Unobtrusive Monitoring System Based on Ballistocardiography (BCG)

# Your chair can hear your heart.

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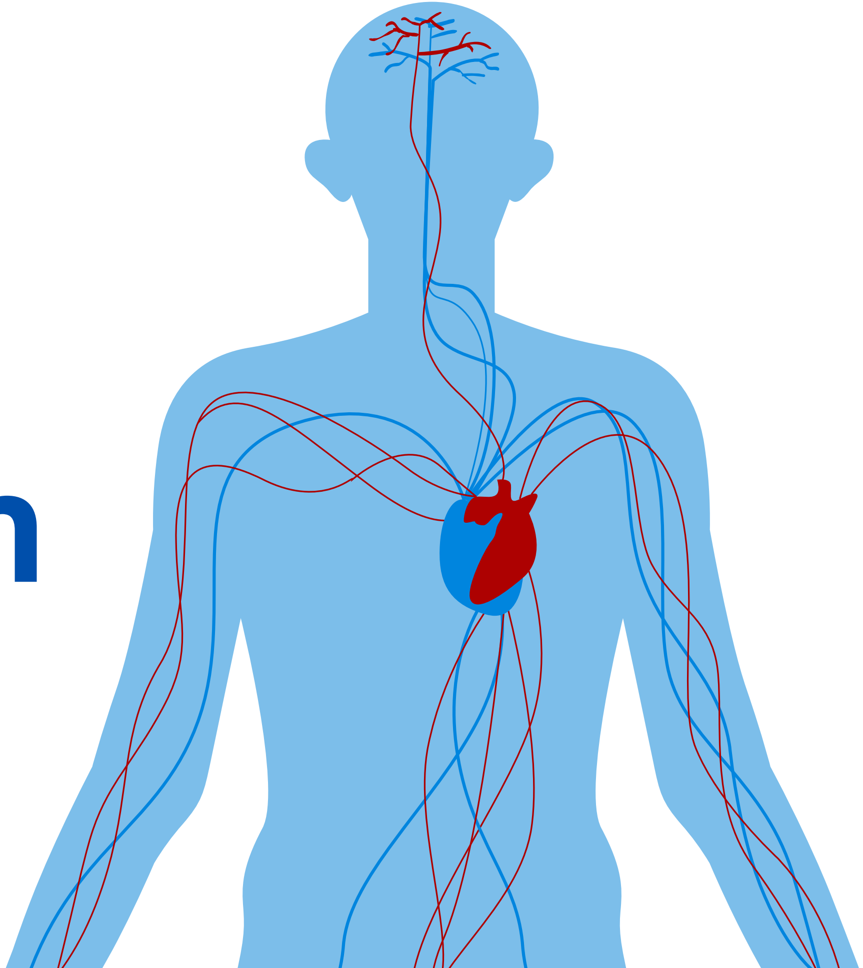
# Introduction



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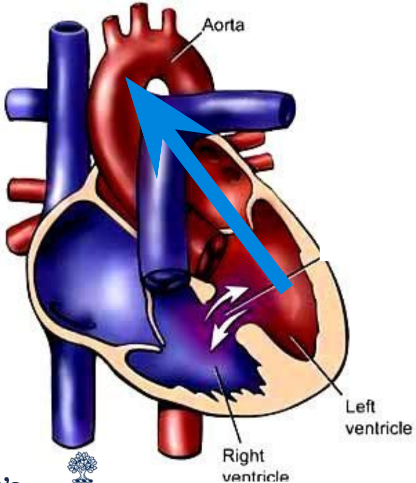
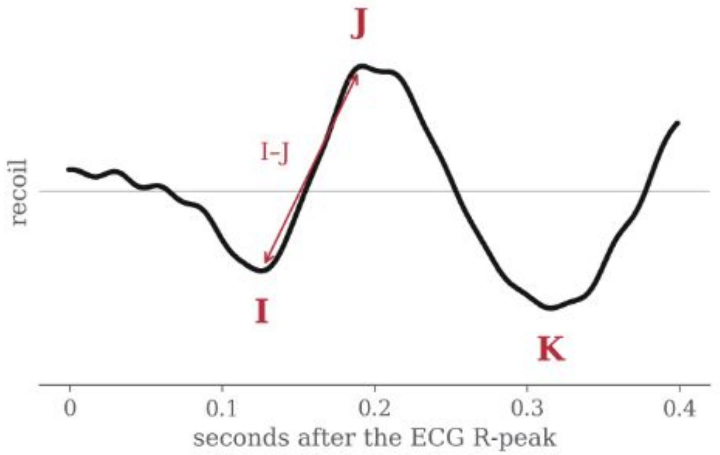
# What is a ballistocardiogram (BCG)?

Every heartbeat moves your whole body.

When your ventricle ejects blood into the aorta, the body recoils in the opposite direction (N3).




A ballistocardiogram (BCG) is a recording of that recoil, measured as displacement, velocity, or acceleration.




*One averaged beat from our own recordings, aligned to the ECG R-peak*

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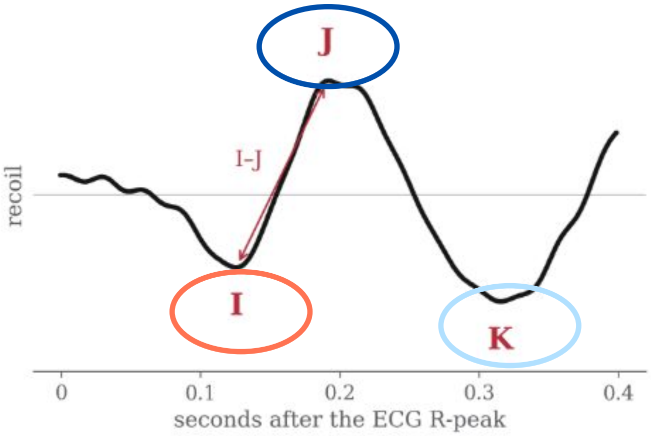
# What is a ballistocardiogram (BCG)?

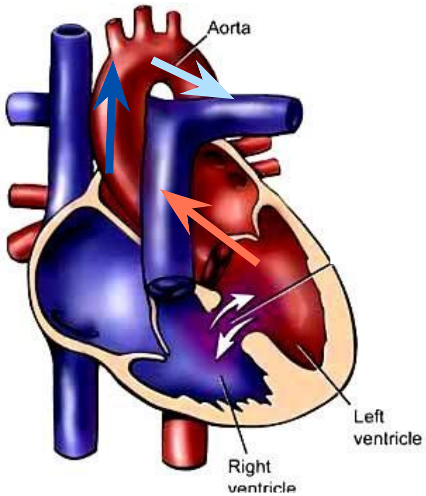
*Described in 1877, formalized by Starr in 1930s–40s on suspended beds, and abandoned by the 1980s, revived by sensors small enough to hide in furniture*




*One averaged beat from our own recordings, aligned to the ECG R-peak*

The waveform is labelled H-I-J-K-L-M. The main are I-J-K.

