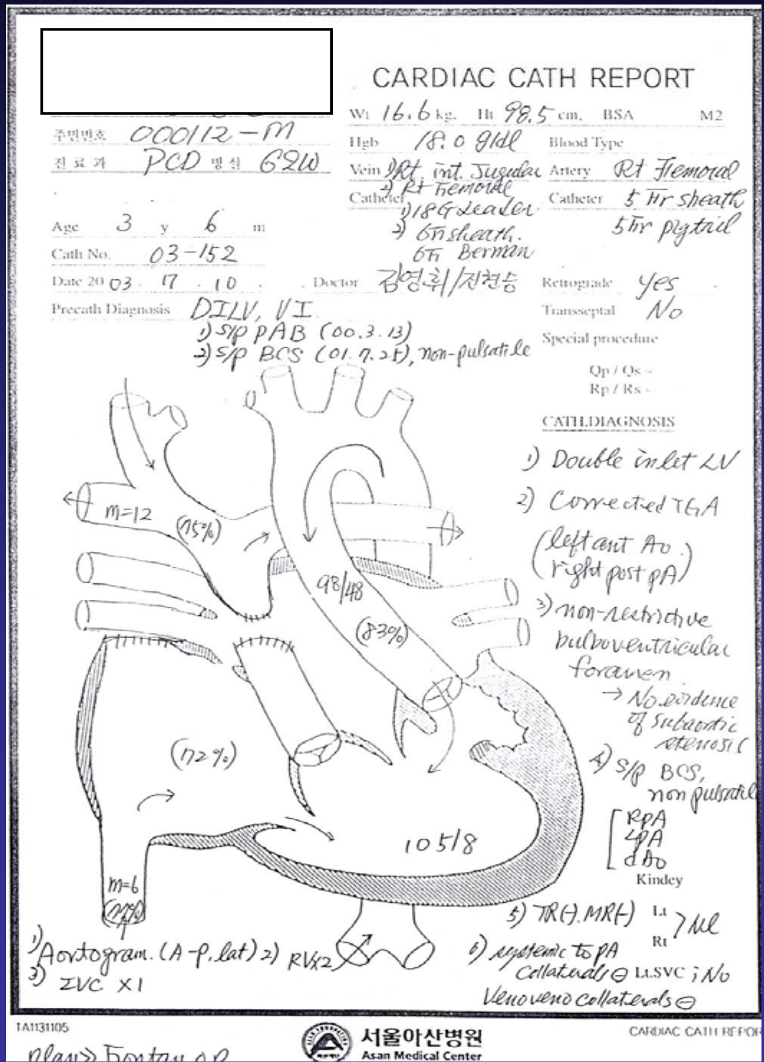
Pulmonary Vascular Compliance:

Pre-operative and intra-operative assessment

Tae-Jin Yun

Asan Medical Center, University of Ulsan

Case 1



CARDIAC CATH REPORT

주민번호 000112-M
진료과 PCD 병실 62W
Age 3 y 6 m
Cath No. 03-152
Date 20 03 . 7 . 10 . Doctor 김영휘/전천동
Precath Diagnosis DILV, VI
1) S/P PAB (00.3.13)
2) S/P BCS (01.7.25), non-pulsatile

Wt 16.6 kg. Ht 98.5 cm. BSA M2
Hgb 18.0 g/dl Blood Type
Vein 1) Rt int. Jugular 2) Rt femoral Artery Rt Femoral
Catheter 1) 18G Leader 2) 6Fr sheath. 6Fr Berman Catheter 5 Fr sheath 5Fr pigtail
Retrograde Yes
Transseptal No
Special procedure
Qp / Qs =
Rp / Rs =

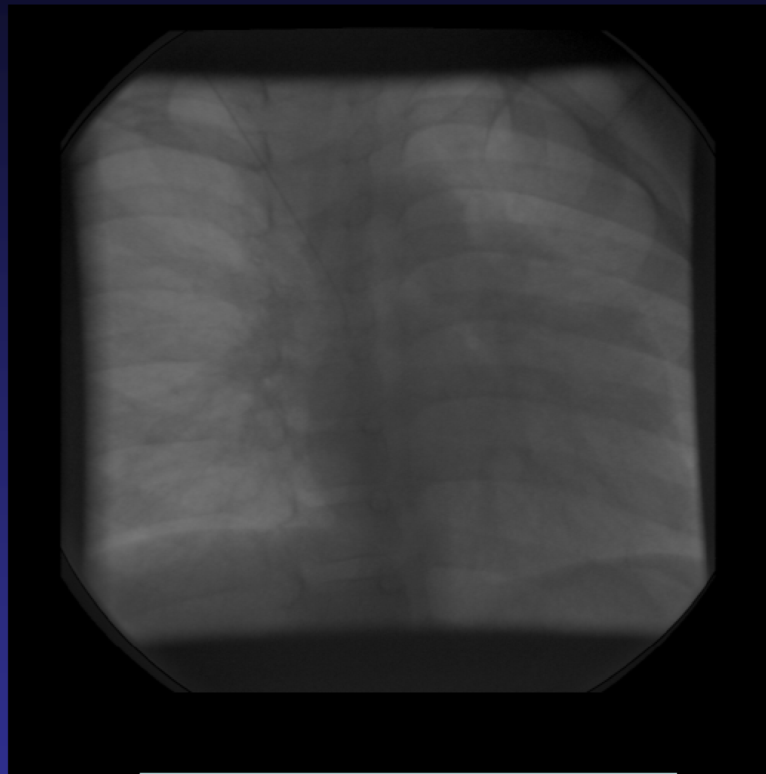
CATH.DIAGNOSIS
1) Double inlet LV
2) Corrected TGA (left ant Ao, right post PA)
3) non-restrictive bulboventricular foramen → No evidence of Subaortic stenosis
4) S/P BCS, non pulsatile [RPA LPA d Ao] Kindey
5) TR(-), MR(-) Lt Rt 7 ml
6) systemic to PA collaterals ⊖ Lt.SVC ; No
Venovenous collaterals ⊖

m=12 (75%) 98/48 (83%) (72%) 105/8 m=6 (72%)

1) Aortogram (A-P, lat) 2) RVx2 3) IVC X1

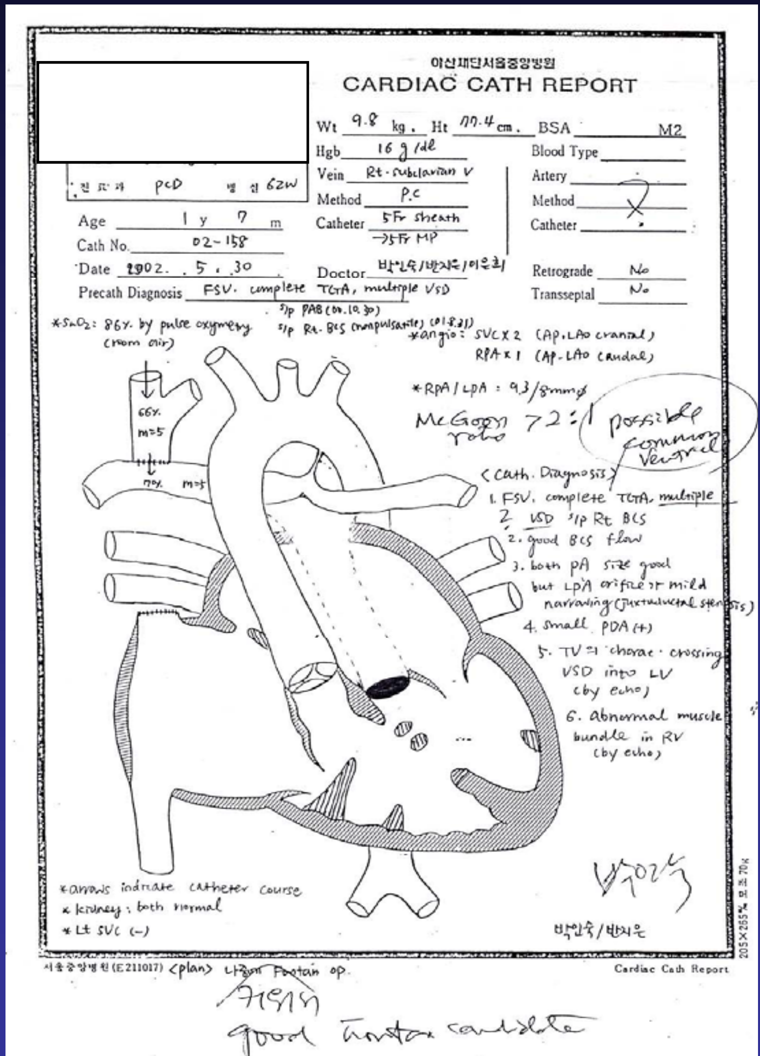
TA1131105 서울아산병원 Asan Medical Center CARDIAC CATH REPORT

