %fat: body fat percentage, MVPA: moderate-to-vigorous physical activity, min: minutes, wk: week

	n (%)	**Age (yrs)**	**BMI (kg/m^2)**	**%fat**	**MVPA (min/wk)**
Total Sample	26	49.2 ± 5.2	24.9 ± 3.6	28.1 ± 6.8	199.7 ± 137.9
Male	11 (42.3)	49.3 ± 5.0	24.8 ± 3.2	21.4 ± 2.7	239.1 ± 154.8
Female	15 (57.7)	49.1 ± 5.5	25.0 ± 4.0	33.1 ± 4.0*	170.8 ± 121.3

*Significantly different than males ($p < 0.05$)

Table 2. Frequencies of participant demographics.

	n (%)
Race	
Asian	2 (7.7)
Black/African American; NOT Hispanic/Latino/a	2 (7.7)
White/Caucasian; NOT Hispanic/Latino/a	19 (73.1)
White/Caucasian; Hispanic/Latino/a	2 (7.7)
White/Caucasian; NOT Hispanic/Latino/a, American Indian or Alaskan Native	1 (3.8)
Education	
Bachelor's degree (Example: BA, AB, BS, BBA)	13 (50.0)
Master's degree (Example: MA, MS, MEng, MEd, MBA)	10 (38.5)
Professional school degree (Example: MD, DDS, DVM, JD)	2 (7.7)
Doctoral Degree (Example: PhD, EdD)	1 (3.8)
Income	
$30,000 -- $60,000	2 (7.7)
$60,000 -- $100,00	3 (11.5)
$100,000 -- $150,000	6 (23.1)
$150,000+	13 (50.0)
Prefer not to answer	2 (7.7)
Menstruation Status (Females only, N=15)	
Premenopause	3 (20.0)
Perimenopause	7 (46.7)
Postmenopause	5 (33.3)

Detailed usage of the Oura application features are presented in Table 3. Over the 28-day trial, the average non-wear time for the Oura Ring was 1.3±1.1 hours per day.

Table 3. Frequency of use for Oura Ring application tabs and features.

Week	**1 (n=26)**			**2 (n=25)**			**3 (n=24)**			**4 (n=26)**		
Frequency of Use (days/wk)	**0**	**1-3**	**4+**	**0**	**1-3**	**4+**	**0**	**1-3**	**4+**	**0**	**1-3**	**4+**
"Home" tab	0 (0.0)	2 (7.7)	24 (92.3)	1 (4.0)	2 (8.0)	22 (88.0)	0 (0.0)	4 (16.7)	20 (83.3)	1 (3.8)	3 (11.5)	22 (84.6)
"Readiness" tab	2 (7.7)	5 (19.2)	19 (73.1)	3 (12.0)	7 (28.0)	15 (60.0)	3 (12.5)	7 (29.2)	14 (58.3)	4 (15.4)	4 (15.4)	18 (69.2)
"Sleep" tab	0 (0.0)	1 (3.8)	25 (96.2)	0 (0.0)	2 (8.0)	23 (92.0)	0 (0.0)	2 (8.3)	22 (91.7)	1 (3.8)	1 (3.8)	24 (92.3)
"Activity" tab	1 (3.8)	2 (7.7)	23 (88.5)	2 (8.0)	3 (12.0)	20 (80.0)	0 (0.0)	6 (25.0)	18 (75.0)	2 (7.7)	4 (15.4)	20 (76.9)
"Resilience" tab	7 (26.9)	12 (46.2)	7 (26.9)	7 (28.0)	6 (24.0)	12 (48.0)	5 (20.8)	8 (33.3)	11 (45.8)	6 (23.1)	10 (38.5)	10 (38.5)
Meditations	22 (84.6)	4 (15.4)	0 (0.0)	18 (72.0)	5 (20.0)	2 (8.0)	21 (87.5)	1 (4.2)	2 (8.3)	23 (88.5)	1 (3.8)	2 (7.7)
Guided Breathing Sessions	23 (88.5)	3 (11.5)	0 (0.0)	20 (80.0)	4 (16.0)	1 (4.0)	20 (83.3)	3 (12.5)	1 (4.2)	23 (88.5)	2 (7.7)	1 (3.8)
Sleep Stories	25 (96.2)	1 (3.8)	0 (0.0)	23 (92.0)	1 (4.0)	1 (4.0)	22 (91.7)	1 (4.2)	1 (4.2)	23 (88.5)	2 (7.7)	1 (3.8)
"Learn" Segments	21 (80.8)	4 (15.4)	1 (3.8)	21 (84.0)	2 (8.0)	2 (8.0)	20 (83.3)	4 (16.7)	0 (0.0)	23 (88.5)	3 (11.5)	0 (0.0)
Educational Material	20 (76.9)	4 (15.4)	2 (7.7)	19 (76.0)	6 (24.0)	0 (0.0)	20 (83.3)	4 (16.7)	0 (0.0)	22 (84.6)	3 (11.5)	1 (3.8)
Bedtime Guidance	16 (61.5)	4 (15.4)	6 (23.1)	7 (28.0)	8 (32.0)	9 (36.0)	13 (54.2)	4 (16.7)	7 (29.2)	14 (53.8)	6 (23.1)	6 (23.1)
Unguided Session	25 (96.2)	1 (3.8)	0 (0.0)	24 (96.0)	0 (0.0)	1 (4.0)	24 (100.0)	0 (0.0)	0 (0.0)	26 (100.0)	0 (0.0)	0 (0.0)

Objective Sleep Outcomes

Average values of sleep duration, latency, and efficiency for Weeks 1-4 are presented in Table 4. Based on Week 1 sleep duration, only 2 participants were classified as short sleepers (<7 hrs; 6.3-6.9 hrs) and 4 participants were classified as long sleepers (>9 hrs; 9.01-9.7 hrs). Given the limited variability in Week 1 sleep durations, we did not evaluate short and long sleepers separately. We assessed change in sleep duration across the entire sample.