- **I - Early systole:** rapid acceleration of blood through aortic valve
- **J - Mid systole:** deceleration in ascending aorta. Largest peak, so amplitude tracks pulse pressure
- **K - Late systole:** deceleration in descending aorta against peripheral resistance

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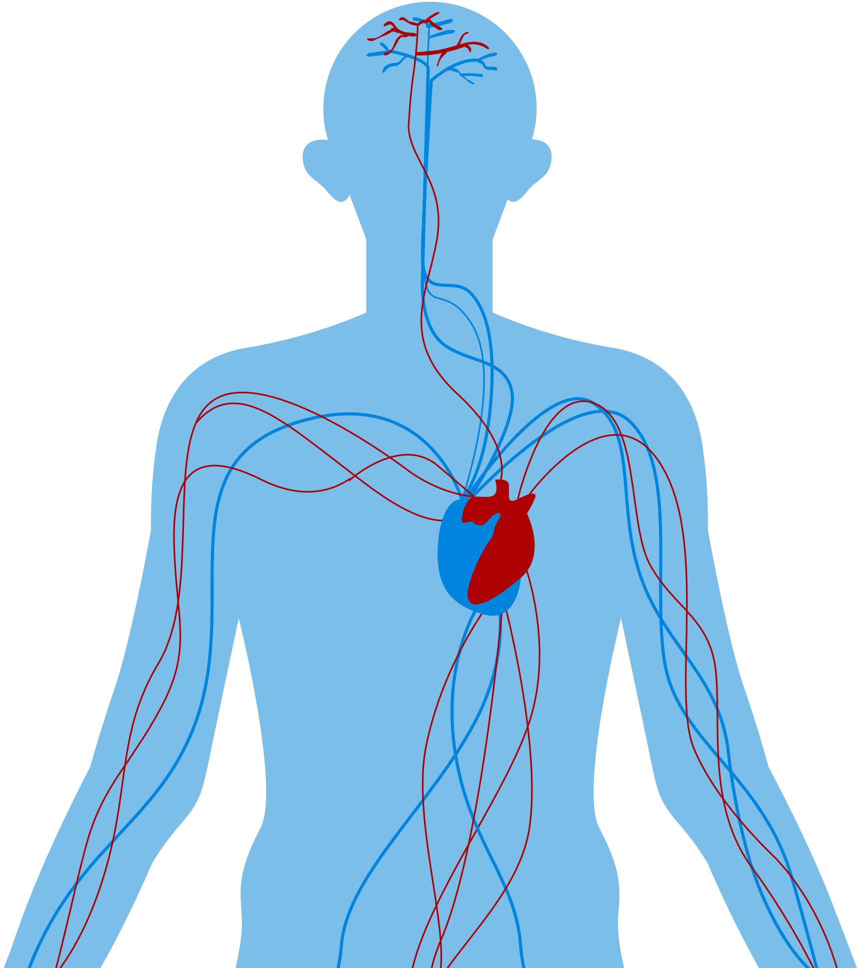
# Background



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# Heart failure (HF) is managed on lagging information

**750,000** Canadians with HF

**70%** Patients are 65+

**1 in 5** readmitted in 1 month

**10–30%** HF patients have cognitive impairment

- Weight-based self-monitoring detects congestion late (after symptoms appear).
- Wearables and cuffs need DAILY patient action.
- **Design implication:** monitoring has to be PASSIVE. Must require as little as possible from the patient.

Heart & Stroke Canada; Poon et al., CJC Open 2022;4:667–75; Huynh et al., Circ Heart Fail 2019;12:e006086

# BCG gives heart rate, but clinicians need hemodynamics.

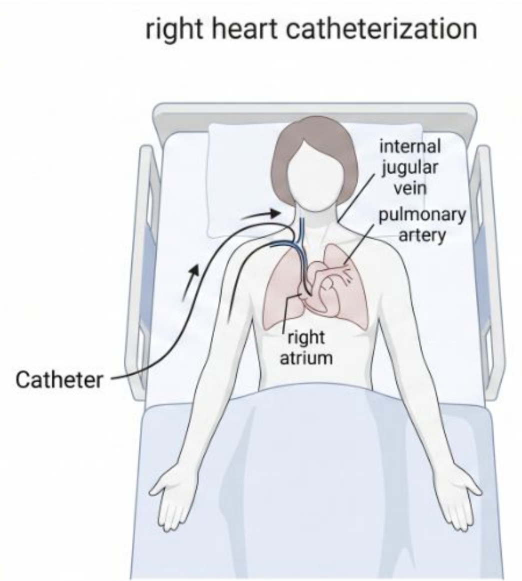
## BCG (currently) gives:

- ✔ Heart rate, from distance between J-peaks
- ✔ Beat-to-beat interval variability
- ✔ Coarse healthy vs. clinical separation

## HF management needs:

- ➕ Stroke volume and cardiac output
- ➕ Myocardial contractility (pre-ejection period)
- ➕ Filling pressure and diastolic function
- ➕ Total mechanical work of the ventricle

**ISSUE:** Gold standard for all four is right heart catheterization, an invasive, in-hospital reading. NOT an at-home solution.



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# Objective

*Design a **passive** monitoring system that extracts **hemodynamic** parameters (not only heart rate) from a **low-cost 3-axis BCG**, validated against right heart catheterization.*

# Design Objectives, Requirements, and Constraints

## Functional requirements (FR)

1. 6 DOF: 3 linear + 3 rotational
2. Covering the 0.5–35 Hz BCG band
3. Preserve physiological waveform timing

## Constraints (C)

1. No skin contact and no patient action required
2. Portable and low-cost compared to force plates
3. Fits a chair, bed or scale form factor
4. Tolerates noise

## Success Criteria (SC)

1. Heart rate error vs. ECG < 5 bpm
2. Can separate HF from healthy
3. Repeatable across posture and session

# Design Objectives, Requirements, and Constraints

## Functional requirements (FR)

By default

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Materials

## Success Criteria (SC)

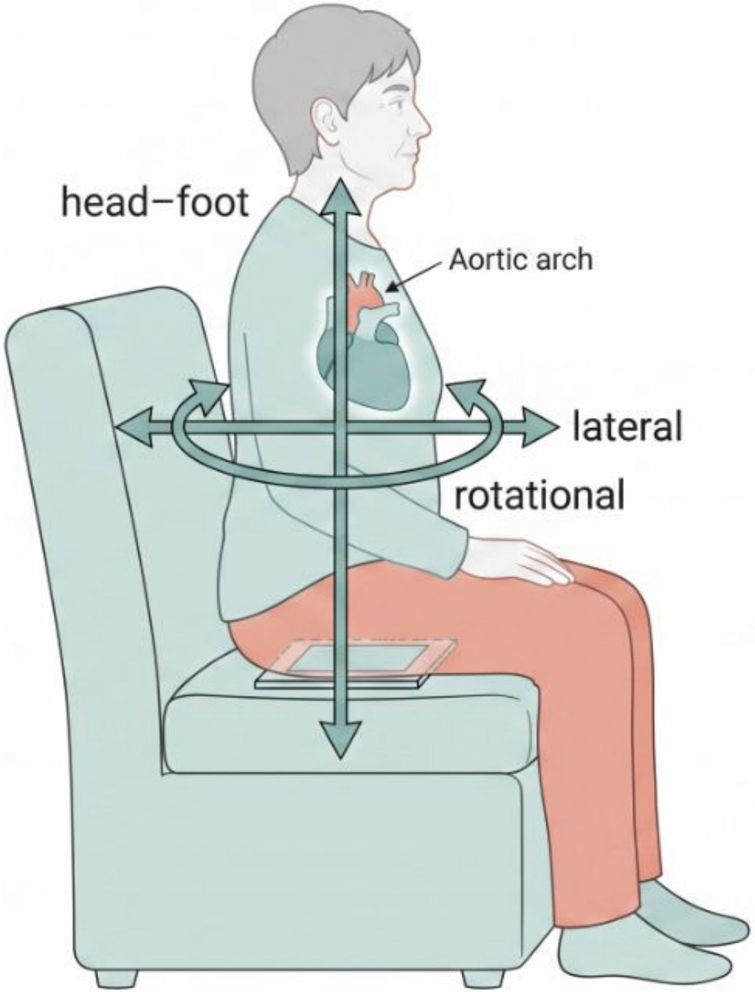
1. Heart rate error vs. ECG < 5 bpm
2. Can separate HF from healthy
3. Repeatable across posture and session

