Flow-Controlled Ventilation and Ventilator-Induced Lung Injury in On-pump Cardiac Surgery:

Insights from the FLOWVENTIN HEARTSURG RCT using Digital Twins

euro anaesthesia 2026 ROTTERDAM 6›8 June

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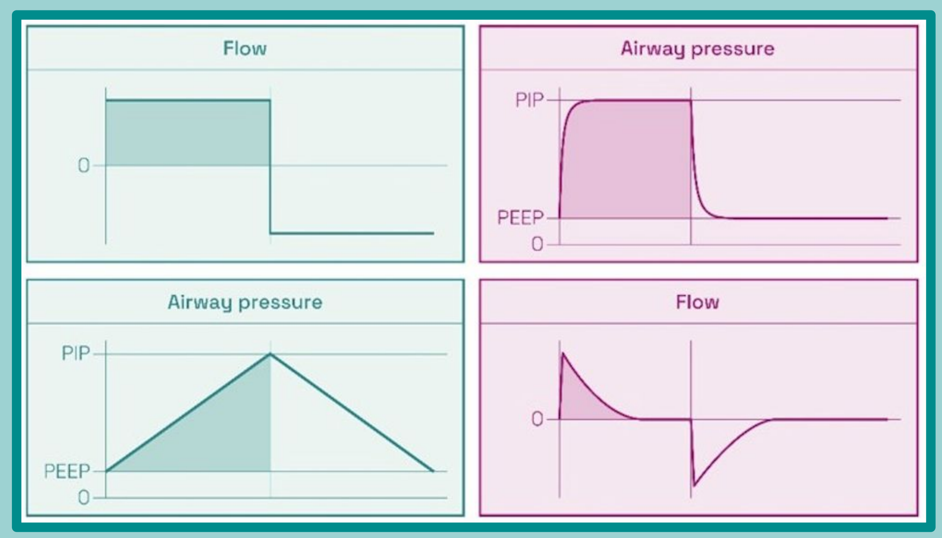
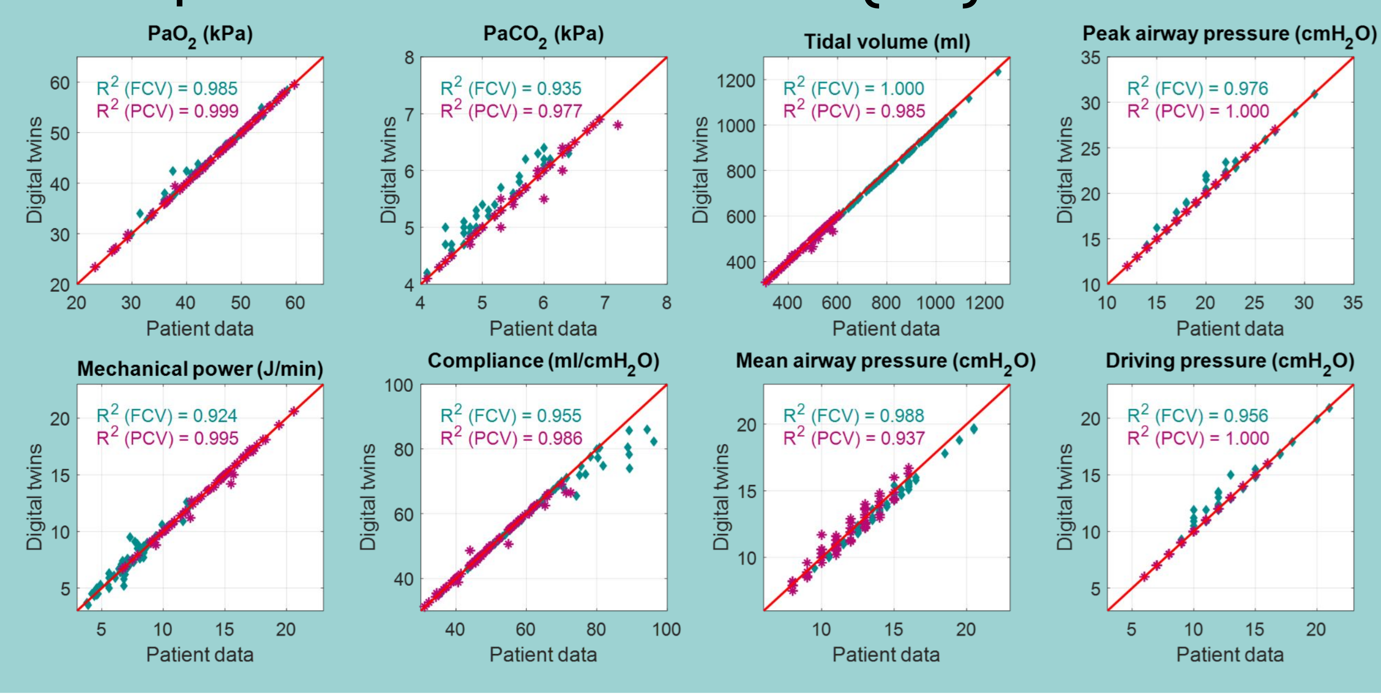
Introduction:

. **Flow-controlled ventilation (FCV)** is characterised by constant inspiratory and expiratory flows that enable active control of the entire ventilatory cycle [1]
. FCV avoids passive expiratory recoil and limits peak flows, unlike traditional modes, and it aims to modify resistive pressure components and **reduce mechanical power** [2]



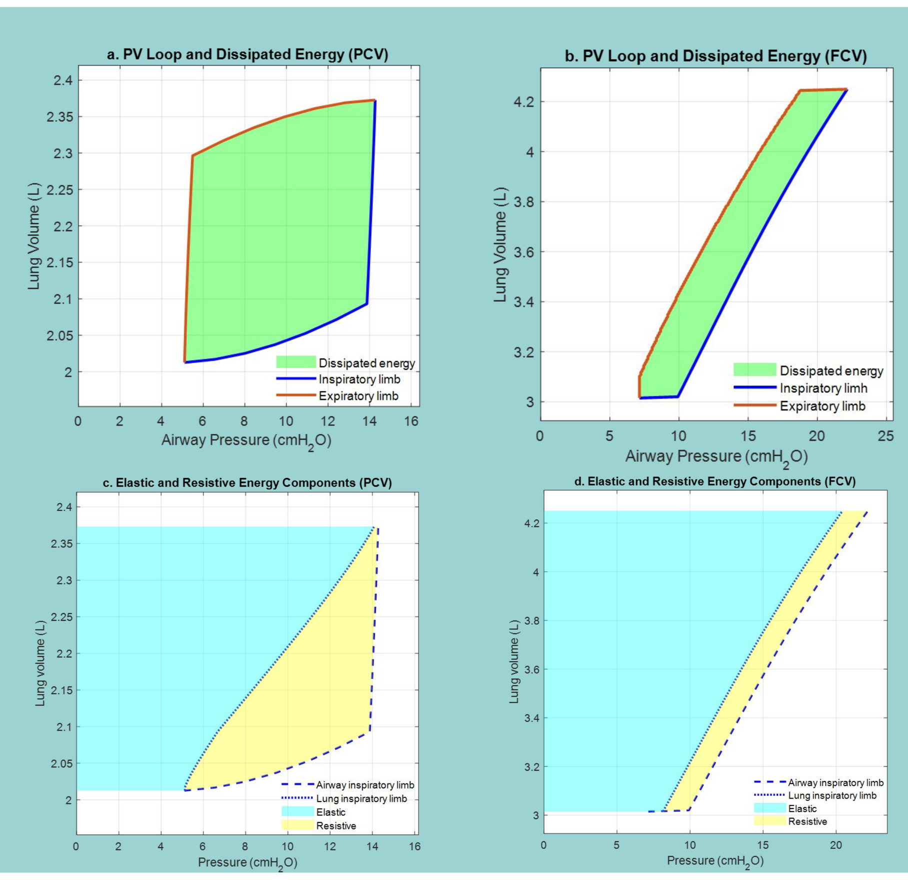
	PCV	FCV
Tidal volume (ml/kg PBW)	7.3±0.4	12.1±1.8
PaO_2 (kPa)	44.7±9.12	44.9±6.9
$PaCO_2$ (kPa)	5.6±0.8	5.2±0.6
Mean airway pressure (cmH_2O)	11.6±2.3	13.8±2.4
Compliance (ml/cmH_2O)	49.4±11.1	65.4±13.7
Mechanical power (J/min)	14.1±4.2	7.1±1.9
Driving pressure (cmH_2O)	10.2±2.1	13.2±2.4

. **Digital twins** provide an opportunity to reconstruct internal lung mechanisms, pressures and volumes based on measurable data from individual patients, enabling **estimations of ventilator-induced lung injury (VILI) indices under clinically applied ventilator settings that cannot otherwise be measured in vivo** [3-7]
. Aim of the present study is to **create digital twins of the patients enrolled in the FLOWVENTIN HEARTSURG RCT** [8] and use them to provide a comprehensive **quantitative comparison of all important ventilatory injury indices under FCV and pressure-controlled ventilation (PCV)**

