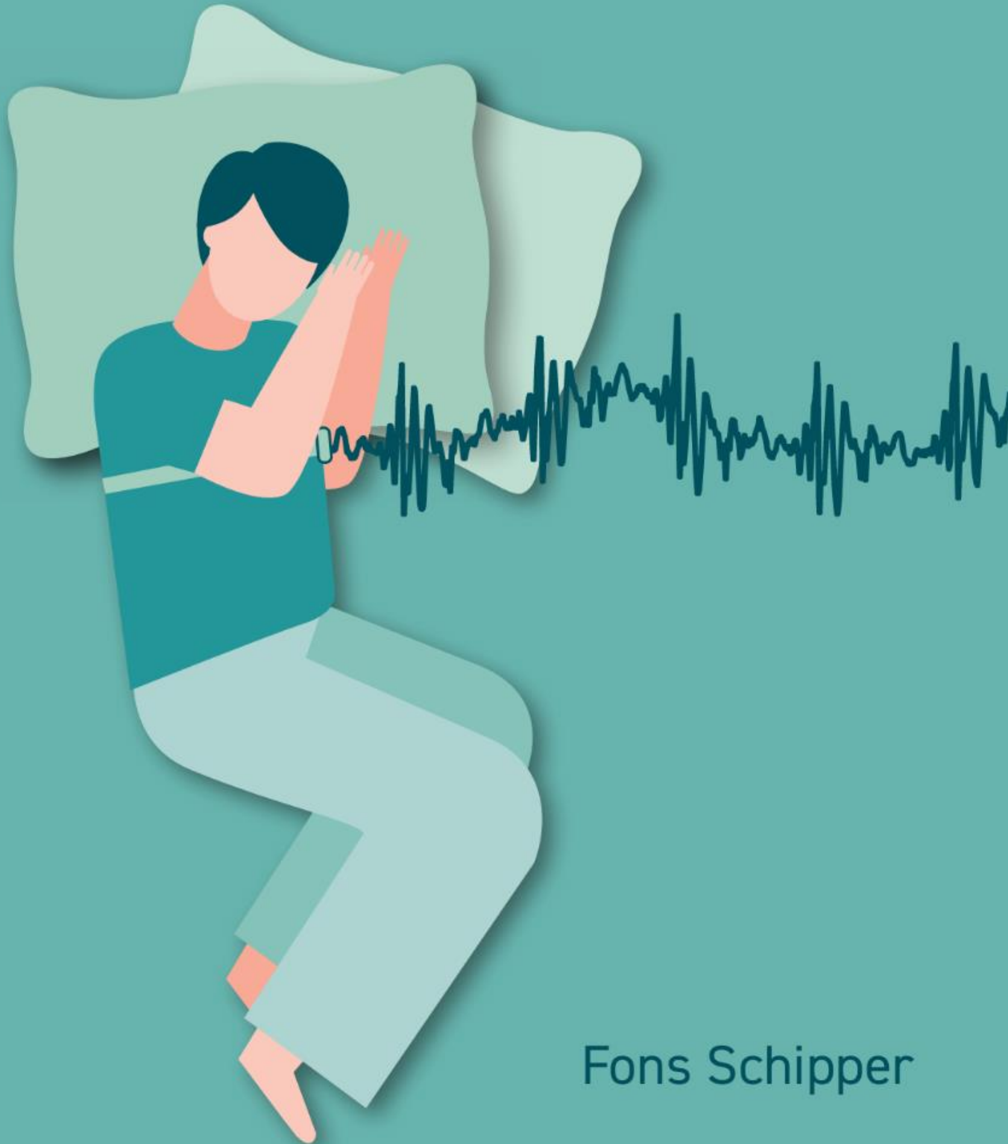
Measuring Sleep and Respiration with Chest-Wall Accelerometry



Fons Schipper

Dear Reader,

This little booklet contains the handouts for the introductory presentation to be held during the defense of my thesis.