**FR1:** 6 DOF: 3 linear + 3 rotational

**C1:** No skin contact and no patient action required

**Part of C2:** Portable

**C3:** Fits a chair, bed or scale form factor



# Design Objectives, Requirements, and Constraints

## Functional requirements (FR)

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## Success Criteria (SC)

1. Heart rate error vs. ECG < 5 bpm
2. Can separate HF from healthy
3. Repeatable across posture and session

Can work on these without touching hardware (WIP for patent)

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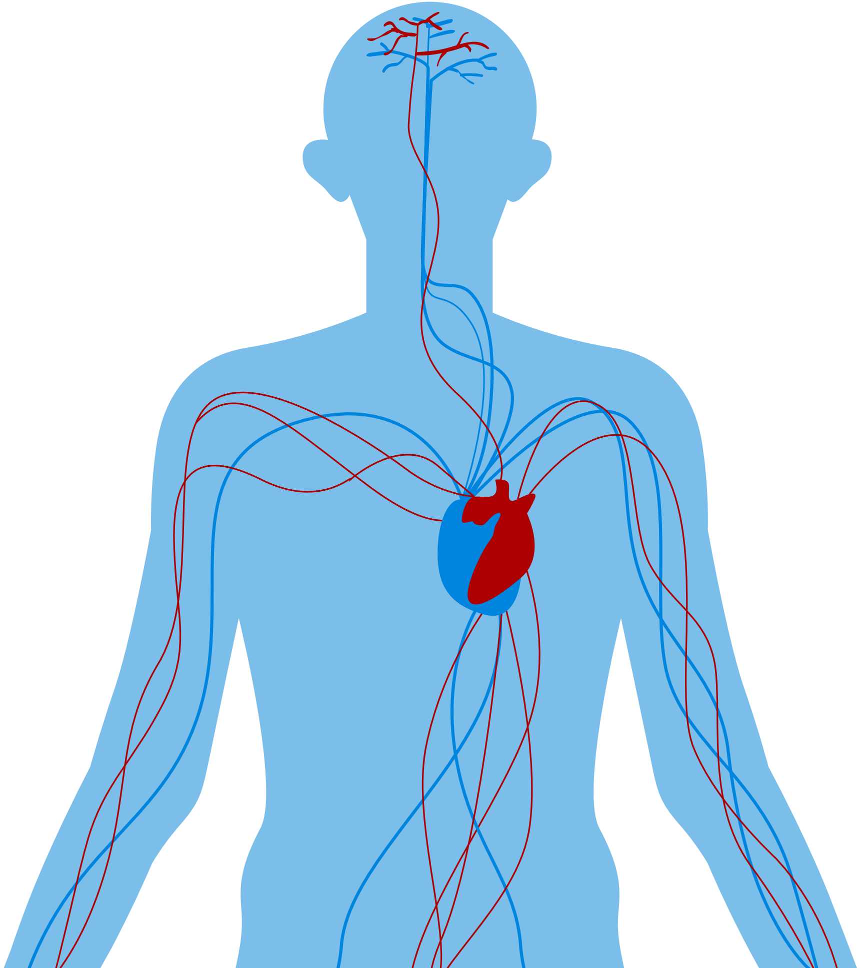
04

# Methods



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# 3 sections we have worked on

| | | |
|---|---|---|
| 01 | **Architecture & Algorithm** | |
| | Code integration & functions | FR 2, 3 |
| 02 | **BCG Integration** | |
| | Integrating & filtering | C 4, FR 3 |
| 03 | **Kinocardiography** | |
| | Research & theory & applying 4.2 | SC 2 |

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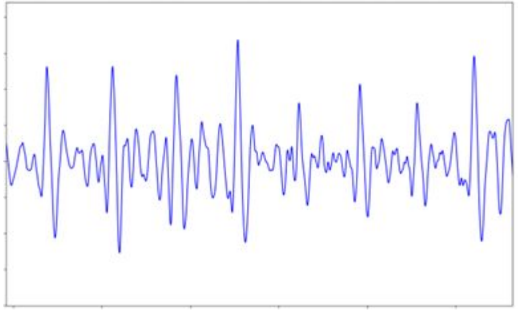
# BCG Sensors

Sample BCG



Sample ECG

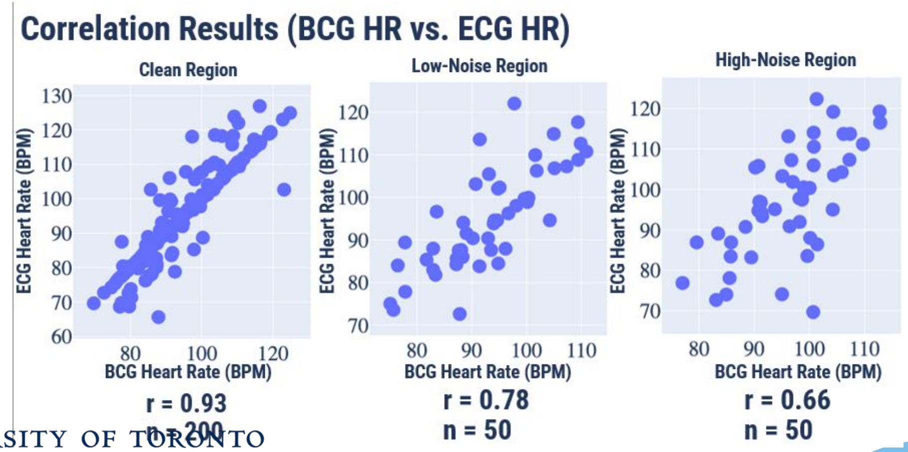
# Recruitment + Procedure

Healthy population (n = 50, mean age: 26, 18 female)

- 6 minute recording
- Valsalva maneuver at 1 minute

HF population (n = 10, mean age 62, 1 female)

- 3 minute recording
- *recorded prior to catheterization procedure



# BCG vs ECG

| | Within 5 bpm | Within 3 bpm | Within 1 bpm |
|---|---|---|---|
| Static HR (clean) region | 80% | 78% | 68% |
| Dynamic HR (low-noise) region | 59% | 54% | 33% |
| Dynamic HR (high-noise) region | 40% | 31% | 10% |

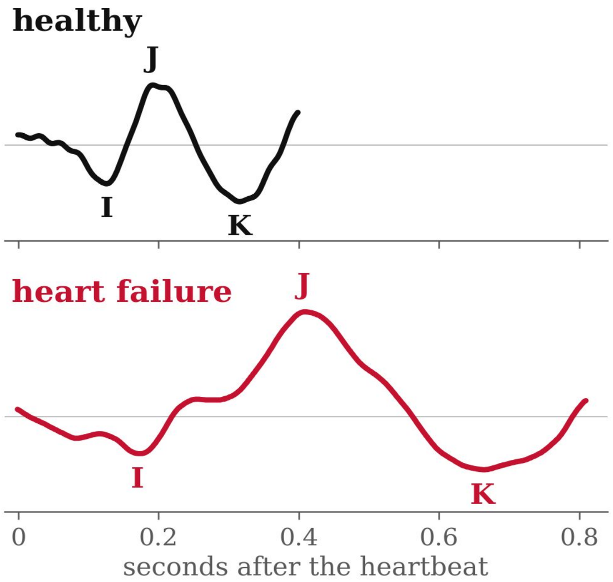
# Peak amplitude is the wrong metric in HF

👎👎

The standard approach picks out peaks and measures how tall they are.