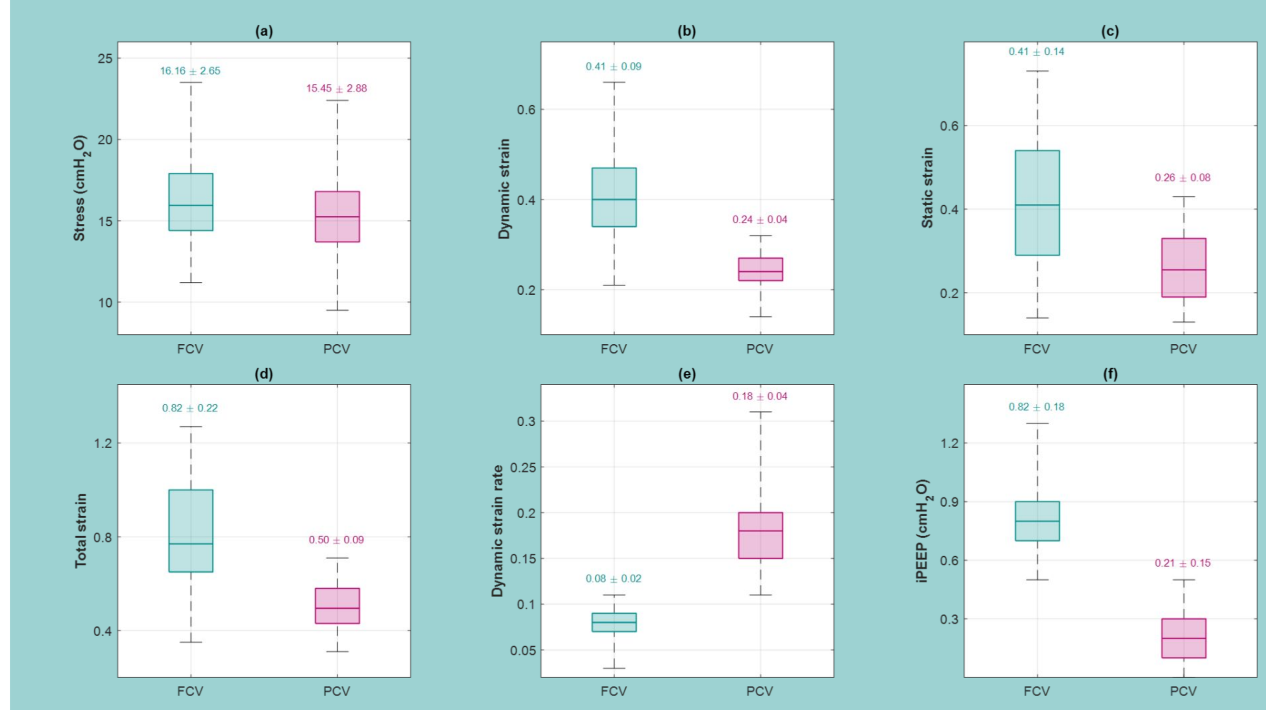


Methods:

. **124 digital twins** (62 FCV, 62 PCV) were created with a previously validated high-fidelity computational model of the cardiopulmonary system [5-7]
. These allowed all relevant VILI indices (lung stress, static and dynamic strain, strain rate, intrinsic positive end-expiratory pressure, mechanical power (MP), and pressure-volume (PV) loop-derived elastic, resistive, and dissipated energy) to be computed and compared
. **PV loops** were generated by plotting airway (or lung) pressure against lung volume during inspiration and expiration for a single breath