There was no significant effect of time on duration (p=0.427), latency (p=0.739), or efficiency (p=0.990) in the unadjusted model. After controlling for age and sex, the effect of time on duration (p=0.506), latency (p=0.724), and efficiency (p=0.585) remained non-significant. There were no interaction effects between time and age (duration: p=0.482, latency: p=0.747, efficiency: p=0.653) or time and sex (duration: p=0.919, latency: p=0.661, efficiency: p=0.428). There were also no significant main effects for age (duration: p=0.681, latency: p=0.988, efficiency: p=0.165) or sex (duration: p=0.080, latency: p=0.828, efficiency: p=0.602).

Individual objective sleep data for Weeks 1-4 is presented in Figure 11A, Figure 12A, and Figure 13A. Simplified data visualization presented in Figure 11B, Figure 12B, and Figure 13B; using Week 1 data, participants were stratified into groups for each objective sleep outcome as follows: 1) Duration – Above the mean (≥ 8.2 hrs): n=12, Below the mean (< 8.2 hrs): n=13, 2) Latency – Above the mean (≥ 21.9 min): n=9, Below the mean (< 21.9 min): n=15, and 3) Efficiency – High (≥ 85%): n=11, Low (< 85%): n=14.

Table 4. Objective Sleep Outcomes (n=25). Mean ± Standard Deviation (SD). hrs: hours, min: minutes.

Week	Duration (hrs)		Latency (min)		Efficiency (%)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
1	8.2 ± 0.9	6.3 – 9.7	21.9 ± 9.6	8.0 – 48.4	83.8 ± 4.6	76.4 – 91.1
2	8.3 ± 0.7	6.3 – 9.6	23.0 ± 8.5	8.6 – 38.3	83.7 ± 4.0	77.6 – 91.3
3	8.1 ± 1.0	6.4 – 10.6	20.6 ± 11.6	6.8 – 54.7	83.8 ± 5.4	69.2 – 92.1
4	8.1 ± 0.9	6.1 – 9.9	21.5 ± 11.2	6.6 – 49.9	83.9 ± 4.2	75.7 – 90.9

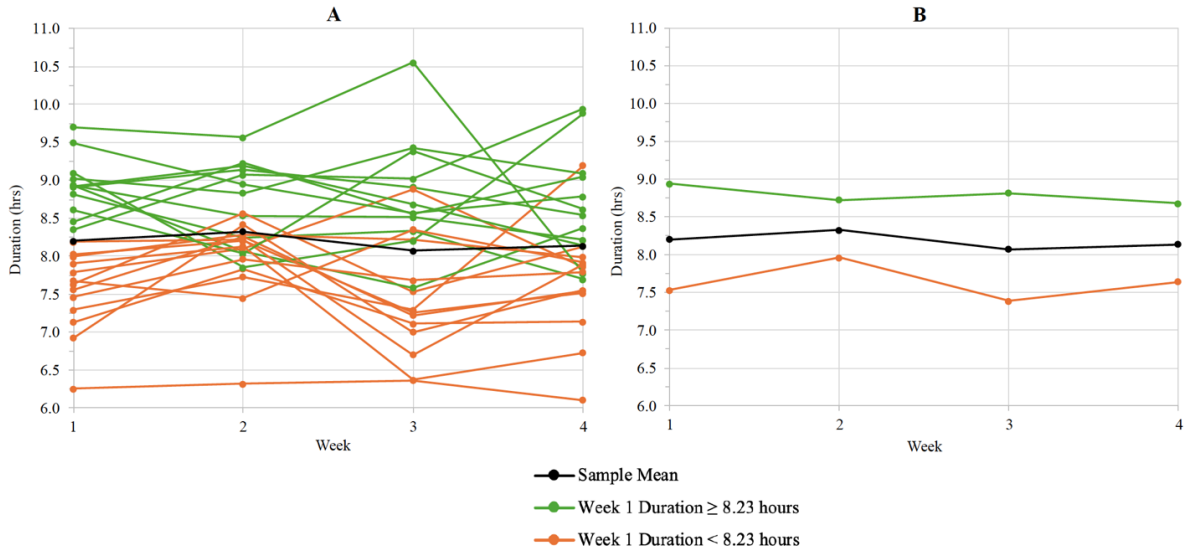

Figure 11. Objective sleep duration (hrs) for Weeks 1-4 (n=25).
A: Weekly averages for all participants. B: Stratified by Week 1 duration

