# Tube-Load Model as a Digital Twin for Abdominal Aortic Aneurysm Patients

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## INTRODUCTION & OBJECTIVE

### ➢ Introduction

Abdominal aortic aneurysms (AAA) is a balloon-like bulge in the main artery which supplies blood to the body. AAA alters pulse wave propagation and reflection characteristic of arteries. Thus, analysis of non-invasive blood pressure waveforms may allow for AAA monitoring.

### ➢ Objective

Investigate the feasibility of tube-load (TL) models as digital twins to enable personalized AAA monitoring.

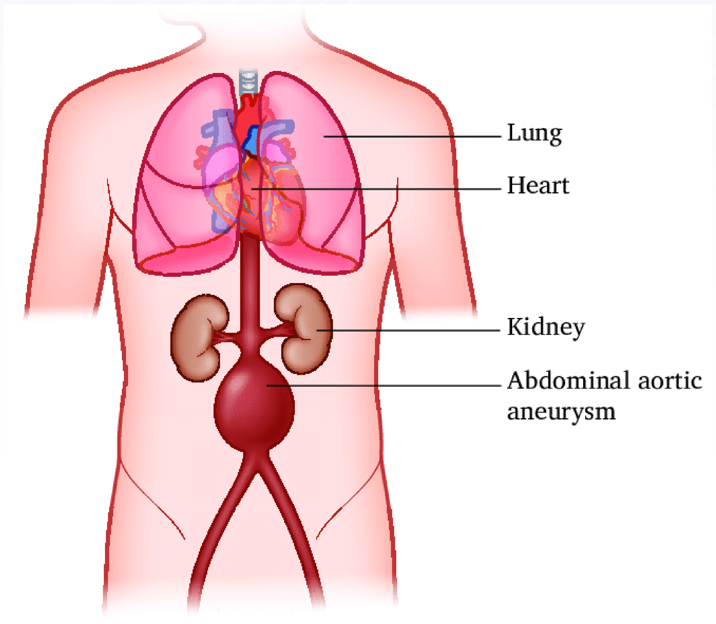



Fig 1. Abdominal aortic aneurysm (AAA).

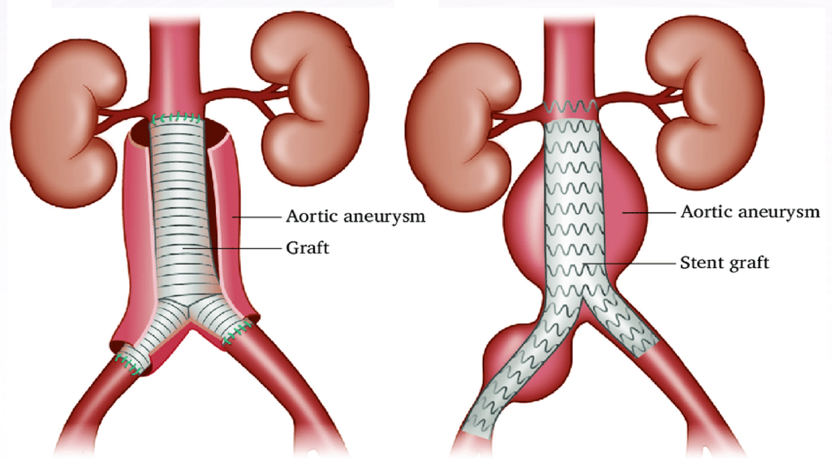
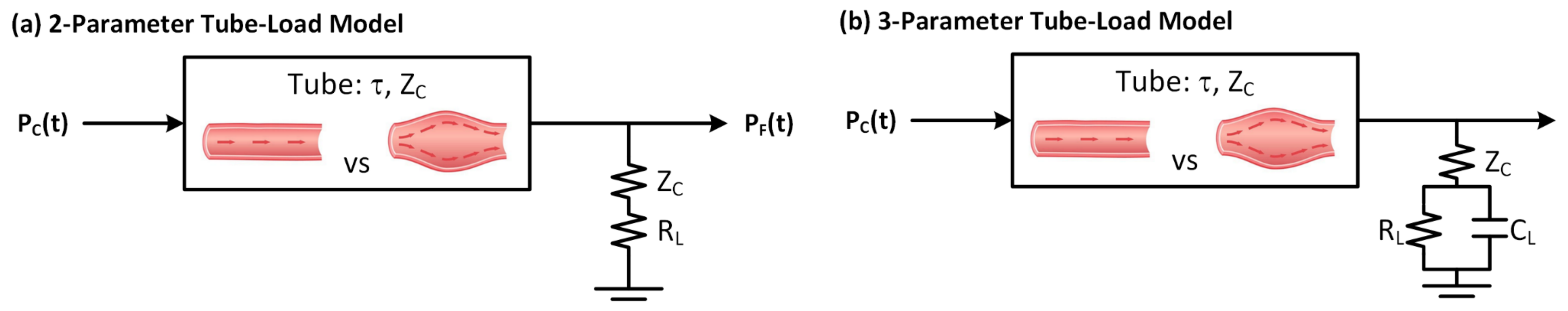