Plan ⇒ Fontan op



LV type FSV
PAI: 603 mm²/m²
mPAP: 12 mmHg
PVR: 1.73 W.U.m²
VEDP: 8 mmHg
No AVVR, PVS, BPAS

Case 2



아산재단서울중앙병원
CARDIAC CATH REPORT

Wt 9.8 kg. Ht 77.4 cm. BSA ______ M2
Hgb 16 g/dl　Blood Type ______
Vein Rt-subclavian V　Artery ______
Method P.C　Method ______
Catheter 5Fr sheath →5Fr MP　Catheter ______
Age 1 y 7 m
Cath No. 02-158
Date 2002. 5. 30
Doctor 박인숙/반지은/이은희
Retrograde No
Transseptal No
Precath Diagnosis FSV. complete TGA, multiple VSD
s/p PAB (00.10.30)
s/p Rt. BCS (nonpulsatile) (01.8.21)

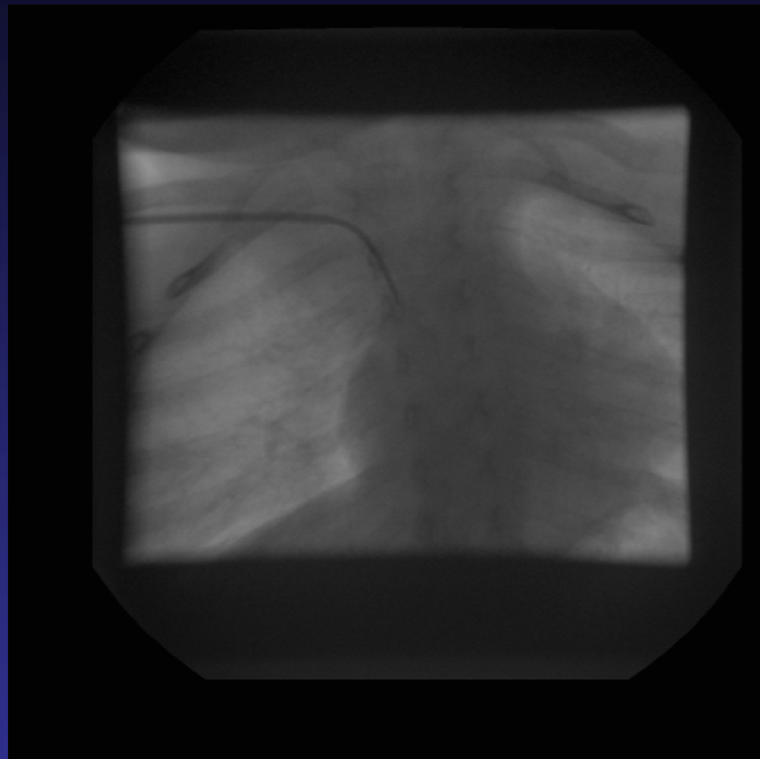
*SaO2: 86% by pulse oxymetry (room air)
*angio: SVC x 2 (AP, LAO cranial)
RPA x 1 (AP-LAO caudal)
*RPA/LPA : 9.3/8mmø
McGoon ratio 2.2:1
possible common ventricle

<Cath. Diagnosis>
1. FSV, complete TGA, multiple VSD
2. s/p Rt BCS
2. good BCS flow
3. both PA size good but LPA orifice에 mild narrowing (juxtaductal stenosis)
4. small PDA (+)
5. TV의 chorae crossing VSD into LV (by echo)
6. Abnormal muscle bundle in RV (by echo)

66% m=5
70% m=5

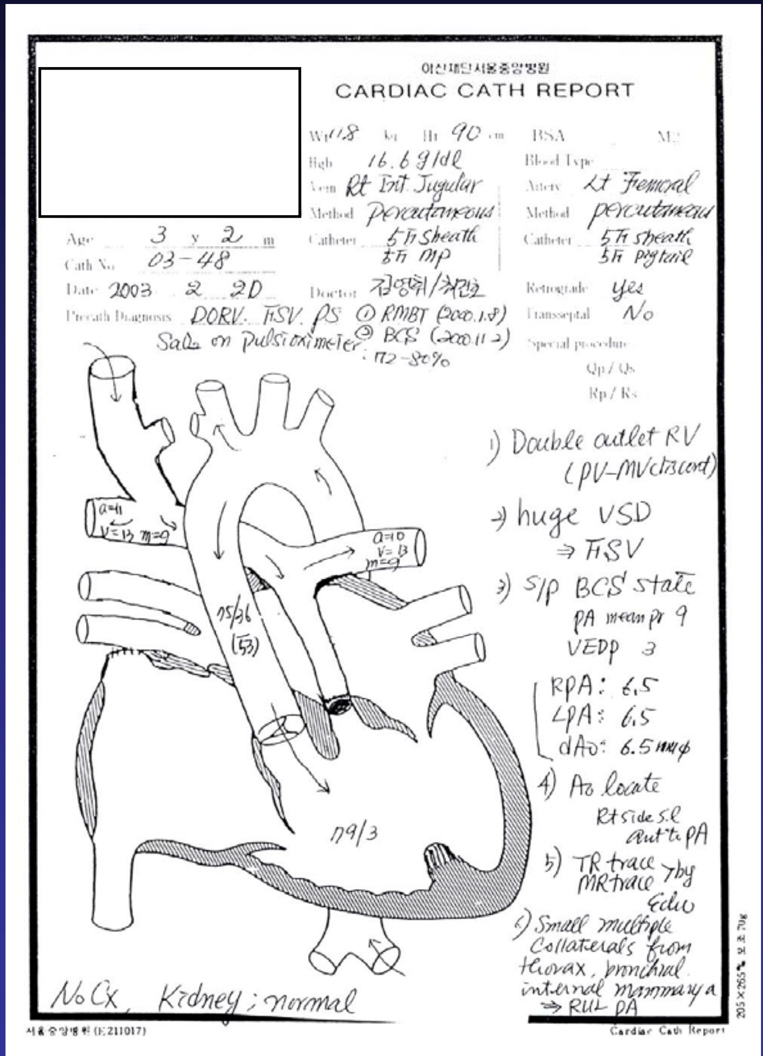
*arrows indicate catheter course
*kidney: both normal
*Lt SVC (-)