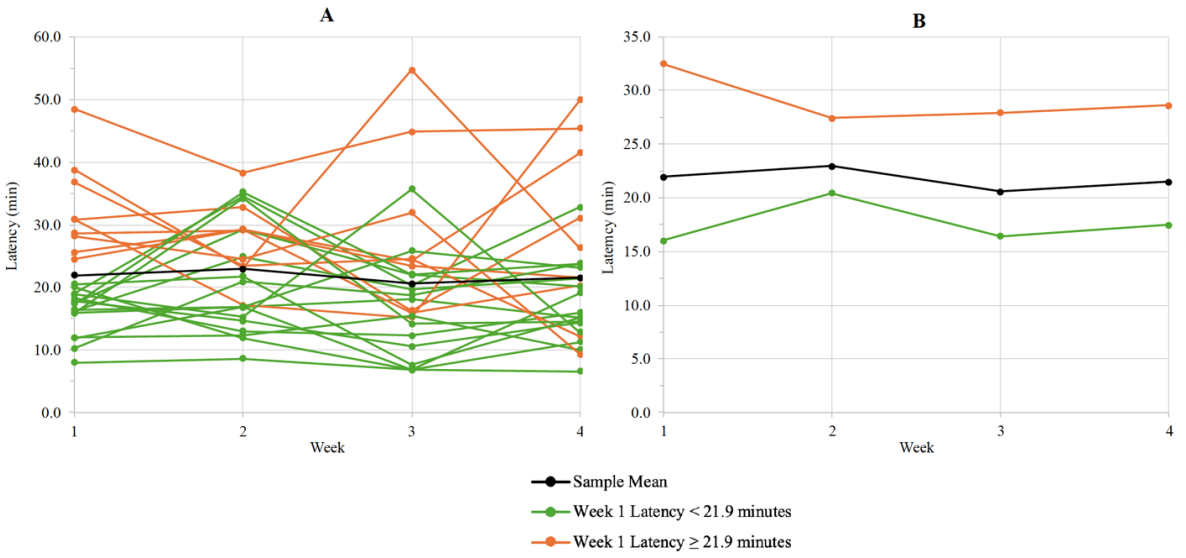

Figure 12. Objective sleep latency (min) for Weeks 1-4 (n=25).
A: Weekly averages for all participants. B: Stratified by Week 1 latency

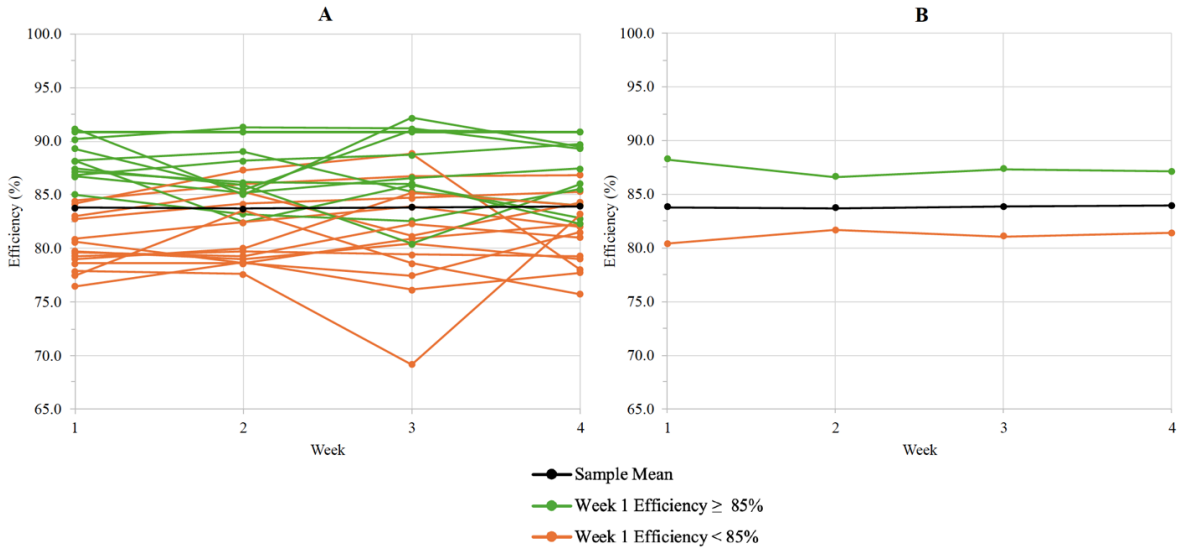

Figure 13. Objective sleep efficiency (%) for Weeks 1-4 (n=25).
A: Weekly averages for all participants. B: Stratified by Week 1 efficiency

Subjective Sleep Quality

There was no significant difference (p=0.923) between pre-trial (5.6±2.4) and post-trial (5.5±1.8) PSQI score (Table 5, Figure 14). However, 13 (54.2%) participants were classified as good sleepers (PSQI score ≤ 5) at post-trial, compared to 8 (33.3%) participants at pre-trial (Table 5). After including age and sex, the overall model was not significant (p=0.532). Further, there were no interaction effects between time and age (p=0.624) or time and sex (p=0.297); there were also no significant main effects for age (p=0.602) or sex (p=0.225).

Table 5. PSQI Scores (n=24). Mean ± Standard Deviation (SD).