Fig 2. Endovascular repair (EVAR) surgery procedure for AAA. EVAR is associated with low mortality rates of 2-3% which emphasizes the importance of regular screening to prevent rupture which has a high mortality rate (>80%)[1].

## METHODOLOGY

### ➢ Tube-Load Model

Two variants of the uniform lossless tube-load model were used[2]: (a) 2-parameter and (b) 3-parameter TL models.




$$P_C(s) = \frac{e^{\tau s} + e^{-\tau s}\Gamma}{1+\Gamma}P_F(s), \quad \Gamma = \frac{R_L}{R_L + 2Z_C}$$

$$P_C(s) = \frac{e^{\tau s}(s+\eta_1) + e^{-\tau s}\eta_2}{s+\eta_1+\eta_2}P_F(s)$$

$$\eta_1 = \frac{R_L + 2Z_C}{2Z_C R_L C_L}, \quad \eta_2 = \frac{R_L}{2Z_C R_L C_L}$$

Fig 3. Uniform lossless tube-load model. $P_C(t)$: carotid artery tonometry waveform. $P_F(t)$: femoral artery tonometry waveform. $\tau$: pulse transit time (PTT). $Z_C$: tube characteristic impedance. $R_L$: load resistance. $C_L$: load compliance.

### ➢ Model Fitting

The TL model was fit to the carotid and femoral waveforms pertaining to each subject. The subject-specific set of model parameters were inferred based on a nonlinear optimization procedure[2].