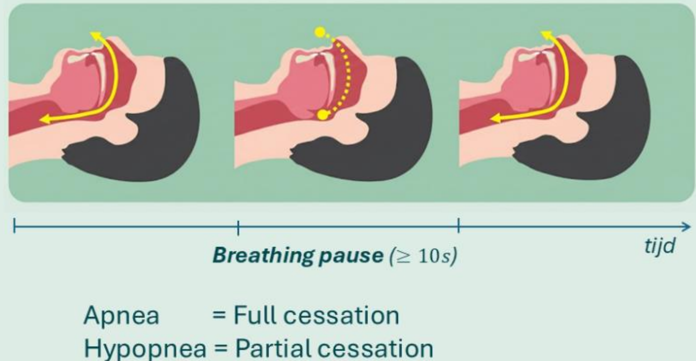
Thank you for your attention, I appreciate it!

Fons.

Title slide:

My thesis is motivated by a common sleep disorder, Obstructive Sleep Apnea, or OSA, the repetitive pausing of breathing due to obstructions in the upper airways.

Obstructive Sleep Apnea (OSA)

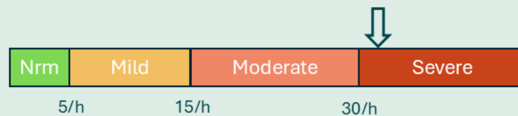


The image shows successive states of the upper airways during a pause in breathing. In a normal state, the airway remains fully open. However, during a pause, the soft tissue at the back of the throat collapses, temporarily interrupting breathing. Fortunately, the body detects this and signals the airway muscles to contract, successfully reopening the passage. Clinically, a complete cessation of breathing is known as an **apnea**, while a partial reduction in airflow is called a **hypopnea.**

Here, we will treat these equally and speak of breathing pauses.

Apnea Hypopnea Index (AHI)

$$AHI = \frac{\#Apneas + \#Hypopneas}{Total\ sleeptime\ (h)}$$



The severity of OSA is measured using the Apnea-Hypopnea Index, or **AHI**. This index represents the average number of breathing pauses per hour of sleep. The AHI is displayed on a scale ranging from **Normal** (on the left) to **Severe** (on the right).

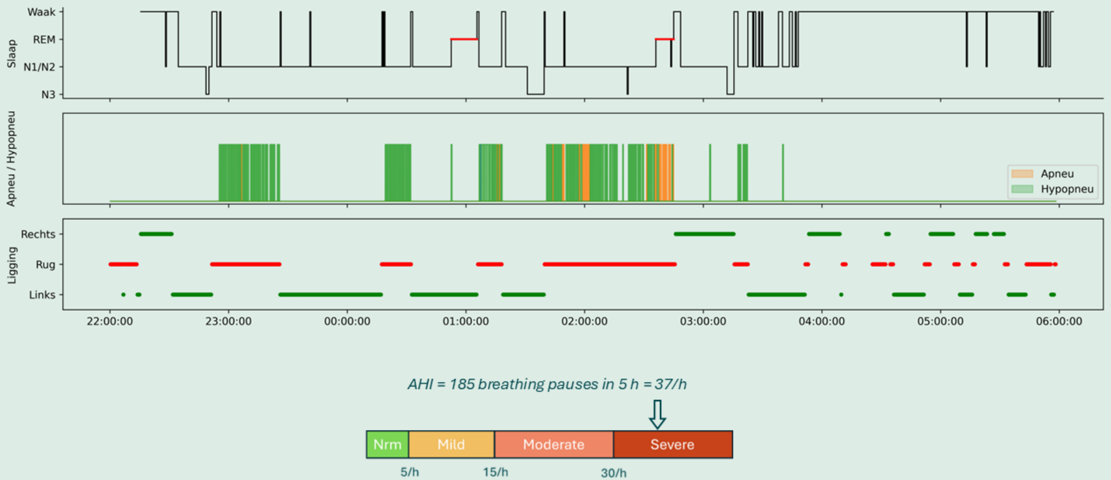
Sleepstudy

Chest band

Heart electrodes

Photo: Kempenhaeghe

A sleep study remains the gold standard for measuring the AHI. During this diagnostic procedure, the patient is fitted with various sensors on the head, torso, and limbs to monitor a full night of sleep. For the purposes of this research, we focus specifically on the chest band and heart electrodes: the chest band measures (surrogate) respiratory effort, while the electrodes monitor the heart rhythm.