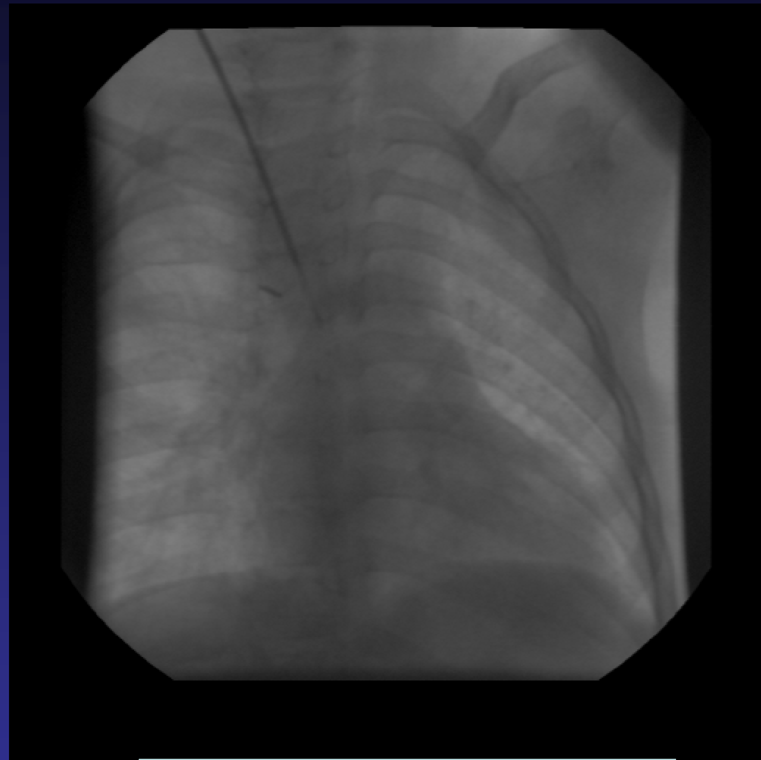
박인숙/반지은
Cardiac Cath Report
<plan> Fontan op
good Fontan candidate



Common V type FSV
PAI: 263 mm^2/m^2
mPAP: 5 mmHg
PVR: < 1 $W.U.m^2$
No AVVR, PVS, BPAS