	Pre-trial PSQI	**Post-trial PSQI**
Mean ± SD	5.6 ± 2.4	5.5 ± 1.8
Range	1 – 10	3 – 9
Good Sleep Quality (≤ 5)	8 (33.3%)	13 (54.2%)
Poor Sleep Quality (>5)	16 (66.7%)	11 (45.8%)

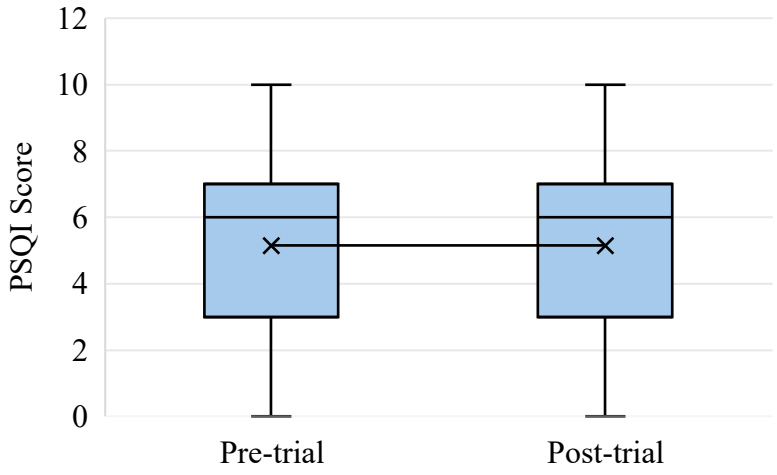

Figure 14. Box plot for pre-trial and post-trial PSQI scores (n=24). Mean Difference=0.04, p=0.923.

Individual subjective sleep data is presented in Figure 15A. Simplified data visualization presented in Figure 15B; participants were stratified by pre-trial PSQI score into groups as follows: Good (≤ 5): n=8 and Poor (> 5): n=16.

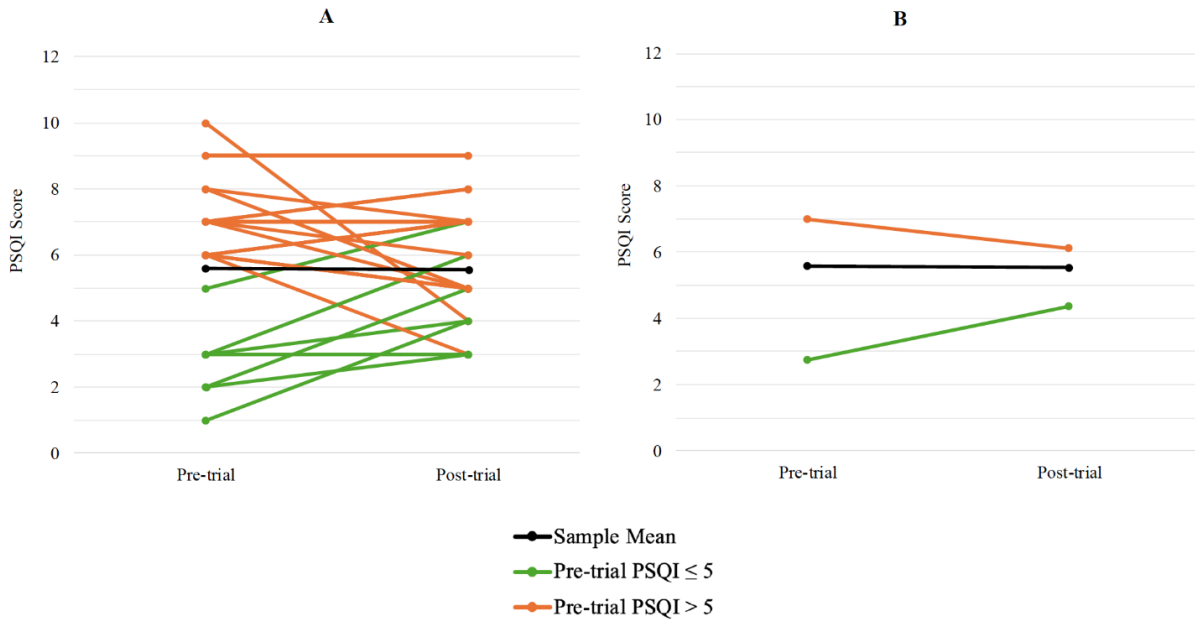

Figure 15. Pre-trial and post-trial PSQI scores (n=24).
A: Individual scores for all participants. B: Stratified by pre-trial PSQI score

Discussion

The current study did not find any significant changes in objective sleep outcomes (duration, latency, efficiency) or subjective sleep quality over the 4-week Oura Ring trial. Our hypothesis that there would be no change in sleep duration for individuals within the optimal range of 7 to 9 hours was supported. However, our hypotheses that 1) latency would decrease, 2) efficiency would increase, and 3) PSQI score would decrease were not supported. The existing literature evaluating the effects of standalone WHM use on sleep outcomes is limited. To the best of our knowledge, no studies have evaluated these effects on objective sleep outcomes and a singular study (Berryhill et al. 2020) has evaluated these effects on subjective sleep quality (28).

Our results were inconsistent with Berryhill et al. (2020) who reported an improvement in subjective sleep quality in healthy individuals (n=32, 23.8±5 yrs, 18-45 yrs) after the use of a wrist-worn WHM (WHOOP Strap 2.0) and its associated smartphone application for 1 week (28). The authors reported significant improvements in Patient-Reported Outcomes Measurement Information System (PROMIS) sleep disturbance (short form) scores between the intervention and control condition in a randomized crossover trial (28) The current study utilized the PSQI to assess sleep quality due to its widespread use. However, the PROMIS sleep disturbance (short form) questionnaire used by Berryhill et al. (2020) has been reported to have greater measurement precision than the PSQI (116). The discrepancy in findings may be attributed to differences in research design and methodology. Additionally, slight differences in the WHMs and the associated smartphone applications may have led to variation in results between the current study and Berryhill et al. (2020). Although Oura Rings and WHOOP Straps measure similar metrics such as sleep outcomes,

activity outcomes, and heart rate variability, the features displayed on the application can differ. For example, the WHOOP application provides users with a "sleep need" value which is the optimal amount of sleep needed for peak performance, as defined by their algorithm (117,118). This value takes sleep debt into consideration which is the amount of extra sleep needed due to short sleep on previous nights (117,118). To date, this feature has not been implemented in the Oura application. Further, the young adult participants in Berryhill et al. (2020) study may have interacted with the respective smartphone applications in a different way compared to our middle-aged adult sample, potentially influencing experiences and outcomes. Additional research is needed to evaluate the effectiveness of various WHMs as standalone interventions to improve sleep as they are marketed.