- A failing ventricle can still produce one forceful contraction
- Peak amplitude is sensitive to respiration, body movement, etc.

***Design decision**: integrate over the beat rather than detect peaks, to capturing both the magnitude and the duration of mechanical effort.*




*Our own recordings: the failing heartbeat is broader and slower*

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# 04.2 – BCG Integration

***Design rationale:*** *without the intermediate high-pass, any sensor bias integrates into a parabolic drift and the reconstructed displacement diverges. The waveform becomes physiologically meaningless.*

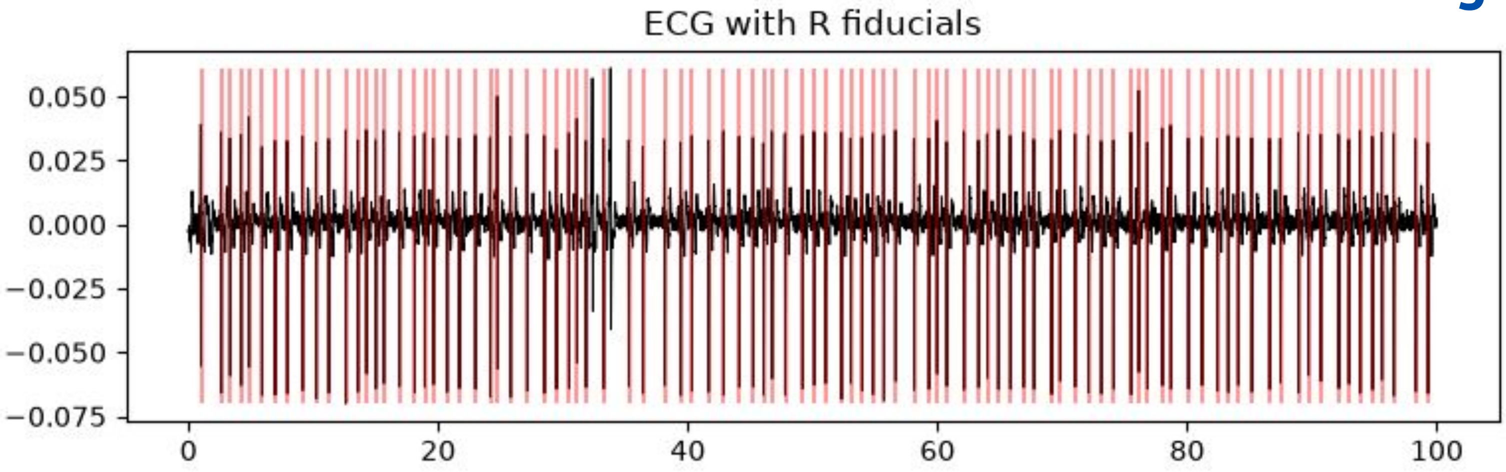
BCG signal recoil force → 1st integral velocity → 2nd integral displacement

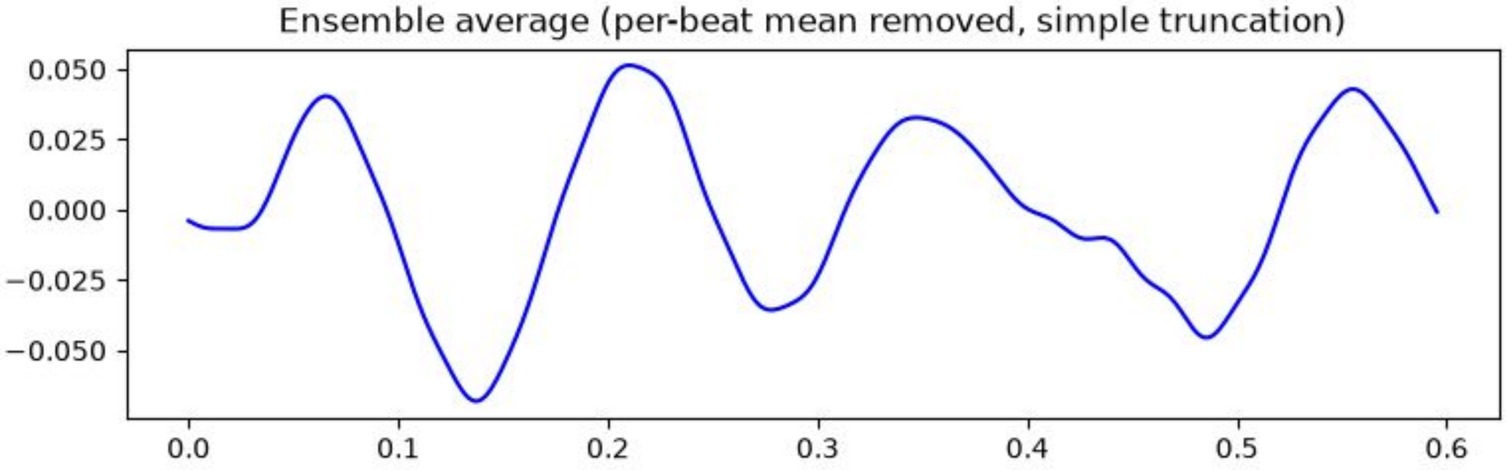
- **Goal:** use BCG waveform to predict cardiac parameters
- **Approach:** Integrate BCG waveform

How do you deal with the integration constant?

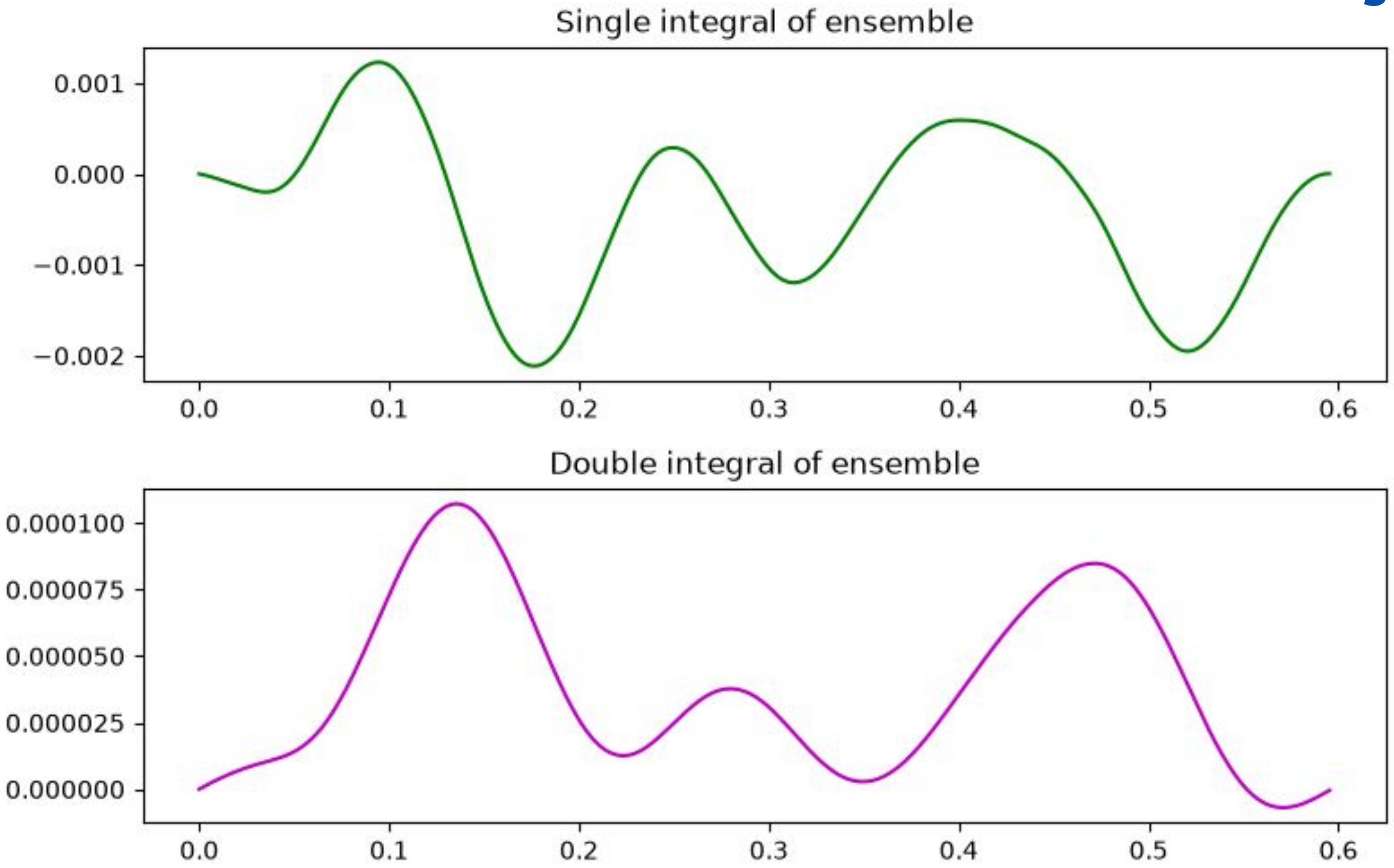
1. Assume it is 0
2. Remove DC offset before integration
3. Apply several high pass filters before integration