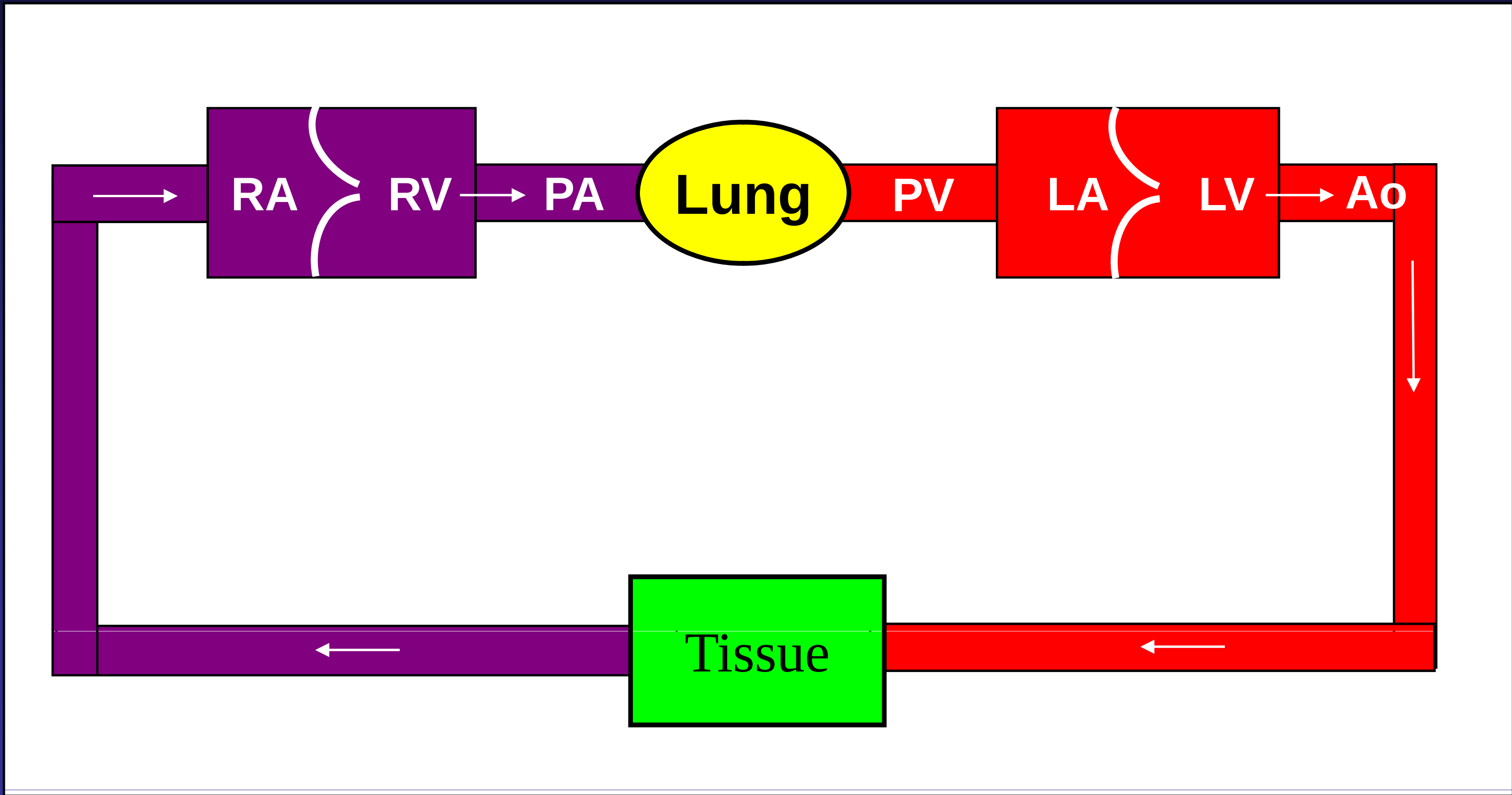
Case 3



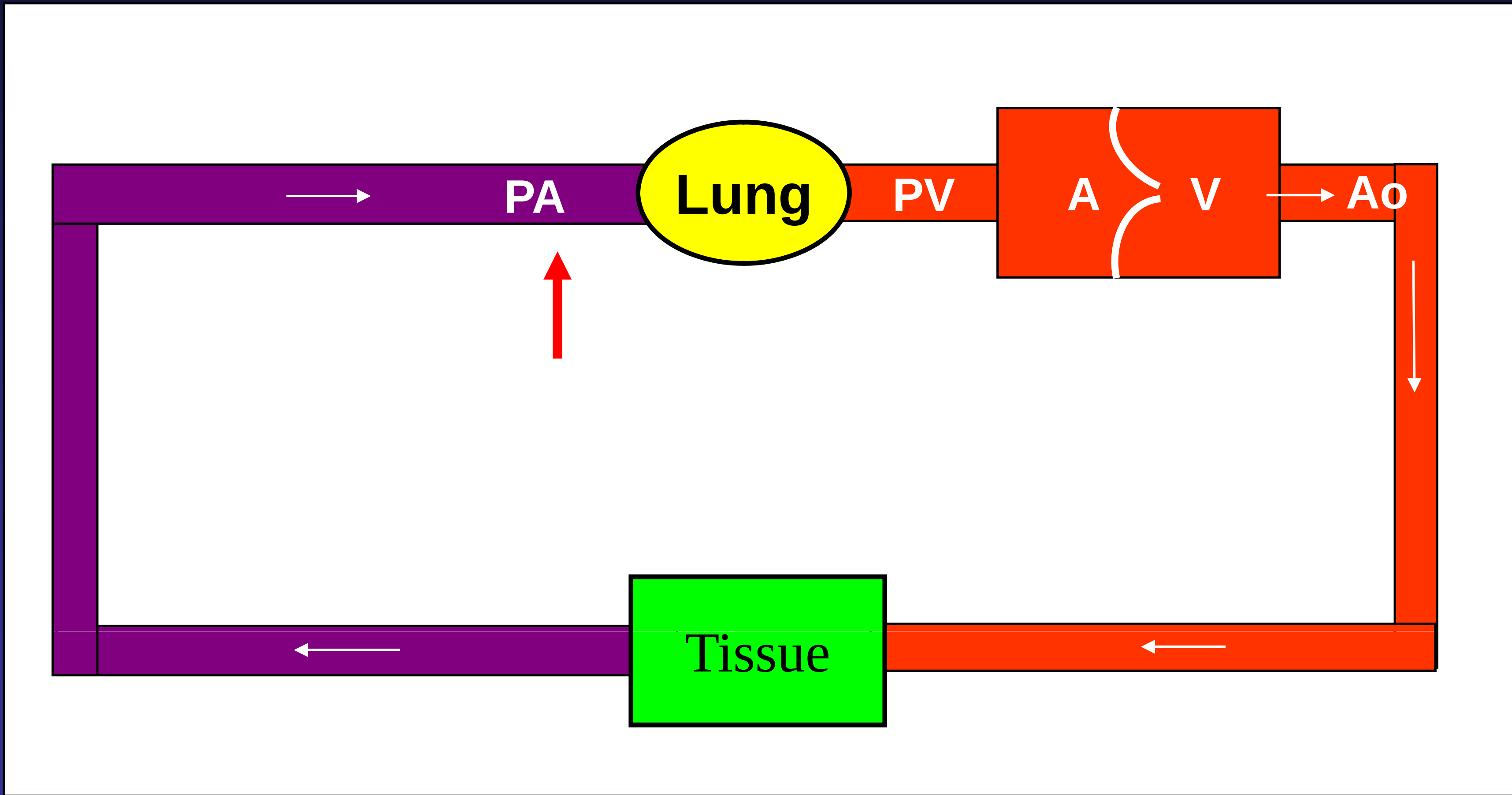


Common V type FSV
PAI: 207 mm²/m²
mPAP: 9 mmHg
PVR: 2.17 W.U.m²
VEDP: 3 mmHg
No AVVR, PVS, BPAS

