Monte Carlo Simulation of CIED Longevity

STAT 400: Computational Statistics — Colorado State University

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Motivation

- CIED (pacemaker) batteries require surgical replacement.
- Longevity prediction helps avoid too-early or too-late replacement.
- Lead impedance affects pacing current $\rightarrow$ may affect battery life.
- We use a Monte Carlo simulation to test whether impedance variability changes predicted longevity.

Simulation Inputs

- 100,000 simulated patients.
- Variables included: heart rate, pacing %, battery capacity, background current, impedance.
- Two impedance conditions:
  - **Base:** fixed at 500 Ohms
  - **Extended:** N(500 Ohms, SD = 100 Ohms)
- Purpose: isolate the effect of impedance variability.

Problem Statement & Methodology

- **Question:** Does impedance variability meaningfully change predicted longevity?
- **Steps:**
  1. Implement PCI model.
  2. Simulate patient and device parameters.
  3. Compute longevity under both impedance scenarios.
  4. Compare means and distributions.

PCI Model: Concept Overview

- PCI $=$ electrical load relative to battery capacity.
- Lower impedance $\rightarrow$ more current $\rightarrow$ shorter longevity.
- Components:
  - Pacing current
  - Background/system current
  - Optional features current

PCI Model: Pacing Current Formula

```r
p_current <- function(v, pw_ms, r_ohm, hr = 60,
                      pace_fraction = 0.3){
  # Convert Pulse width to seconds
  pw_sec  <- pw_ms / 1000

  # Current during pulse
  i_pulse <- v / r_ohm

  # Charge per pulse in Coulombs
  q       <- i_pulse * pw_sec

  # Convert to microcoulombs
  q_micro <- q * 1e6

  # Average current over 1 minute
  i_avg_microamps <- (q_micro * hr * pace_fraction)/60
  return(i_avg_microamps)
}
```

PCI Model: Longevity Formula

```
long <- function(i_background, i_pacing,
                 i_options, c_mah){
  # Convert battery capacity from mAh to µAh
  c_uah      <- c_mah * 1000
  # Total current in µA
  i_total    <- i_background + i_pacing +
    i_options
  # Power Consumption Index (PCI)
  PCI        <- i_total / c_uah
  # Longevity in hours
  long_hours <- 1 / PCI
  # Longevity in years
  long_hours / 8760
  return(list(
    i_total = i_total,
    PCI = PCI,
    years = long_years))
  }
```

Monte Carlo Framework (How We Tested)

For each of 100,000 patients:

1. Calculate longevity with perfect 500 Ohms impedance
2. Calculate longevity with realistic variable impedance
3. Compare the two results

This isolates the effect of impedance variability by controlling for other patient differences

Longevity Summary Table

Scenario	Mean	Median	SD	Q1	Q3	n
Base (500 Ohms)	15.33	15.12	2.31	13.68	16.76	100,000
Extended ($\pm$100 Ohms)	15.26	15.08	2.37	13.58	16.73	100,000

- Longevity slightly lower under impedance variability.
- Differences are small.

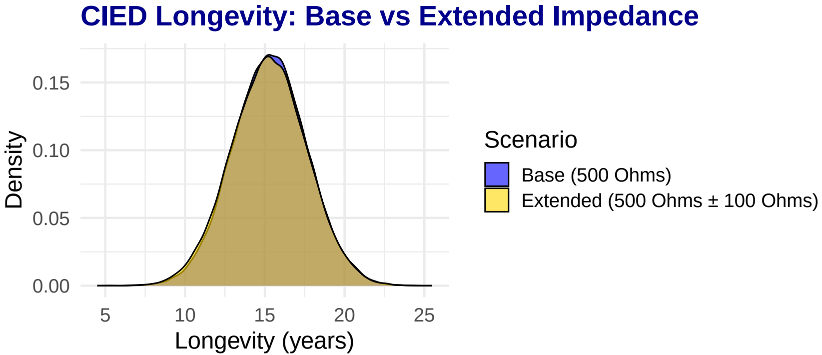
T-Test Results

```
Welch Two Sample t-test

t = 6.61
p-value = 3.76e-11

95% CI: 0.049 to 0.090 years
Mean(Base)     = 15.33
Mean(Extended) = 15.26
```

Longevity Distribution Plot



- Strong overlap → impedance variability has small effect.
- Near-identical distributions → minimal practical difference.
- Slight separation aligns with statistical findings.
- Same distribution shape → consistent prediction patterns.

Discussion

- Background/system current has strongest influence on longevity.
- Impedance variability causes small, predictable changes.
- Pacing burden + background current dominate longevity outcomes.

Limitations & Future Work

- Impedance treated as static (real devices drift).
- Model excludes multi-lead systems and adaptive algorithms.
- Could expand with dynamic impedance or clinical validation.

Conclusion

- Impedance variability slightly reduces longevity.
- Predictions remain stable across realistic impedance ranges.
- Monte Carlo simulation provides strong framework for CIED evaluation.

Thank You

Questions?