# 04.2 – BCG Integration



# 04.2 – BCG Integration




Approach: remove DC offset

# Kinocardiography (KCG): cardiac work as an integrated energy

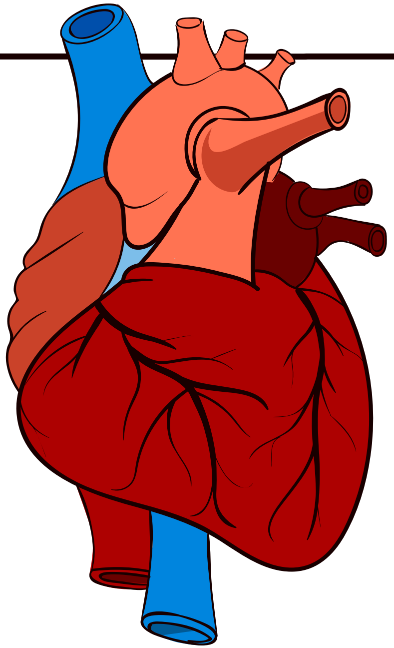
## Instantaneous kinetic energy

$$K_{lin} = \tfrac{1}{2}\, m\, (v_x^{\,2} + v_y^{\,2} + v_z^{\,2})$$

$$K_{rot} = \tfrac{1}{2}\, (I_{xx}\, \omega_x^{\,2} + I_{yy}\, \omega_y^{\,2} + I_{zz}\, \omega_z^{\,2})$$

m from body mass; inertia tensor from anthropometric tables (subject-specific )

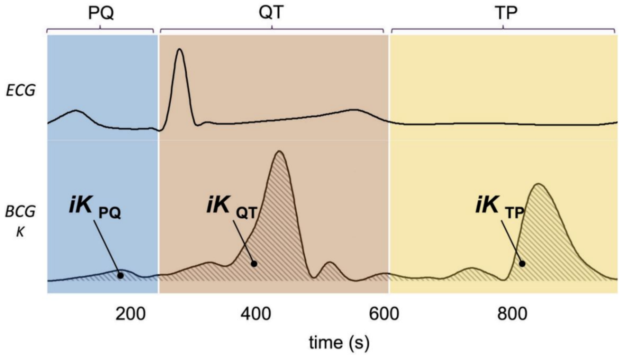
**by using KCG, we are enforcing FR 1 as well, because KCG dof can match 1-to-1 with BCG



## Metrics (time integrals)

$iK_{systolic}$ = ∫ K(t) dt over the QT window

$$\Delta iK_{diastolic} = a\, (iK_{TP} - iK_{PQ}) / (iK_{TP} + iK_{PQ})$$

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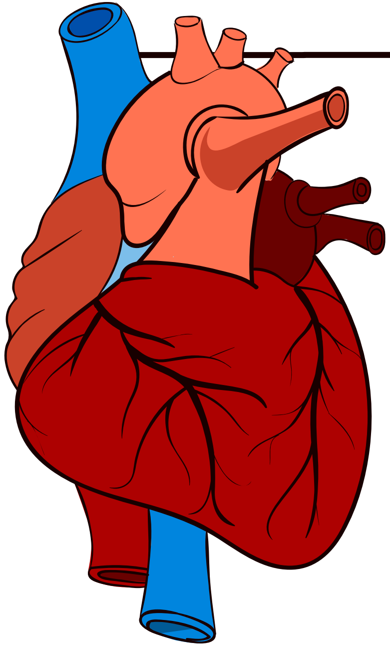
# Kinocardiography (KCG): cardiac work as an integrated energy

In patients with impaired ejection fraction, both are reduced. Higher $iK_{systolic}$ is associated with better survival

BCG energy is less associated with ventricular dilatation than SCG (chest) energy. Senses **aortic recoil** rather than local wall motion.



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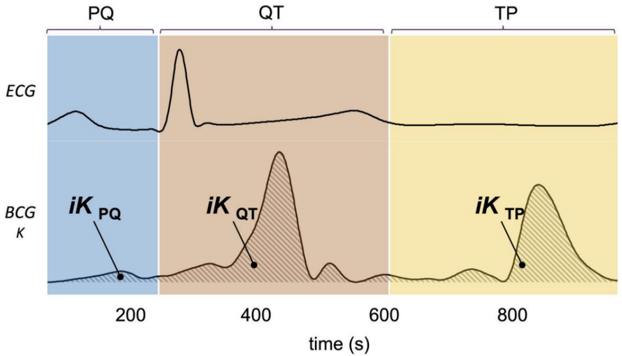


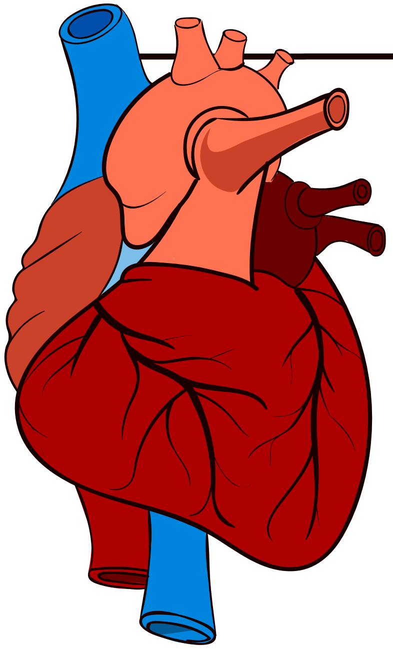
# Using KCG in our sensor

**Sensor site**

Published KCG: BCG + SCG. Using *just* BCG would work fine as well (1 less modality).

**Primary metric**

$\Delta iK_{diastolic}$ is dimensionless. Mass and inertia scaling cancel. Body-size independent where absolute $iK_{systolic}$ is not.