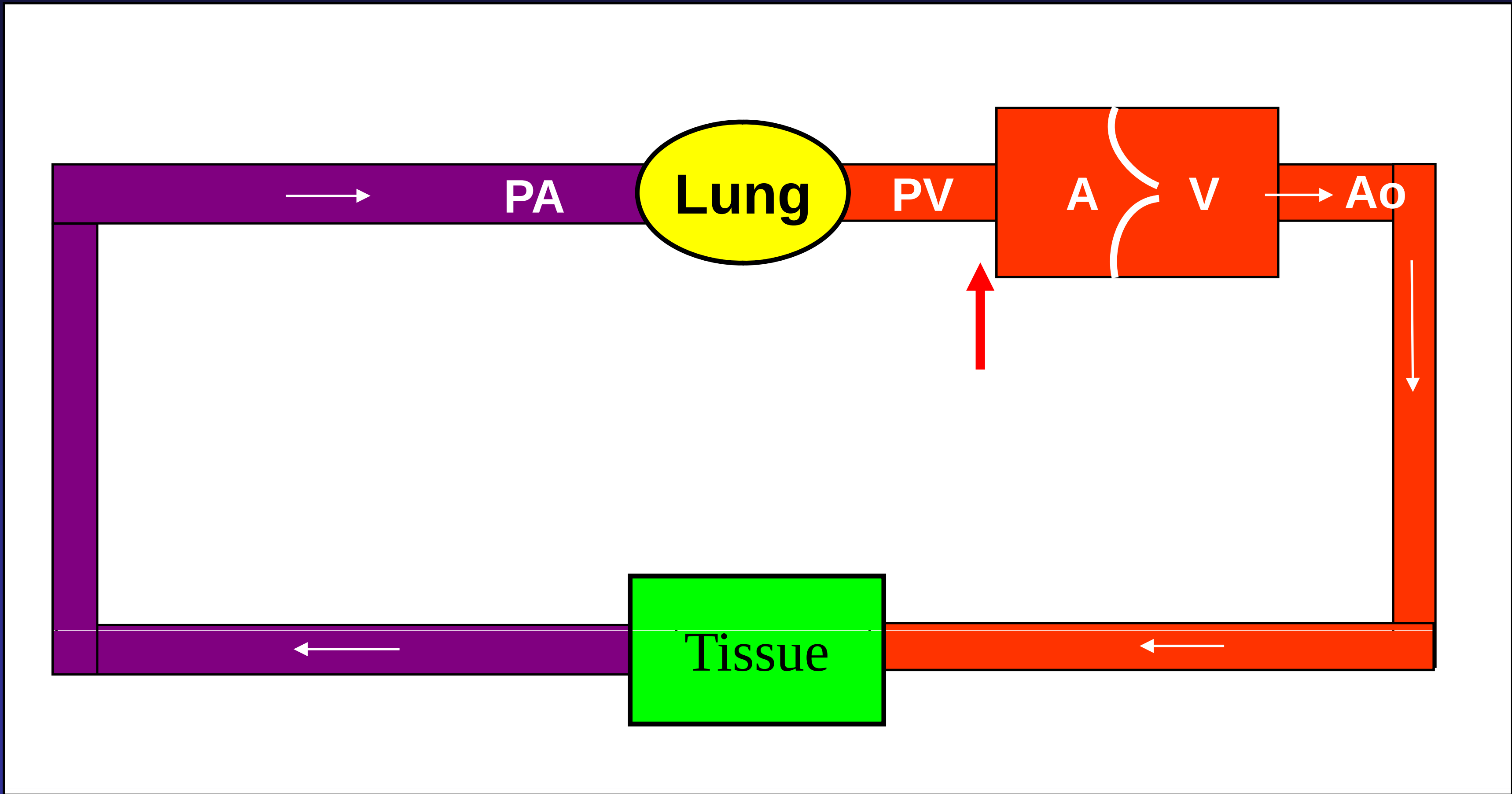
Normal Circulation



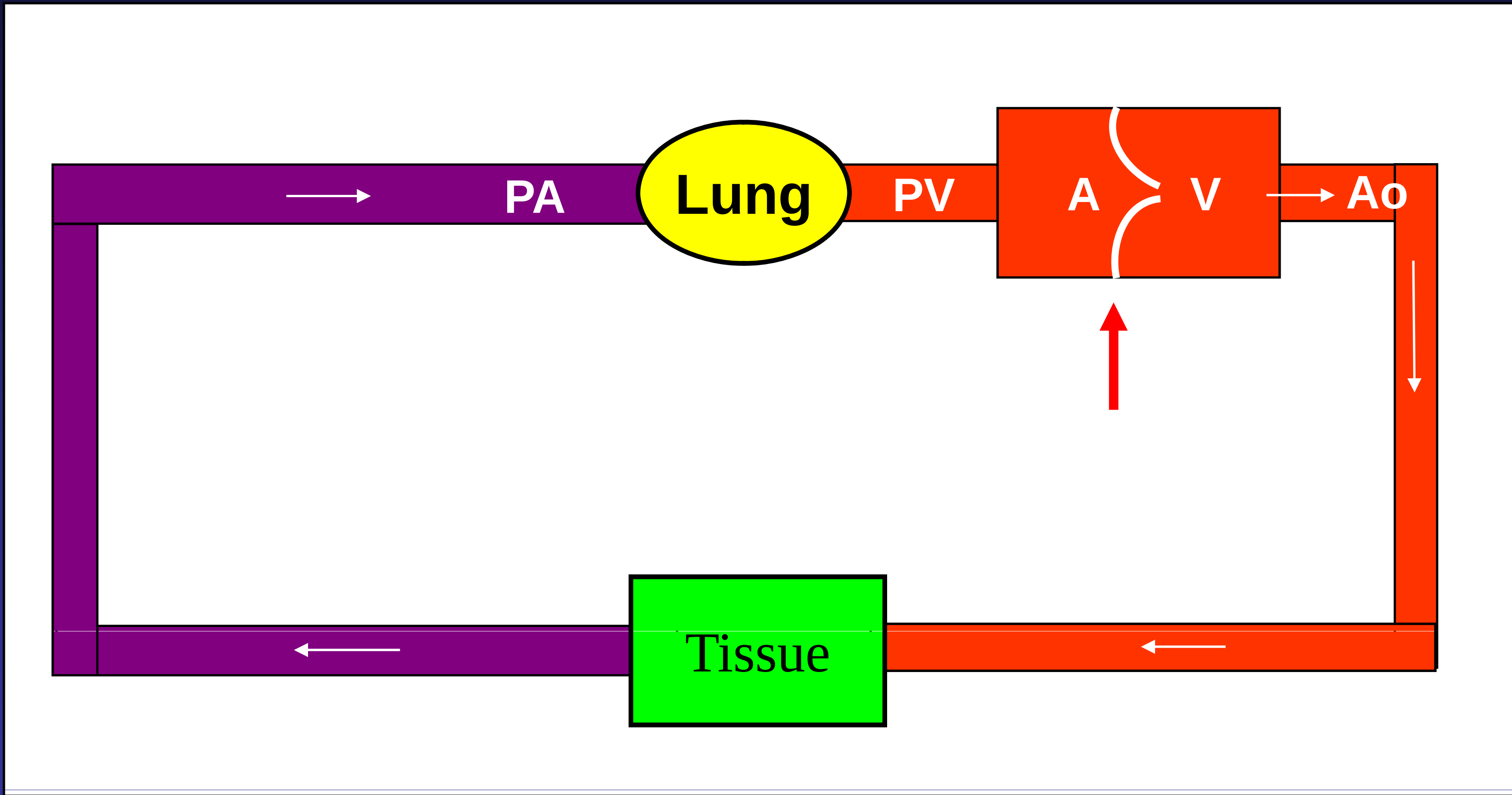
Fontan Circulation



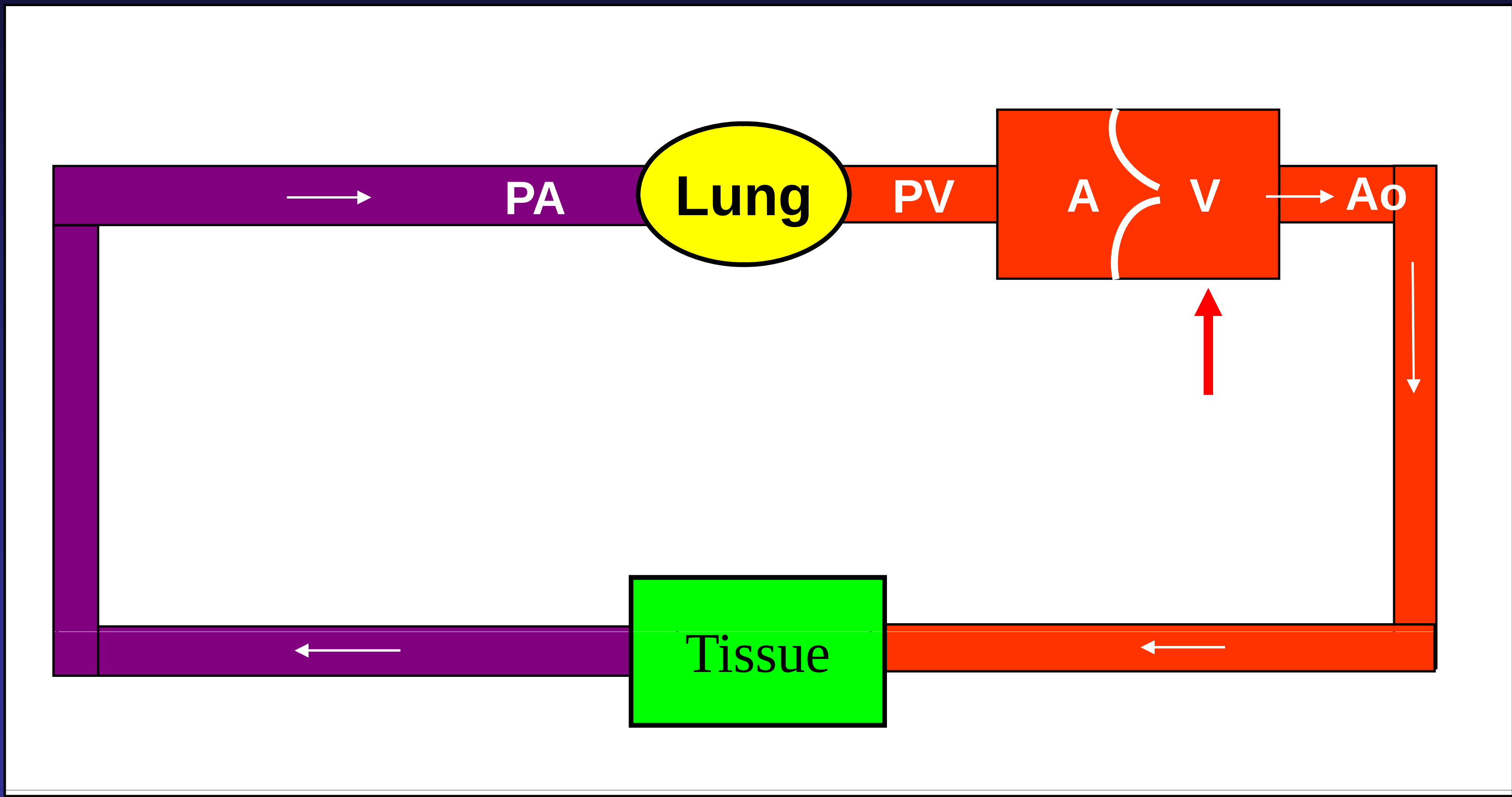
Fontan Circulation



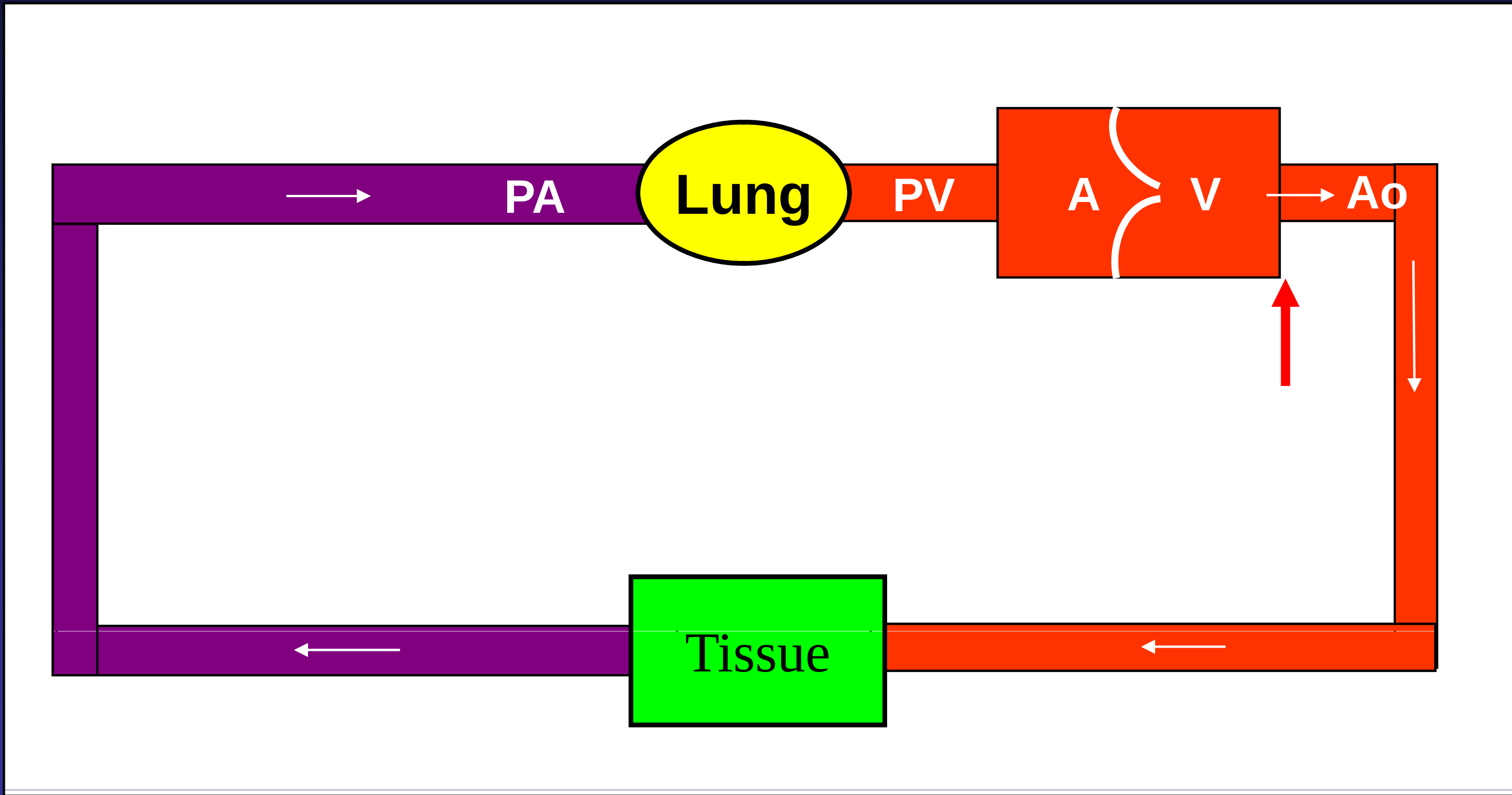
Fontan Circulation



Fontan Circulation



Fontan Circulation



Fontan risk score

Factor/score	0	1	2	3
1. Age(months)	>12	6-12		< 6
2. Ventricle	LV	RV		
3. Syst outflow obst		(+)		
4. PV obst			(+)	
5. PA hypoplasia	(-)	Mild	Moderate	Severe
McGoon ratio	>2	1.8-2.0	1.5-1.8	<1.5
Nakada index	>200	100-200	50-100	<50
Diameter(z)	-2 to +2	-2 to –3	-3 to –4	<-4
6. Mean PAP	<15	15-20	20-25	>25
7. PABS or distortion	(-)	disc-sing	disc-multi	diffuse