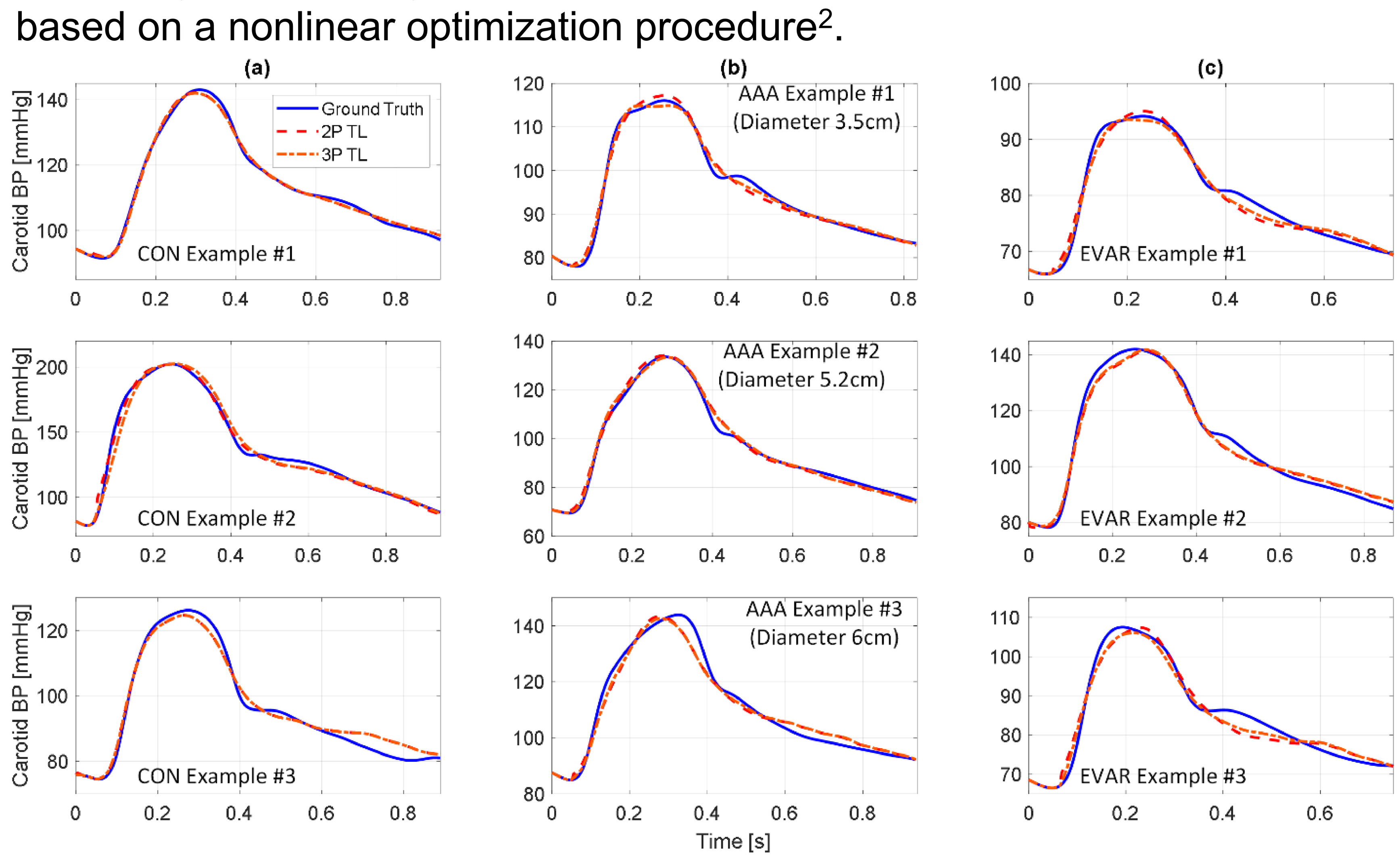



Fig 4. Representative examples of ground truth carotid artery waveforms vs. the same waveform replicated by two TL models pertaining to 3 (a) CON, (b) AAA, and (c) EVAR subjects when femoral waveform was inputted. CON: matched controls. AAA: AAA patients. EVAR: AAA patients post-EVAR. 2P TL: 2-parameter TL model. 3P TL: 3-parameter TL model.

## RESULTS

- ➢ **TL models can fit to AAA, CON, and EVAR subjects equally well.**
- ➢ **Model parameters exhibit changes in physiologically explainable ways.**

Pulse transit time (PTT) and reflection constant (RC) are expected to increase in the presence of AAA due to their dependence on aortic radius.

PTT can be expressed by: $\tau = d\sqrt{\frac{2\rho r_T}{Eh}}$. AAA largely increases the aortic radius, $r_T$, while moderately decreasing aortic stiffness (E) which suggests that PTT should increase in the presence of AAA.