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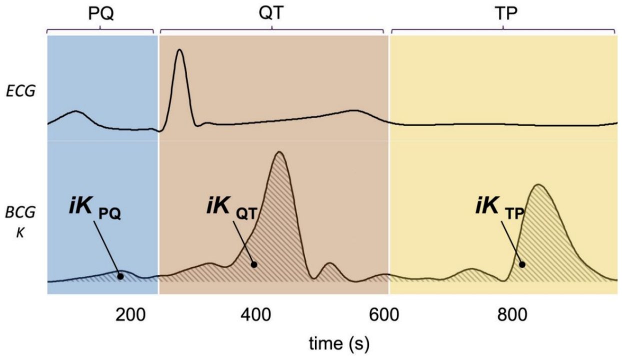


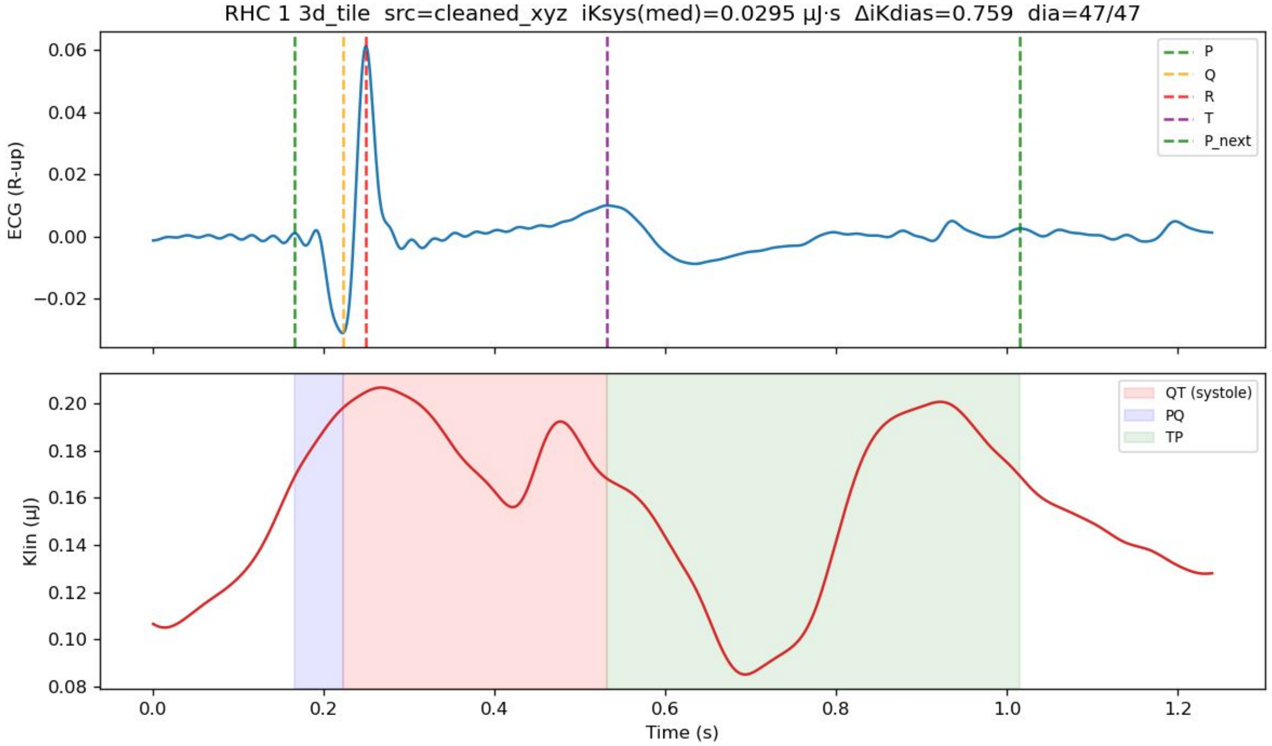
# Using KCG in our sensor

**Success criteria:** same continuous xyz for patients and healthy, velocity must NOT be dominated by integration drift, QT/PQ/TP windows must be real ECG intervals.
**Constraint:** do not have healthy weights available. Used 70kg for n=6.

| Must | Cannot |
|---|---|
| a=F/m, then one integrate to v | Use healthy kg |
| Band-pass force 0.5-25 Hz, high-pass v at 0.5Hz | - |
| Median of beats, not mean | Have n=11 HF patients, 6 healthy |

*NOTE: our setup is a 3-axis load-cell force (no SCP or gyroscope). Reference papers used MEMs accelerometers and gyroscopes. **-> hardware gap***

# Computing iK from our signal

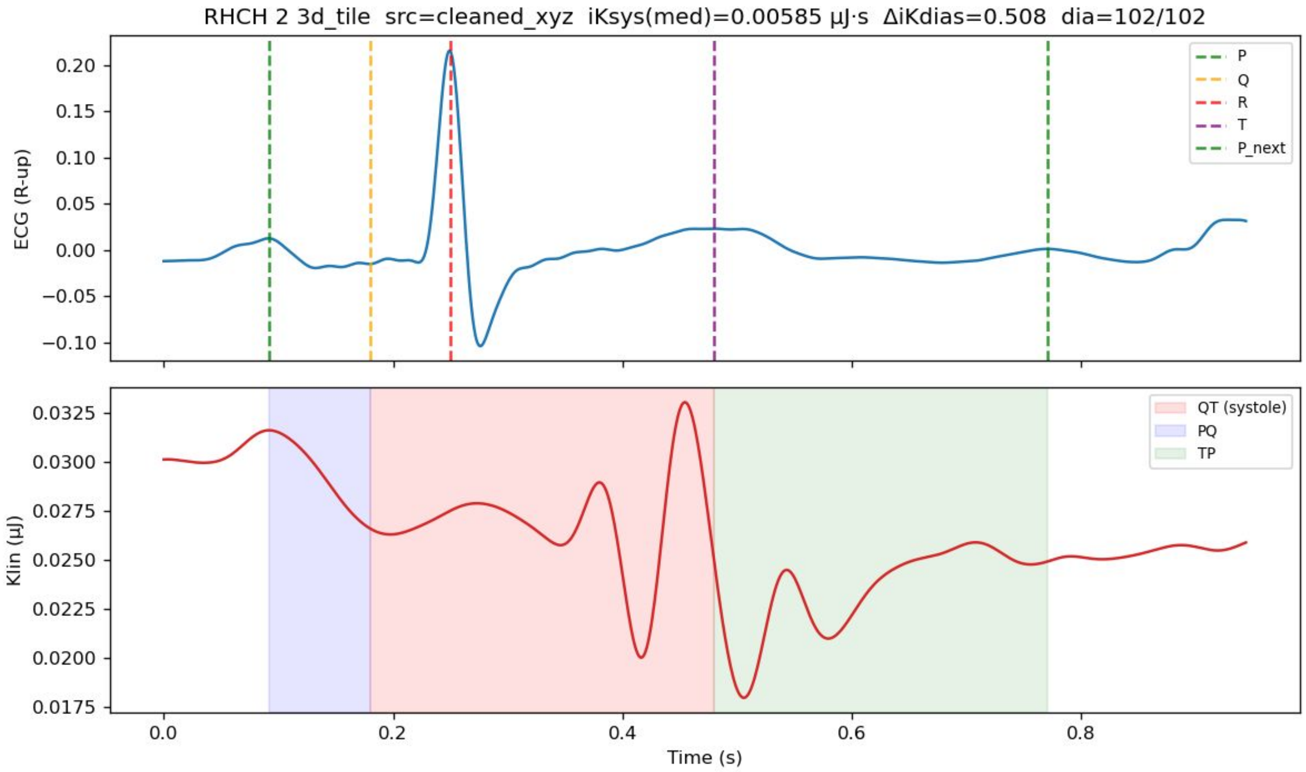



One beat from a heart failure patient: ECG landmarks (top), linear kinetic energy with integration windows (bottom)

$iK_{diastolic}$=0.759

# Results in healthy

n=6, mass-free metrics.