8. Rp unit	<2	2-3	3-4	>4
9. AVV regurg	(-)	Mild	Moderate	Severe
10. V syst dysfun	(-)	Mild	Moderate	Severe
EF(%)	>55	55-45	45-40	<40
SF(%)	>32	31-28	27-24	<231
11. V diast dysf				
VEDP(mmHg)	<10	10-12	12-14	>14
12. V hypertrophy	nl	Mild	Moderate	severe
mass(echo)	-2 to +2	-2 to -3	-3 to –4	<-4

* Fontan risk score : 0-3 (low risk), 4-5 (moderate risk), ≥6 or one item ≥3 (high risk)

Fontan risk score

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Pitfalls in Qp calculation

1. O2 consumption from a normogram (age, HR)

   Is it fit for cyanotic baby?

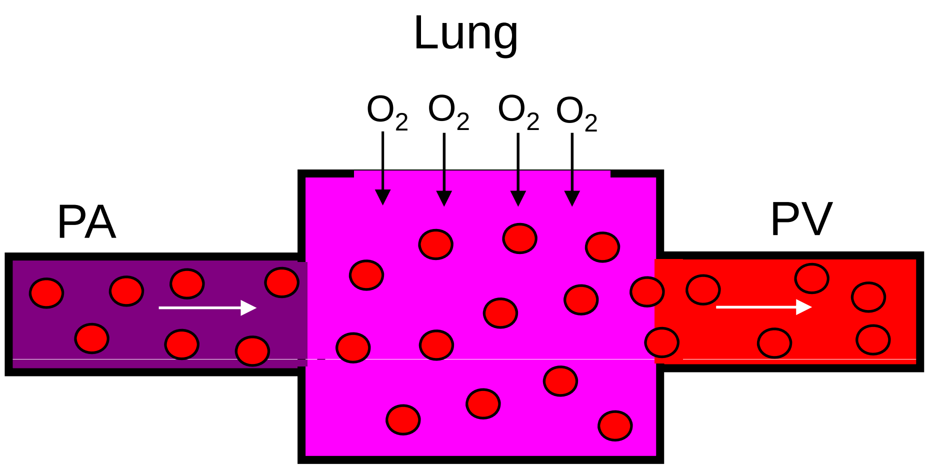
2. O2 saturation data in a fully sedated patient

   Is it the same in an awake baby?