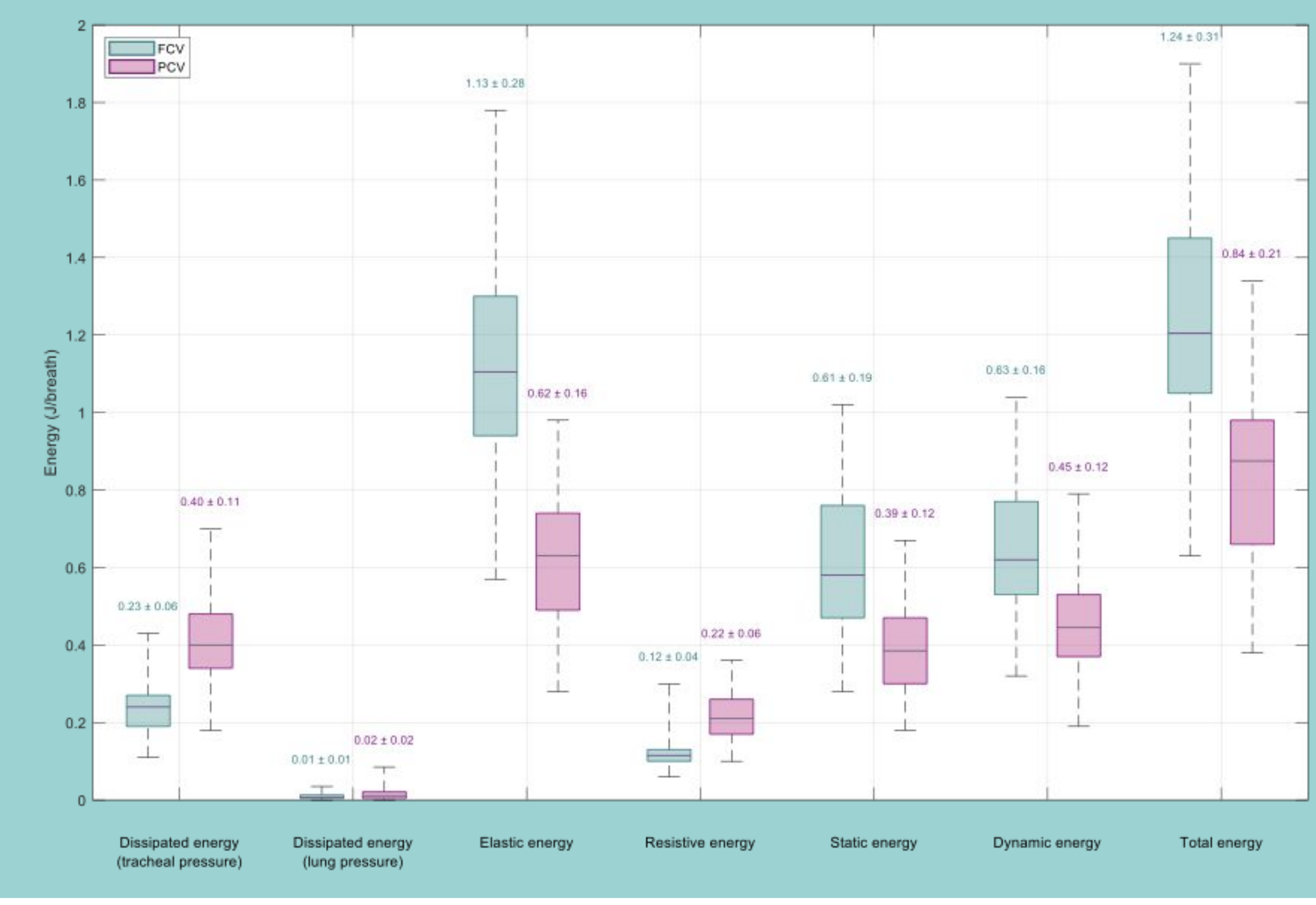
Outputs of the Digital Twins vs Patient Data:



. Mean absolute percentage errors between patient data and digital twin outputs in both cohorts were 0.6% for PaO2, 1.6% for PaCO2, 1% for tidal volume, and 1.4% for peak airway pressure. Furthermore, mean absolute percentage errors between patient data and digital twin outputs were 3.4% for MP, 1.6% for compliance, 3.9% for mean airway pressure, and 2.3% for driving pressure
. Consistent with clinical observations, **FCV reduced MP compared with PCV in the digital twins** (7.21 vs 13.9 J/min, p<0.05), was associated with **higher dynamic and static strain** (0.41 vs 0.24 and 0.41 vs 0.26, respectively, p<0.05), but **lower dynamic strain rate** (0.18 vs 0.08, p<0.05)

PV-loop Derived VILI Indices:

. PCV was associated with significantly **higher levels of dissipated energy in the lung and airway combined, as well as in the lung alone** (0.4 vs 0.23 J/breath and 0.02 vs 0.01 J/breath, respectively, p<0.05)
. PCV also exhibited a **larger resistive energy** component (0.22 vs 0.12 J/breath, p<0.05). In contrast, FCV demonstrated **higher elastic energy** (1.13 vs 0.62 J/breath, p<0.05), **higher static energy** (0.61 vs 0.39 J/breath, p<0.05), and **higher dynamic energy** (0.63 vs 0.45 J/breath, p<0.05), which **ultimately resulted in greater total energy per breath**, (1.24 vs 0.84 J/breath, p<0.05)



Discussion:

. FCV was associated with higher static and dynamic strain amplitudes but **substantially lower dynamic strain rates**
. Partitioning energy into elastic, resistive, and dissipative components suggests that **FCV reduces energy components plausibly associated with tissue injury while increasing reversible elastic energy storage**
. **By reducing time-dependent and dissipative injury indices, Digital Twin analysis suggest that FCV may shift energy transfer towards reversible elastic storage and away from irreversible tissue-level dissipation**

References:

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