Although the existing literature evaluating changes in sleep in response to a standalone WHM intervention is limited, previous studies have evaluated the effects of multi-faceted interventions that incorporate WHMs along with components such as counseling, motivational challenges, and additional educational material. Our study supports the conclusions of Melton et al. (2016) who evaluated the effects of a 6-week multi-component intervention on objective sleep outcomes in African American college-aged females (n=69, 19.9±1.7 yrs, 18-24 yrs) (85). Sleep outcomes were evaluated by actigraphy after 6 weeks of intervention and 2 weeks later at an 8-week follow-up (85). Participants in the intervention group (n=28) were provided with a WHM (Jawbone UP Band) and full access to the associated smartphone application for all 8 weeks (85). Additionally, they were instructed to engage with the application on a daily basis and received weekly reminder emails with general health tips and encouragement during the 6-week intervention period (85). There were no significant changes in sleep duration, latency, or efficiency within or

between the intervention and control (n=41) groups (85). Similar to the current study, this suggests that additional components may be needed when developing an effective WHM-based sleep intervention.

A similar, yet conflicting, 6-week intervention study by Baron et al. (2019) evaluated the effects of a sleep extension intervention in a small sample of short sleepers with prehypertension or hypertension (n=16, 45.8±9.8 yrs, 30-60 yrs) (39). The intervention group (n=11) was instructed to increase their time in bed and improve sleep schedule consistency (39). They received a WHM (Fitbit Flex 2), access to the Fitbit application, weekly email newsletters with tips on how to improve sleep, along with weekly telephone coaching in which weekly data and barriers were discussed (39). Objective sleep outcomes were measured by actigraphy while sleep disturbances and daytime impairment were respectively evaluated with the PROMIS sleep disturbance and Sleep Related Impairment scales (39). Significant changes in sleep duration (Δ+0.57 hrs), efficiency (Δ+2.6%), and time in bed (Δ+0.56 hrs) were reported in the intervention group (n=11) while no significant changes in objective sleep outcomes were reported in the control group (n=5) (39). Additionally, Baron et al. (2019) reported that the intervention group showed improvements in sleep quality characterized by decreased sleep disturbances and decreased daytime impairment (39). Significant between-group differences were observed in objective sleep duration and subjective sleep quality when comparing the intervention and control group (39). These findings are inconsistent with the current study and Melton et al. (2016) which suggests that the inclusion of one-on-one coaching in a WHM-based sleep intervention may be important to elicit desired changes in sleep.

Similar to coaching, cognitive behavior therapy may be effective at targeting key mediators of behavior change. Kang et al. (2017) evaluated the effects of group cognitive behavioral therapy for insomnia (CBT-I) delivered through a smartphone application in adults with insomnia (n=19, 45.1±9.8 yrs, 18-65 yrs) over 4 weeks (41). One group (n=10) received CBT-I in addition to a WHM (Fitbit Charge HR) while the other only received the CBT-I (n=9) (41). For the entire sample, consisting of both groups, there was a significant increase in sleep efficiency (Δ+7.5%), measured by actigraphy, and improvements in sleep quality indicated by a decrease in PSQI (Δ-5.4) and Insomnia Severity Index scores (81). No significant differences in sleep outcomes were found between the two groups, suggesting that the WHM did not contribute to improvements in sleep efficiency and quality beyond the effects of CBT-I (81). Although the results of Baron et al. (2019) and Kang et al. (2017) show that relatively short intervention periods (4 to 6 weeks) may be enough time to improve sleep outcomes, the generalizability of these findings are limited due to small sample sizes and clinical study populations which may be more responsive to behavior change efforts due to increased motivation. To identify which components of a multi-faceted intervention are effective, future research should focus on comparing full intervention groups to partial intervention and control groups.

Previous literature also suggests that other components such as linking sleep habits to health outcomes (e.g., cognitive function, disease risk) may provoke changes in sleep behaviors (42). Adler et al. (2017) evaluated the effects of wearing an actigraph and receiving personalized feedback on subjective sleep quality in active-duty U.S. soldiers (42). Participants in the intervention group (n=43) wore an actigraph for 3 weeks and were subsequently provided with and talked through a personalized report including: 1) sleep data

from the past 3 weeks including sleep/wake scoring, duration, variability in latency, and efficiency, 2) sleep data comparisons to the general U.S. population, 3) cognitive function estimates based on sleep data, and 4) recommended actions for improving sleep (42). Participants were reassessed 3-4 months after receiving the report (42). At follow-up, the intervention group reported fewer sleep problems, measured by the Insomnia Severity Index, than the control group (n=100) (42). Additionally, longer subjective sleep durations (Δ+25 minutes) were seen in the intervention group when compared to the control group (n=60) (42). These results suggest that, in addition to personalized feedback, establishing a connection between sleep and health outcomes specific to the individual could lead to changes in sleep behaviors. This may help individuals better understand the importance of adequate sleep and the negative impacts of suboptimal sleep.