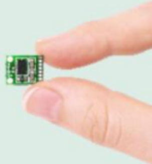


What does the sleep study reveal? First, the **hypnogram** shows the various stages over time: Wakefulness, REM sleep (in red), Light sleep (N1/N2), and Deep sleep (N3). From this, we calculate a total sleep time of 5 hours. Next, we record the breathing pauses—185 in this case—resulting in an **AHI of 37**, which indicates severe OSA.

Notably, these events occur in clusters, which can be explained by looking at the patient's sleep position (shown here with side-sleeping in green and back-sleeping in red). Since the events occur almost exclusively while on the back, this is termed **'Positional Sleep Apnea.'** The recommended therapy is straightforward: avoid sleeping on the back.

Therapy for positional OSA

- Device measures position with accelerometer
- Existing and proven therapy
- **However**, we cannot measure efficacy

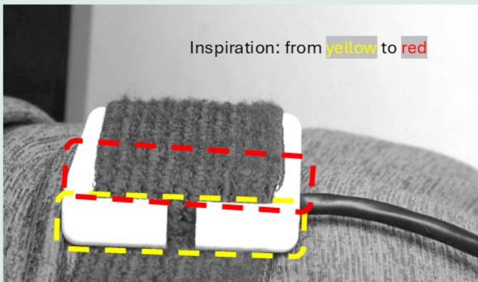


Research question:
Can we measure the AHI?

A common treatment for positional OSA is by means of a small device worn on a chest belt. It uses an **accelerometer** to detect the patient's sleep position; when sleeping on the back, the device vibrates, in this way learning the patient to avoid this position. While this is an existing and proven therapy, **we cannot measure its efficacy**.

Therefore, we aim to accurately **measure the AHI by means of an accelerometer on the chest**. This is the primary objective of research.

How to measure the AHI?



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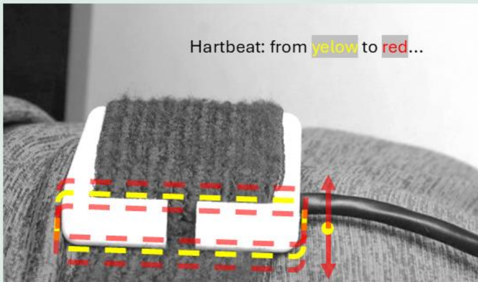
We measure the **respiration** using changes in orientation

Shown here is a prototype of the chest-worn device. The challenge is: how can we measure the AHI using only this? We don't have any of the sensors used in a full sleep study, so we must work with what we have.

As we know, the chest moves during inhalation (illustrated here from yellow to red), which causes the device to tilt slightly. We can measure this tiny tilt by using the **accelerometer as a spirit level**. This is the core principle we use to monitor **respiration**.

How to measure the AHI?



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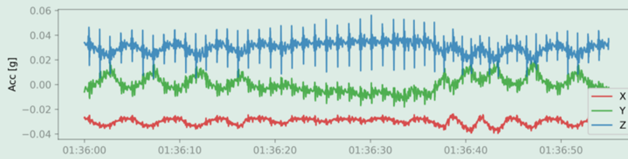
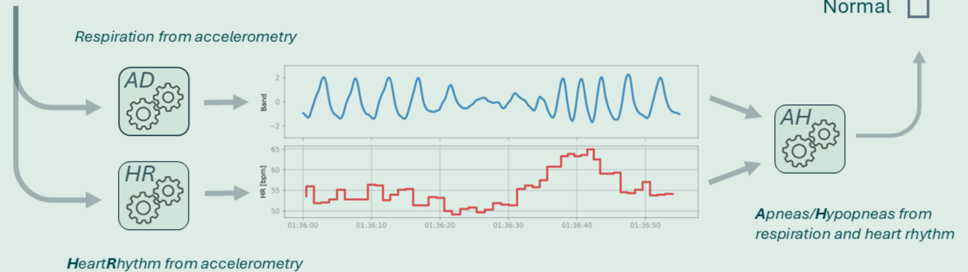
We measure the **heart rhythm** using vibrations