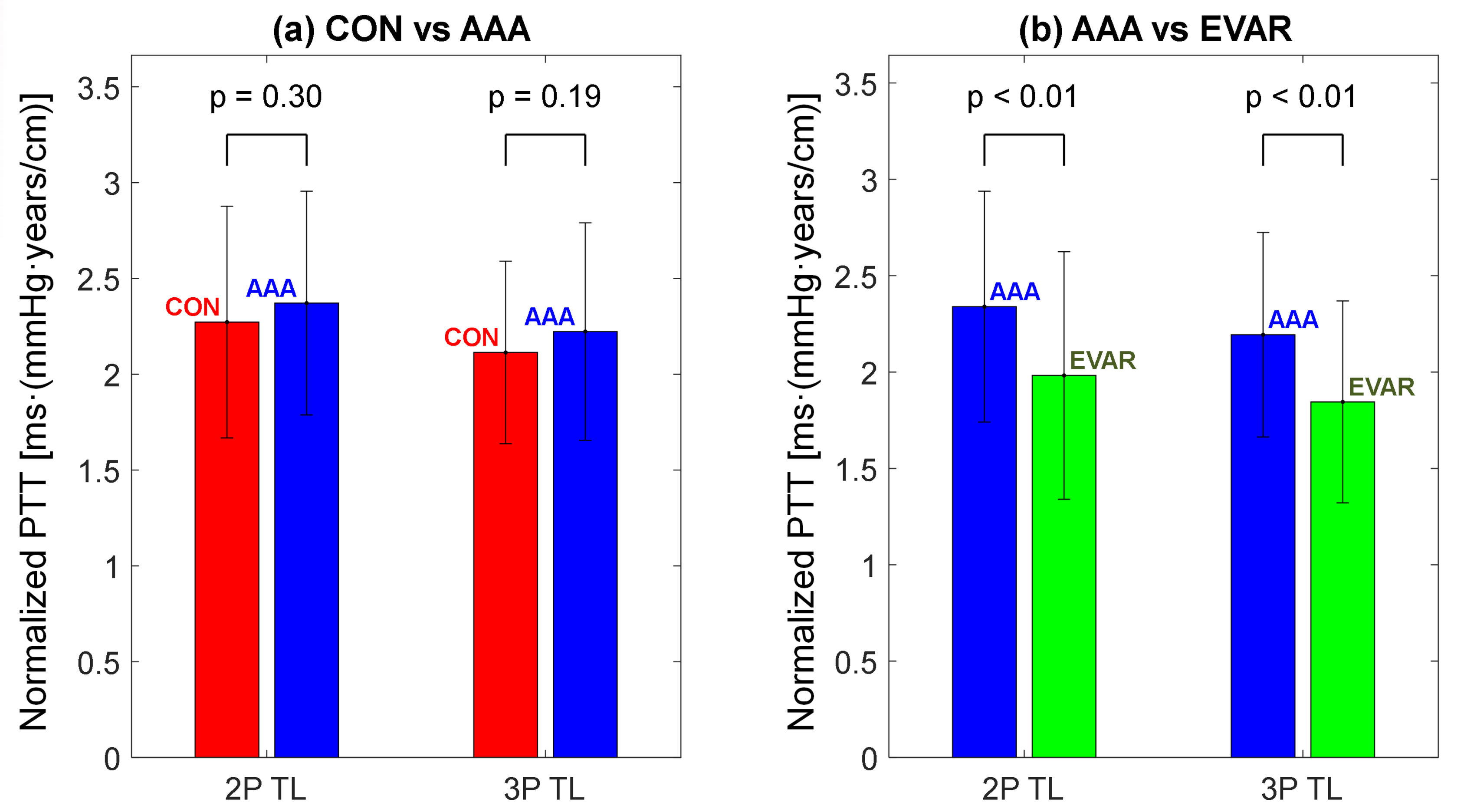



Fig 5. Normalized PTT pertaining to (a) matched controls (CON) vs. AAA and (b) AAA vs. EVAR, associated with the 2-parameter and 3-parameter TL models (2P TL and 3P TL).

### ➢ Reflection Constant

RC is expected to increase in the presence of AAA due to the inverse proportionality between $Z_C$ and aortic radius, $r_T$:

$$Z_C = \frac{1}{A_T}\sqrt{\frac{\rho E h}{2 r_T}}$$

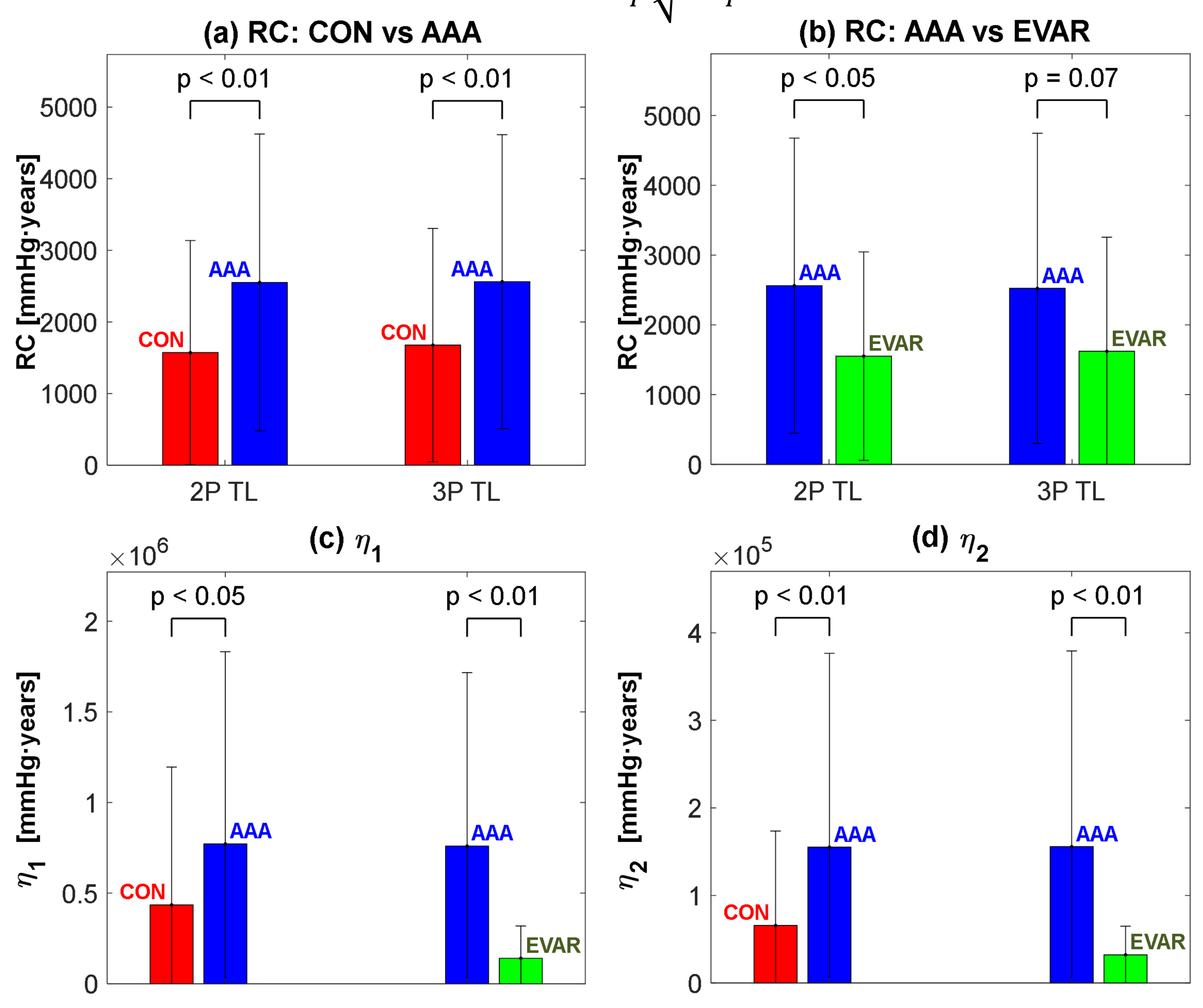



Fig 6. Normalized RC pertaining to (a) matched controls (CON) vs. AAA and (b) AAA vs. EVAR, associated with the 2-parameter and 3-parameter TL models (2P TL and 3P TL), (c) normalized $\eta_1$ pertaining to CON vs. AAA and AAA vs. EVAR, and (d) normalized $\eta_2$ pertaining to CON vs. AAA and AAA vs. EVAR.

## CONCLUSION

- A uniform lossless TL model can capture AAA-induced physiological alterations in blood pressure wave propagation and reflection.
- This makes TL models an attractive candidate as a digital twin suited for personalized AAA monitoring.

## REFERENCES

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