Furthermore, the incorporation of components that promote social interaction are important to consider as social support can play a significant role in behavior change (119,120). In a longer 12-month study, Crowley et al. (2016) found that WHM use (Jawbone UP Band) in addition to motivational challenges, awards, and weekly emails with health tips increased sleep duration in employees at a pharmaceutical company (n=506, 43.5±9.2 yrs, 23-67 yrs) (40). Participants received invitations to optional social events and were provided with aggregated data from the study population to which they could compare themselves to (40). Sleep duration, measured by the WHM, increased steadily throughout the intervention leading to a significant difference between the first and last month of the study period (Δ+0.36 hrs) (40). Crowley et al. (2016) highlights that friendly competitions and reward systems could play a key role in encouraging behavior change, warranting further evaluation of their effectiveness in regards to sleep.

Due to the bidirectional relationship between physical activity and sleep, targeting physical activity with a WHM-based intervention may be an indirect way to improve sleep (121). Two studies (Browne et al. 2021 and Choi et al. 2018) evaluated the effects of multi-faceted interventions that encouraged targeted physical activity. Browne et al. (2021) evaluated the effects of a 3-month intervention in healthy adults (n=56, 28-47 yrs) (114). The intervention group (n=30) received a 2nd generation Oura Ring and access to the smartphone application where they could view all sleep and activity data, similar to the present study (114). Participants in the intervention group also received weekly behavioral modification presentations in which ways of improving sleep, stress, and relaxation were discussed along with individualized recommendations (114). They also received daily text messages with positive reinforcement and additional personalized feedback based on Oura Ring sleep and activity data (114). They were instructed to walk or jog for 150 to 300 minutes per week (114). The control group (n=26) received a wellness education program with similar presentations, however, the topics of sleep, stress, and relaxation were not discussed in these sessions (114). A significant decrease in sleep latency of 11 minutes was observed in the intervention group (114). Additionally, sleep latency was significantly lower in the intervention group when compared to the control group at the 3-month follow-up (114). However, Browne et al. (2021) did not find any significant within- or between- group changes in sleep duration or time in bed (114). Similarly, Choi et al. (2018) did not find significant changes in sleep duration between the intervention (n=33) and control (n=30) group in Korean college students (n=63, 21.2±2.6 yrs) after a 9-week multi-component intervention (86). Sleep duration was measured by WHM (Mi band) (86). In addition to the WHM, participants in the intervention group received counseling, group education and

exercise classes, and membership to a fitness facility (86). These studies suggest that the inclusion of an exercise intervention component in a WHM-based sleep intervention may improve sleep latency but not sleep duration (86). However, other components such as the educational classes, may have played a role in improving sleep latency in Browne et al. (2021).

It should be highlighted that, in addition to sleep data, WHMs provide users with a large amount of metrics and they usually provide information about physical activity. The WHMs used in the current study and previously discussed studies provide users with information about their activity such as daily steps and moderate-to-vigorous physical activity. As with sleep, this feedback may lead to changes in activity behaviors. Reported changes in sleep may have occurred due to changes in physical activity. In order to understand the effects of a WHM-based intervention on sleep specifically, it is important for future research to account for and evaluate changes in physical activity.

Limitations

The current study is one of a limited number of studies that assessed the effects of a standalone WHM on sleep outcomes in middle-aged adults, adding to the current body of literature. However, there are limitations to address. First, our study was in a small sample of adults which potentially limited our ability to detect significant differences in outcomes. This also limited our ability to account for additional factors such as physical activity, stress, and socioeconomic variables. Our sample consisted of relatively good sleepers. The mean values for Week 1 sleep duration (8.2±0.9 hrs), latency (21.9±9.6 min), and efficiency (83.8±4.6%) were all close to the recommended values of 7-9 hours, less than 30 minutes, and greater than 85%, respectively (44–46). Additionally, mean pre-trial PSQI score (5.6±2.4) was close to

the benchmark for good sleep quality (≤5) (110). Therefore, a sleep intervention may have been less of a priority for this sample. The low variability coupled with a small sample likely made it difficult to detect changes in outcomes.

Further, our intervention period was 4 weeks, and although some previous literature has seen a change in this time, it may not have been enough time for a detectable change to occur in this study sample. Future studies should evaluate the effects of WHMs on sleep over longer periods to allow for long-term trends and delayed responses to be captured.

Additionally, our study was quasi-experimental which did not allow us to evaluate differences between intervention and control groups. Another potential limitation of this study is the risk of measurement bias due to the same platform (Oura) being used to deliver the intervention and to measure outcomes. Future studies should consider including an alternative assessment tool and a control group to better isolate the effects of a standalone WHM intervention.

Although participants were given full access to the Oura Ring application throughout the study duration, they were not required to use the app; it was used as the primary intervention with minimal external guidance. While this is a more ecologically valid approach, it limited our ability to determine if Oura Ring interventions that are more structured have the capability to alter sleep outcomes. It is unclear if similar results would have been seen if participants were instructed to use specific features and educational materials in the application. The extent to which individual participants engaged with the application varied therefore, participant responses to the intervention may have introduced variability in the outcomes, making it difficult to generalize findings. The evaluation of individual application features in relation to sleep outcomes may help better understand

which components are needed in a meaningful sleep intervention. Furthermore, performing a day-level analysis may provide additional insight over a weekly analysis. Lastly, conclusions from this study should only be applied to middle-aged adults without pre-existing sleep disorders. Future research is warranted in younger, elder, and clinical populations.