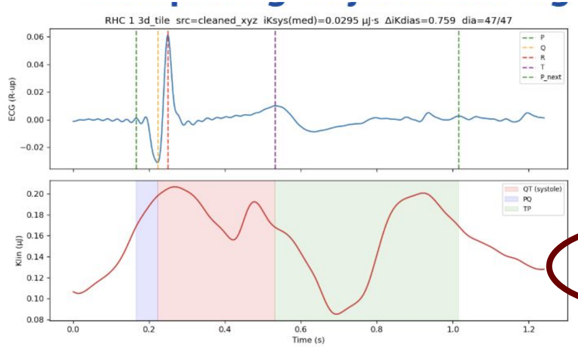

Each row is 1 patient

| # beats kept | $\Delta iK_{diastolic}$ |
|---|---|
| 79 | 0.79 |
| 102 | 0.51 |
| 80 | 0.68 |
| 29* | 0.46 |
| 76 | 0.74 |
| 77 | 0.82 |

**very small, 29/115

# Non–healthy patient’s within healthy range

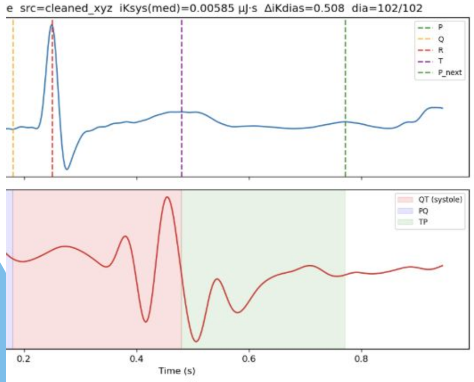
🤔🤔




One beat from a heart failure patient: ECG landmarks (top), linear kinetic energy with integration windows (bottom)

$iK_{diastolic}=0.759$

n=6, mass-free metrics.

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| # beats kept | $\Delta iK_{diastolic}$ |
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| 29* | 0.46 |
| 76 | 0.74 |
| 77 | 0.82 |

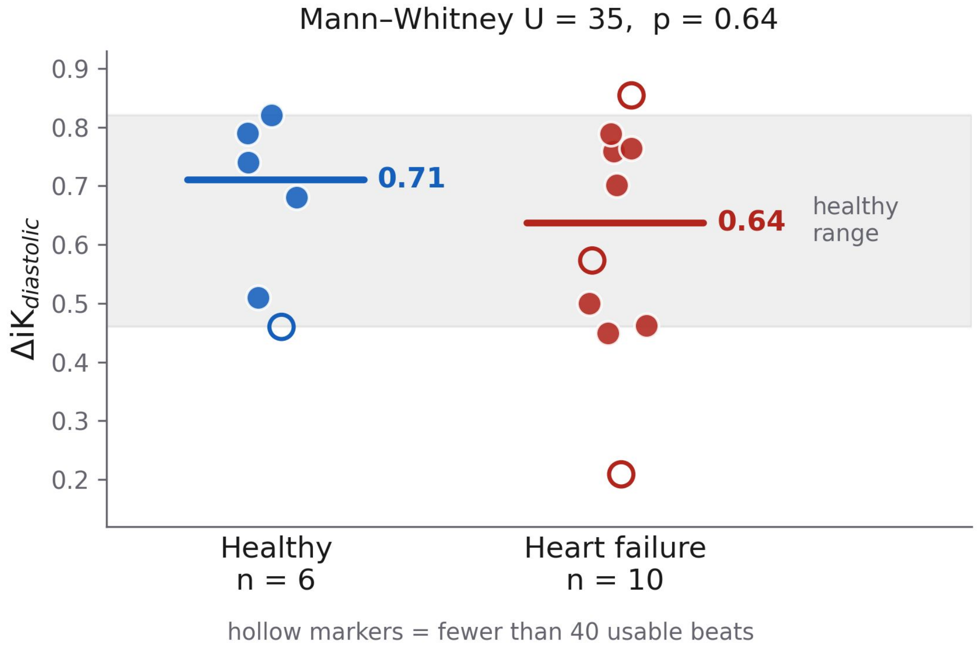
**very small, 29/115

At this sample size, the healthy and HF distributions overlap and we can't separate them yet.

$0.46<0.759<0.82$

# Non–healthy patient's within healthy range

🤔🤔




Literature predicts $\Delta iK_{diastolic}$ is reduced in impaired ejection fraction, and our HF median is lower.

It's just nowhere near separable at this n.

# Cohen's d = 0.33, meaning small effect

Detecting an effect that size at 80% power needs roughly 147 per group. The current study has about 9% power.

At the effect size we observed, that would take around 150 per group, so this is a power problem, not a pipeline problem.

# Validation against requirements

| Requirement | Status | Evidence |
|---|---|---|
| 6 DOF linear + rotational | 3 linear axes met; rotational not yet. Current hardware is load-cell only | 3-axis load-cell force (no SCG or gyroscope) |
| Physiological waveform timing preserved | Yes | Double integration restores the true R-J interval |
| No skin contact and no patient action | Yes | Sensor sits under seat, the patient fully clothed |
| Portable, low cost vs. force plate | Yes | Confidential |
| Heart rate accuracy vs ECG | WIP | Only high accuracy on clean regions |
| Energy metrics separate HF from healthy | WIP | Did not separate the groups at n=6 healthy / n=10 HF |

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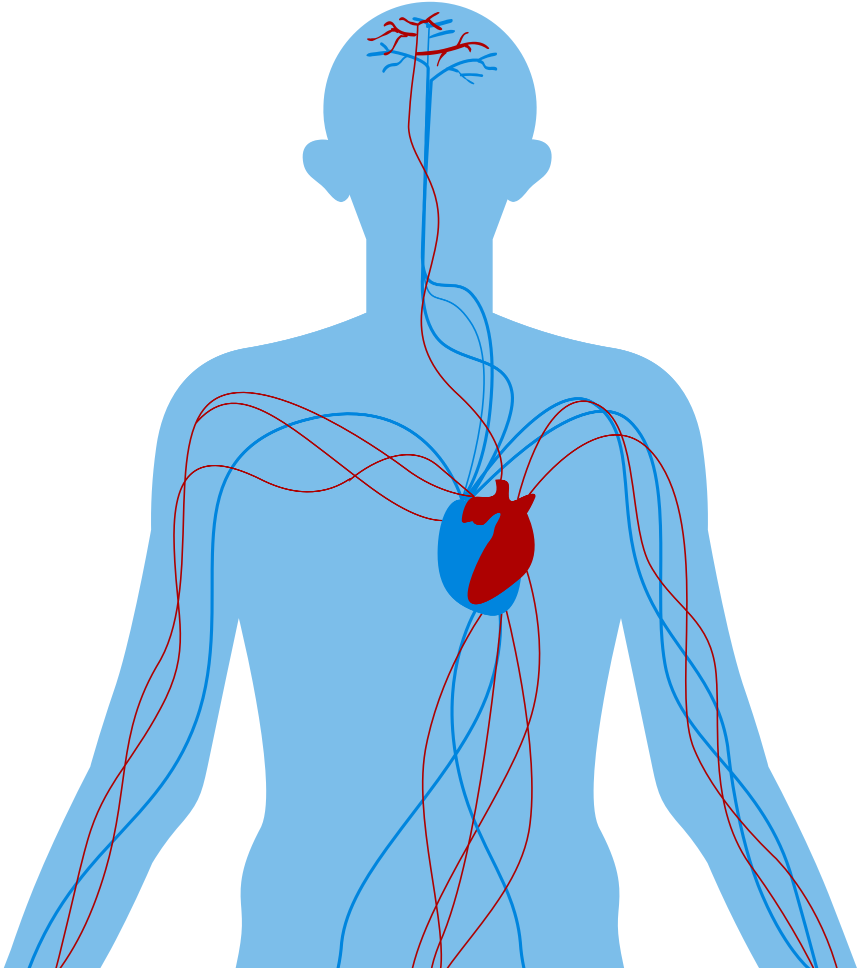
# Conclusion