But there is more. With every beat, the heart ejects a volume of blood, creating a subtle physical recoil. This recoil sends a tiny vibration through the chest wall. By using the **accelerometer as a seismograph**, we can detect these minute movements. We use this principle to accurately monitor the **heart rhythm** without traditional electrodes.

Detection of apneas/hypopneas

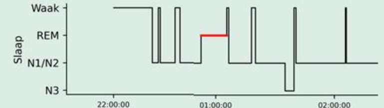




The top graph shows one minute of 3D accelerometer data. The **waves** are caused by breathing. Chapters 1 and 2 detail algorithms that translate chest tilt into a respiratory signal, replicating that from the sleep study. The small **spikes** in the signal are caused by heartbeats. Chapter 3 describes an advanced metod that uses these to measure the heart rhythm with clinical precision.

To detect breathing pauses, we use an algorithm that is based on patterns in **respiration** and **heart rhythm**. This algorithm was trained with large volumes of data from sleep studies. Because we replicate sleep study signals, we can reuse the algorithm after fine-tuning it to our data's specific characteristics. In this example, the combined patterns in breathing and heart rhythm successfully identify a **breathing pause**.

The measurement of sleep



In the same way we measure **sleep**. We apply an algorithm that can detect sleep stages using patterns in respiration and heart rhythm. This algorithm has been trained on large volumes of data from sleep studies. As we replicate these signals, we can use that algorithm here to yield the **hypnogram**.

The AHI

$$AHI = \frac{\#Apneas + \#Hypopneas}{Total\ sleeptime\ (h)}$$

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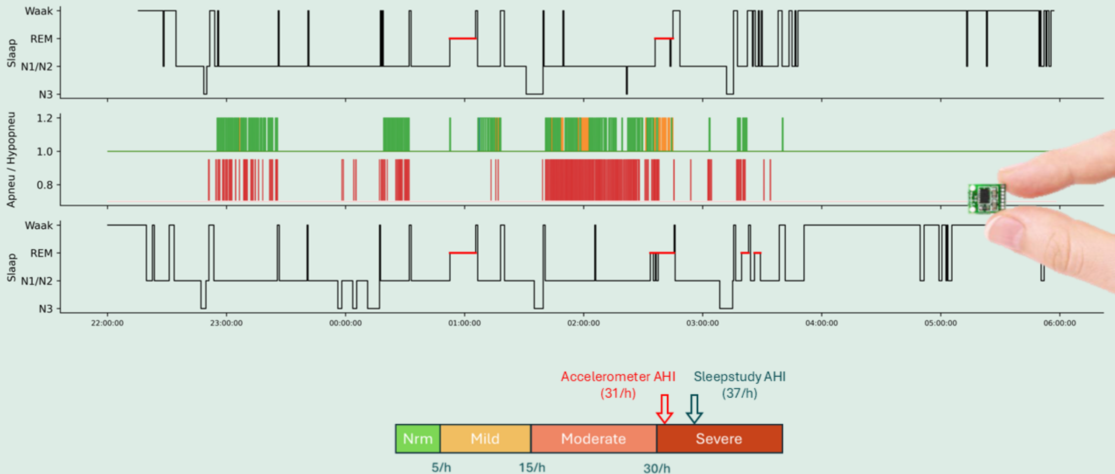
By detecting the **breathing pauses** and generating the **hypnogram**, we now have all the necessary components. We total the number of pauses and calculate the total sleep time, divide them and obtain the **AHI**.