Conclusions

The current study suggests that the standalone use of an Oura Ring for 4 weeks is not enough to elicit changes in sleep outcomes in middle-aged adults. Existing literature has shown that WHMs, in addition to other intervention tools, may lead to improvements in sleep outcomes. However, findings are inconsistent and studies vary on 1) duration, 2) population, 3) type of WHM, and 4) method of sleep outcome assessment which makes it difficult to reach a consensus. Future research should focus on evaluating individual intervention components (coaching, weekly reminders, rewards, exercise intervention, etc.) to better understand which aspects should be included in an effective and feasible sleep intervention. The standalone use of an Oura Ring and its smartphone application as an intervention needs to be further explored. However, the use of Oura Rings as an assessment tool for sleep should be considered. Oura Rings provide validated measures of sleep in free-living environments and provide alternatives to in-laboratory assessments and wrist-worn WHMs which can be burdensome to both participants and researchers (43,87,88). The results of this study also suggest that researchers using Oura Rings as assessment tools may not have to be concerned about participants changing their behaviors and reacting to the device. Incorporating Oura Rings and other WHMs into studies examining sleep is essential for expanding the growing body of literature on objectively measured sleep outcomes.

CHAPTER V: RESULTS AND DISCUSSION FOR EXPLORATORY AIM

Results

Due to the lack of significant changes in objective sleep outcomes, evaluating their associations with cfPWV and HRV were not warranted.

Arterial Stiffness

There was no significant difference (p=0.691) between pre-trial (6.5 ± 0.8 m/s) and post-trial cfPWV (6.5 ± 1.0 m/s) (Table 6, Figure 16). After including age and sex, the overall model was not significant (p=0.760). Further, there were no interaction effects between time and age (p=0.831) or time and sex (p=0.263); there were also no significant main effects for age (p=0.538) or sex (p=0.080).

Table 6. cfPWV (m/s) (n=26). Mean ± Standard Deviation (SD).

	Pre-trial cfPWV	**Post-trial cfPWV**
Mean ± SD	6.5 ± 0.8	6.5 ± 1.0
Range	5.4 – 8.0	5.1 – 9.6

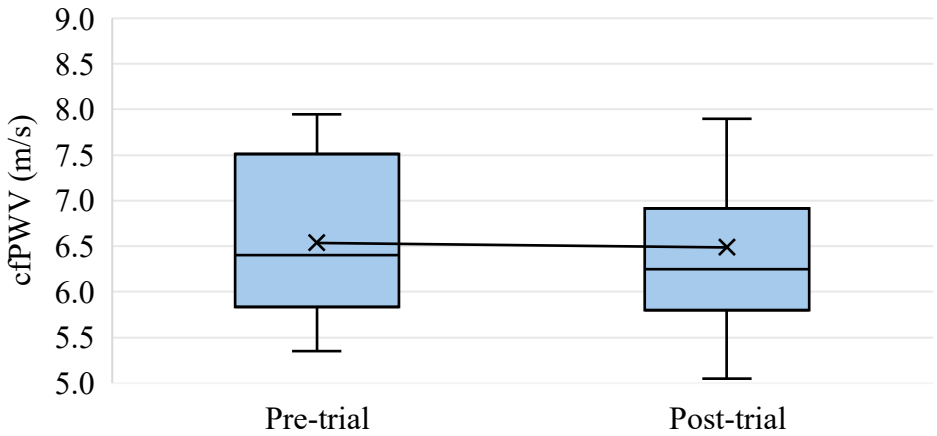

Figure 16. Box plot for pre-trial and post-trial cfPWV (m/s) (n=26). Mean Difference=0.05 m/s, p=0.691.

Heart Rate Variability

There was no significant difference (p=0.438) between Week 1 (30.0±15.4 ms) and Week 4 HRV (29.3±15.7 ms) (Table 7, Figure 17). After including age and sex, the overall model was not significant (p=0.794). Further, there were no interaction effects between time and age (p=0.742) or time and sex (p=0.937); there were also no significant main effects for age (p=0.969) or sex (p=0.686).

Table 7. Week 1 and Week 4 HRV (ms) (n=25). Mean ± Standard Deviation (SD).

	Week 1 HRV	**Week 4 HRV**
Mean ± SD	30.0 ± 15.4	29.3 ± 15.7
Range	11.9 – 66.7	11.0 – 66.7

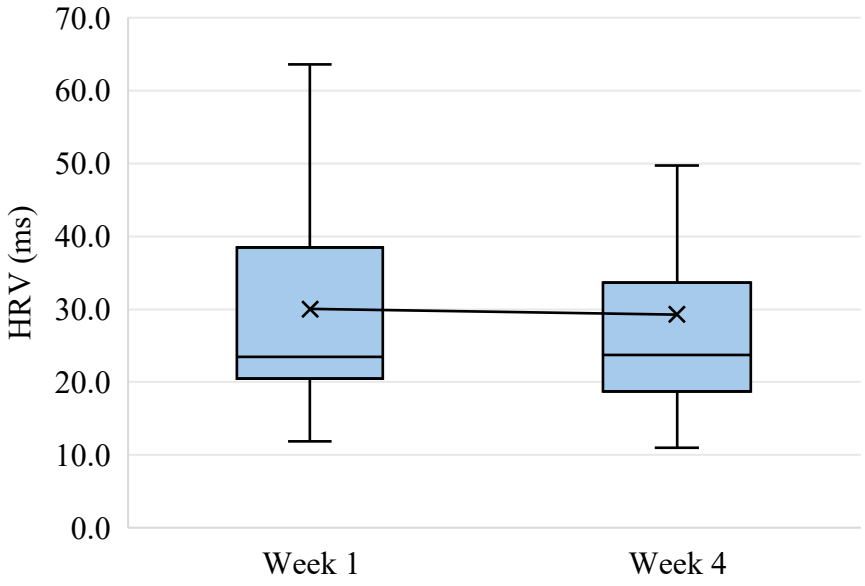

Figure 17. Box plot for Week 1 and Week 4 HRV (ms) (n=25). Mean Difference=0.76 ms, p=0.438.