3. No measurement for AP collateral flow

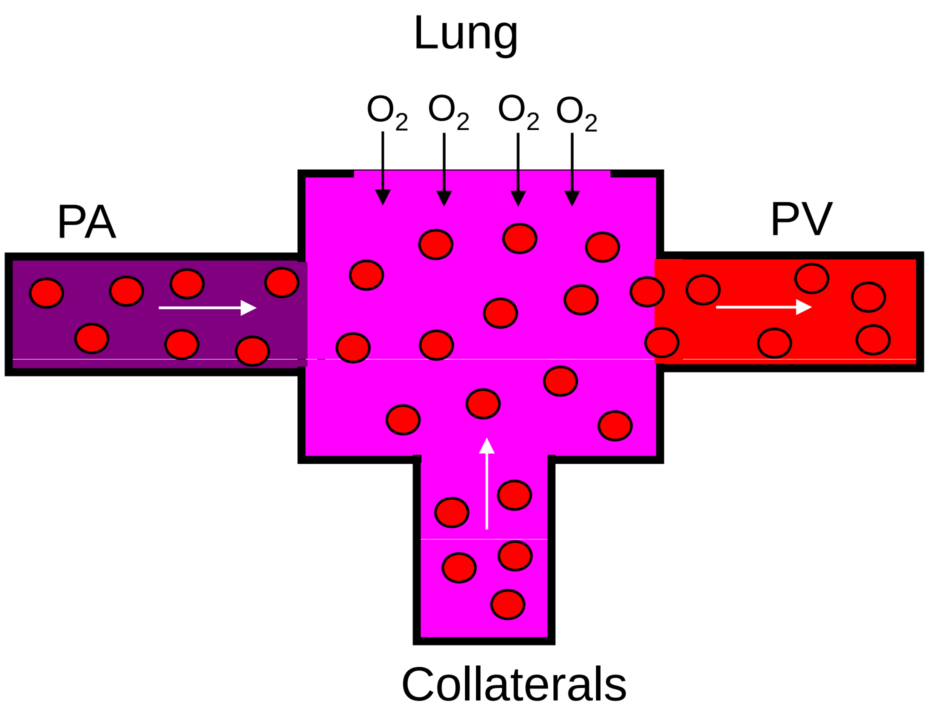
   $Qp = Qep + Qcoll$

Pitfalls in Qp calculation



$$Qp = \frac{O_2 \text{ Consumption}}{PVO_2 - PAO_2}$$

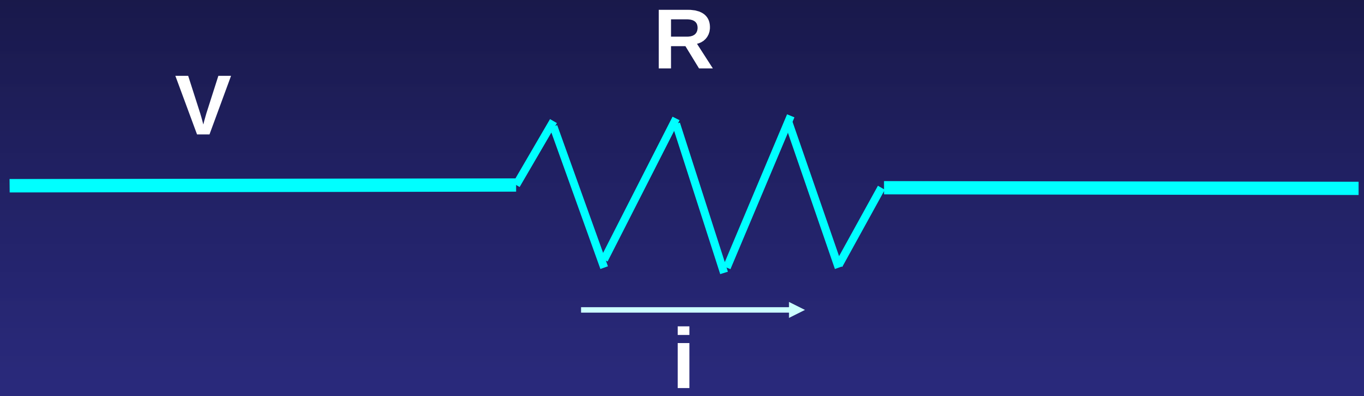
Pitfalls in Qp calculation



$$Qep = \frac{O_2 \text{ Consumption}}{PVO_2 - PAO_2}$$

$$Qp = Qep + Qcoll$$