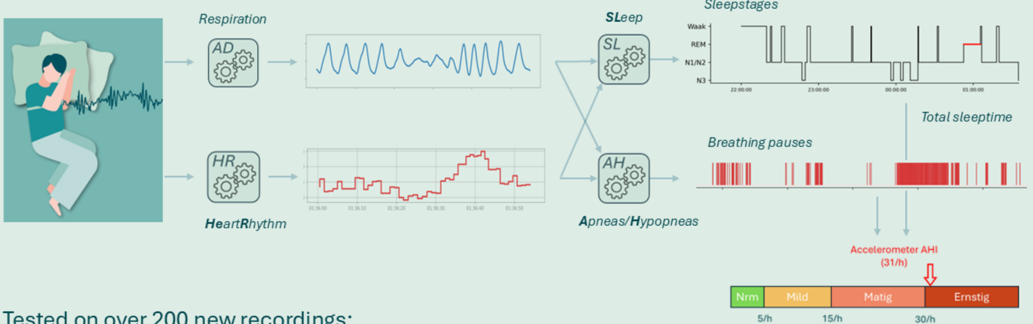


If we return to the earlier sleep study results and place the accelerometer data beneath them, we see a strong agreement in the detection of **breathing pauses**.

This high level of agreement also applies to the **sleep stages** identified throughout the night.

While the resulting **AHI** is slightly lower than the clinical measurement, it still falls within the "Severe" category.

Conclusion



Tested on over 200 new recordings:

- Accurate detection of sleep stages (κ = **0.67**)
- Precise estimation of the AHI (ICC = **0.89**)

→ **Measurement of efficacy of positional therapy**

In **summary**, we measure respiration and heart rhythm through chest wall accelerometry. We then apply algorithms capable of recognizing sleep stages and breathing stops, from which we calculate the AHI.

We have tested this method on over 200 **new recordings**. We were able to detect **sleep stages** accurately, with a Cohen’s kappa of 0.67. We could also precisely estimate the **AHI**, with an intra-class correlation of 0.89. **This should allow for the measurement of the efficacy of positional therapy.**

Propositions

1. Ambulatory sensing from the chest-wall has distinct advantages over other locations such as the wrist.

2. Improving cardiorespiratory measurements enables cross-modal algorithm transfer.

3. Accelerometers are highly versatile for ambulatory physiological monitoring, but as with real estate: location matters.

4. Scientific rigor is the most effective driver of high-quality medical product development.

5. The collaboration between academia, clinics, and industry is a quadruple win, as the patient should not be forgotten.

6. Engineering should be an integral part of the research process, from representative data collection to clinical adoption.

7. The public distrust of algorithms should be countered by demonstrating their value in improving healthcare.

8. A good scientist explains complex ideas without losing their essence.

9. Successfully completing a PhD during the pandemic proves that collaborative creativity does not solely depend on physical proximity.

10. The use of 'football fields' as a unit of measurement should be prohibited.

Measuring Sleep and Respiration with Chest-Wall Accelerometry

Obstructive Sleep Apnea (OSA) can severely impact daily wellbeing and long-term health. Positive airway pressure -such as CPAP- remains the gold-standard OSA treatment, and devices routinely provide an estimation of the apnea-hypopnea index (AHI) as an indicator of treatment efficacy. However, this critical feedback loop is notably absent in other OSA treatments, such as positional therapy. Devices for positional therapy use chest-worn accelerometers to detect body position, and subsequently correct supine sleeping.

The work in this thesis advances the field of sleep monitoring by introducing novel ways to use chest-worn accelerometry for clinical-grade assessment. Advanced methods are presented to derive respiratory effort and instantaneous heart rate solely from the accelerometer signal. By tuning neural networks trained on large datasets, accurate sleep staging and AHI estimation algorithms were developed. This approach enables therapeutic devices to monitor residual OSA and thus increase clinical confidence in treatment outcome.