Discussion

Previous studies suggest that suboptimal sleep may be associated with elevated AS and adverse HRV measures (19–21,70–77). The conditional, exploratory aims of this study were to evaluate changes in AS and HRV in response to changes in sleep outcomes. Counter to our hypotheses, the current study did not find any significant changes in sleep, and subsequently there were no significant changes in AS or HRV.

When evaluating the AS of our middle-aged participants to better understand their overall health and disease risk, interestingly, mean cfPWV at baseline was 6.5 m/s. This value is lower than previously reported in the literature using a VICORDER® device (40-49yrs: 9.1 m/s; 50-59 yrs: 9.9 m/s) (111). However, this value is within the 95% confidence intervals (CIs) (40-49 yrs: 5.6-14.8 m/s; 50-59 yrs: 6.0-16.4 m/s) reported by Baier et al. (2018), suggesting our sample was at a lower risk of developing CVDs (111).

Similarly, the HRV values reported in the current sample of middle-aged adults are in a normal, healthy range. Mean HRV for Week 1 and Week 4 were 30.0±15.4 ms and 29.3±15.7 ms, respectively. These values are lower than the average for all Oura Ring users (41 ms) (122). However, for middle-aged adults, the average HRV, as measured by an Oura Ring, is approximately 30 ms which is consistent with the current study (122).

Both cfPWV and HRV values were within normal ranges. This highlights our sample as healthy, middle-aged adults which may be attributable to positive sleep characteristics as well as other reported characteristics. The physical activity, smoking, health, and socioeconomic statuses of our sample are associated with more favorable CV health (14,123). Our sample was physically active; the mean moderate-to-vigorous physical activity (MVPA) was 199.7 minutes per week. Out of 26 participants, 18 (69.2%) met the

recommended guideline of at least 150 minutes of MVPA per week. In terms of smoking status, 20 (76.9%) had never smoked, 6 (23.1%) were former smokers, and none were current smokers. Only 3 participants (11.5%) reported a history of high blood pressure and 2 (7.7%) reported abnormalities in heart rhythms. The other health conditions reported were asthma (n=2), mental health disorders (n=5), and hernias (n=2). Furthermore, our sample was well educated with all participants (n=26) holding, at minimum, a bachelor's degree. Additionally, 50% (n=13) of our sample reported a household annual income greater than $150,000, indicating a relatively high socioeconomic status. Taken together, these characteristics suggest that our sample represents a relatively healthy and low-risk population in terms of CV and overall health. The lower cfPWV values and normal HRV values observed in our study, compared to previously reported values, may be partially explained by the high levels of physical activity, low smoking prevalence, and favorable socioeconomic status of our participants. Our small sample size limited our ability to account for these additional factors. Further research is needed to understand how these factors may affect responses to a standalone WHM trial in regards to changes in lifestyle behaviors and subsequent physiological changes.

While our reported values for CV health outcomes align with existing literature, some unexpected results warrant further consideration. Despite the well-established association between aging and increased AS and lower HRV, our study did not find significant effects of age on AS or HRV (124–126). This finding may be due to the relatively narrow age range of our sample, which could have limited our ability to detect age-related differences. Additionally, the high levels of physical activity observed in our participants may have mitigated the expected age-related increases in AS and decreases in HRV, as regular exercise

has been shown to preserve vascular health (127). It is also possible that other unmeasured factors, such as diet, genetic predisposition, or stress levels, played a role in maintaining normal CV health across different ages (128,129). Future studies with a broader age distribution and more comprehensive assessments of lifestyle and genetic influences are needed to better understand changes in CV health in response to improvement in sleep in middle-aged populations.

CHAPTER VI: CONCLUSIONS

In conclusion, no significant changes in sleep or CV health outcomes were found during a 4-week Oura Ring trial in 40 to 59 year old adults. Both objective (duration, latency, efficiency) and subjective (quality) sleep outcomes showed no significant improvements, suggesting that the standalone use of the Oura Ring may not be sufficient to elicit measurable changes in sleep in this population. Additionally, there were no significant changes in AS and HRV which is expected due to the unchanged sleep outcomes.

Our study design closely replicated the real-word experience of individuals purchasing and using a WHM without targeted instructions. Although WHMs are often marketed as tools that can improve sleep, our findings suggest that additional intervention strategies may be needed to positively impact sleep. It is important for future larger studies to better understand how WHMs and their associated applications can be used to intervene on sleep and improve health outcomes. Future analyses will be improved by examining factors such as user engagement, incorporating longer intervention periods, and evaluating the effectiveness of complementary intervention strategies such as coaching. This may offer additional insight into the potential of WHMs to influence sleep behaviors and health in a feasible and accessible manner.

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