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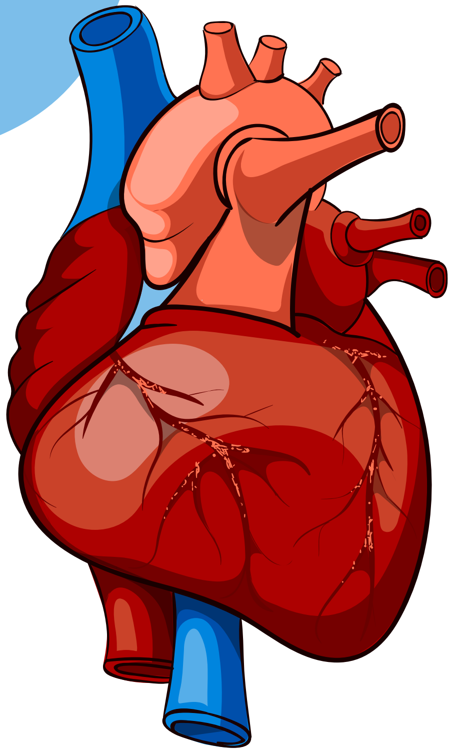
# Takeaways and Future Steps

- BCGs can be a safe, at-home and portable way to monitor heart health without a trip to the hospital.
- Heart rate is not enough! Integrated energy can capture the mechanical work of a  beat.
- Correlate double integral measurements with stroke volume and contractility
- We can compute linear BCG kinetic energy on this lab's force signals and iK tracks force when mass is KNOWN. NEED A HIGHER SAMPLE SIZE, though we do see some initial agreement.

**Your chair can hear your heart.**



# THANKS!

**Do you have any questions?**

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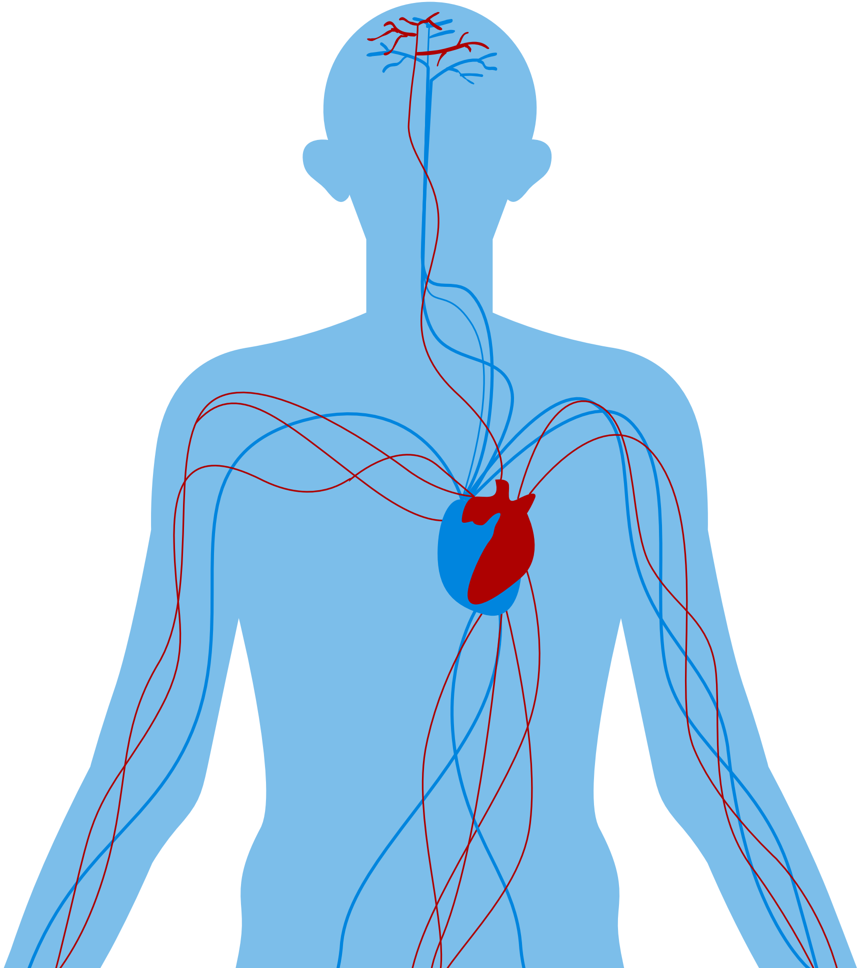
# 06

# Q&A



# Why Valsalva in healthy protocol?

- Valsalva maneuver: test in which the participants hold their breath and increases pressure in the chest while trying to exhale
- Allows team to identify regions of signal with changing heart rates
- Test if heart-rate extraction method stays accurate even when signal is changing rapidly

# Does assuming 70kg for all healthy subjects to compute kinetic energy invalidate iK_systolic

- Yes – it's why we highlighted deltaiK_diastolic as our primary metric

# What's the biggest limitation right now?

- Lack of patients to test → lack of data and validation
- Closing the loop back to clinical gold standard of catheterization to validate the accuracy of BCG

# Who was in your HF cohort and were there any technical difficulties recording data with them?

- Excluded patients unable to remain standing or seated for more than 10 minutes
- Excluded movement disorders (including tremors)
- Patients chosen were all able to undergo the trials safely + patients with uncontrollable movement were excluded → not too many technical difficulties
- May be a limitation as current sample is skewed towards more stable patients

# Does averaging beats together hide problems that matter clinically?

- Yes - ensemble averaging assumes beats are similar enough to combine which smooths out beat-to beat irregularity
- HOWEVER, this allows for much cleaner analysis and much of the signals of heart irregularities can still be noticed even after averaging beats together
- Much of this is simply to clean out factors like breathing which also affect the BCG signal

# How would this system be used in practice? Is it meant to replace catheterization or supplement?

- Currently: not a replacement for catheterization
- Passive, continuous at-home trend monitoring between hospital visits
- Early warning system and  can catch worsening trends quickly

# Current Pipeline Overview

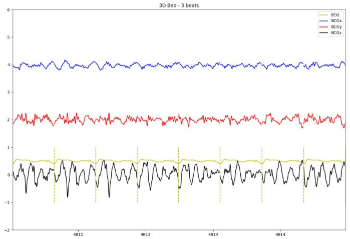
Raw CSV → 1: Clean → 2: Segment → 3: Epoches/Intervals → 4: Features

**1: Clean**
- Trim to recording regions
- Sync BCG + ECG signals

**2: Segment**
- Find ECG R-peaks
- Convert load cell channels → X,Y,Z waveforms

**3: Epoches/Intervals**
- Groups beats
- Ensemble average

**4: Features**
- Compute hemodynamic metrics



# Since data was collected in a lab setting, how confident are you in results holding up outside of clinical environment?

- While there are many sources of vibration in a home, much of the noise should be cleaned out with our current data processing methods
- Yet to be tested. Further testing required!!