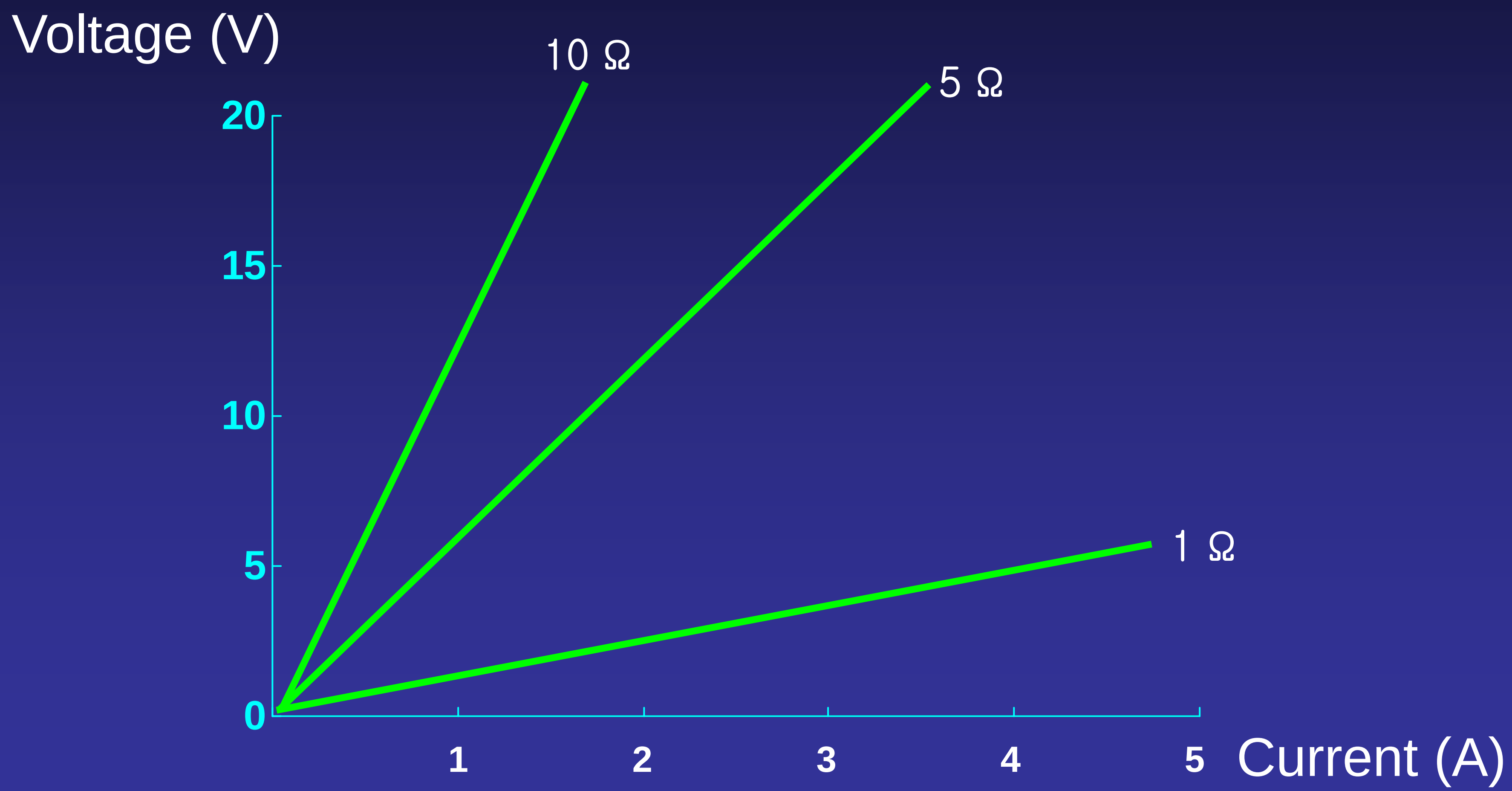
Electrical Circuit Analogy



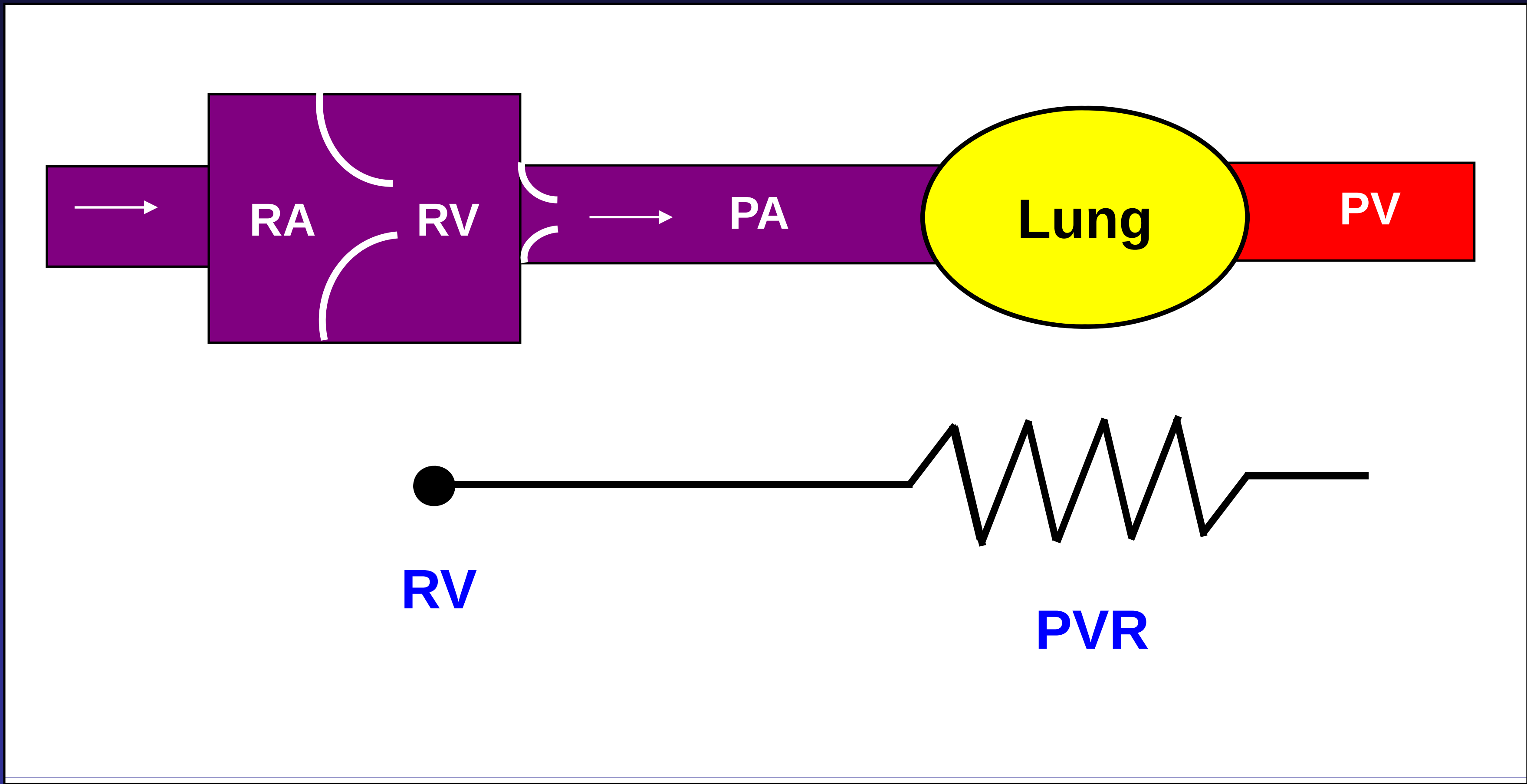
$$V = iR \qquad R = \frac{V}{i}$$

Electrical Circuit Analogy

- Voltage, Current and Resistance -

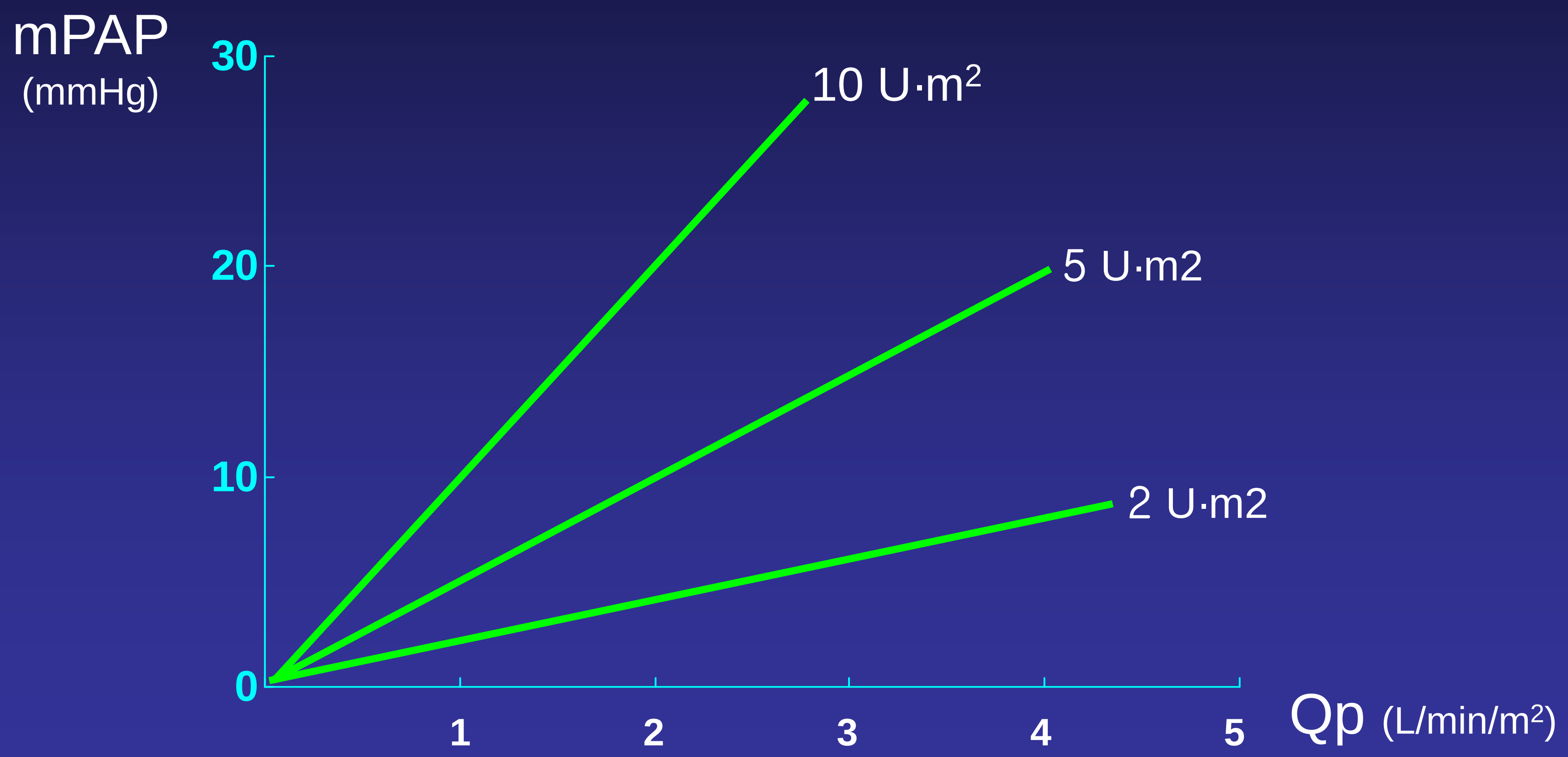


Pulmonary Vascular Resistance

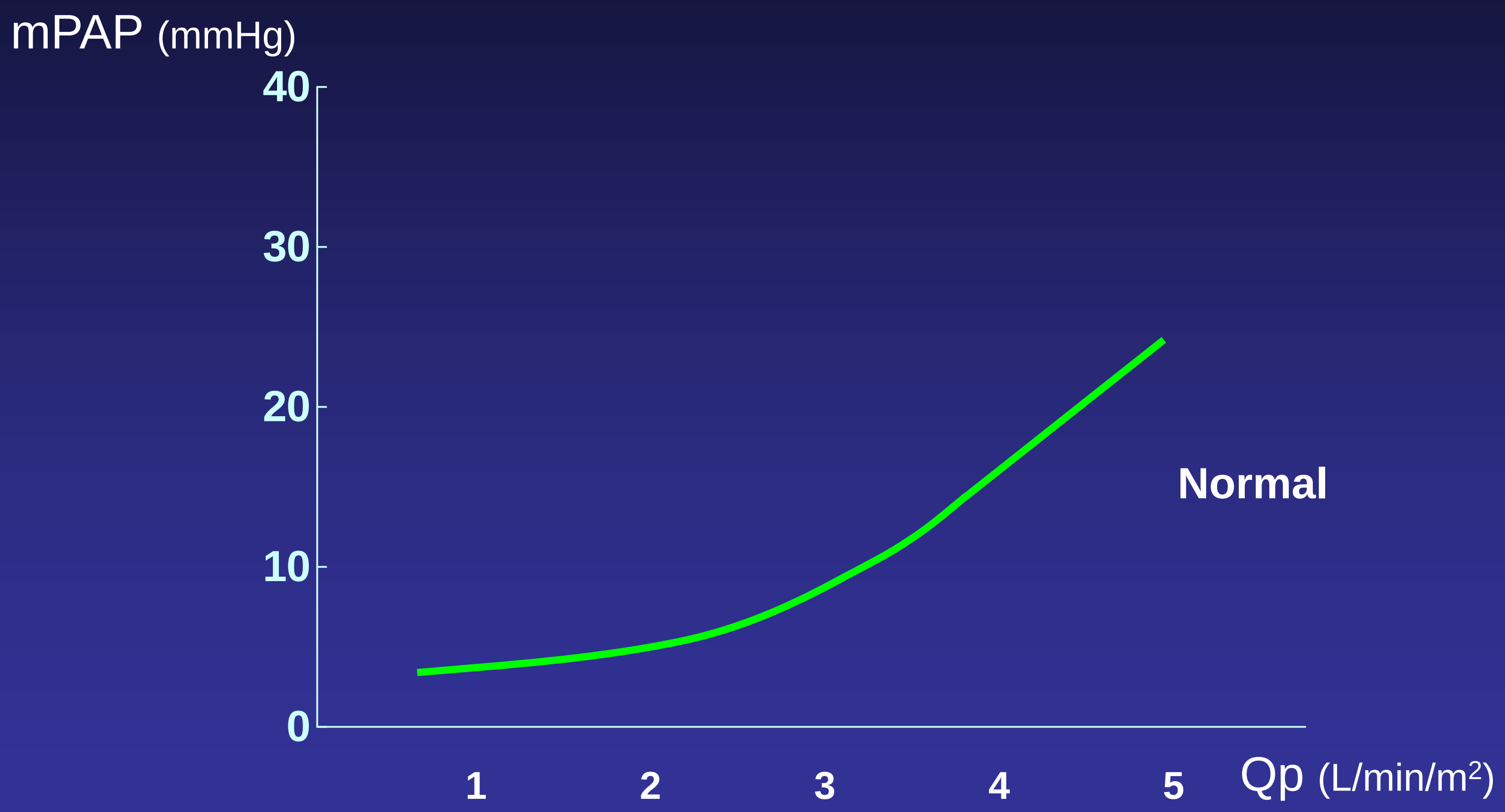


Electrical Circuit Analogy

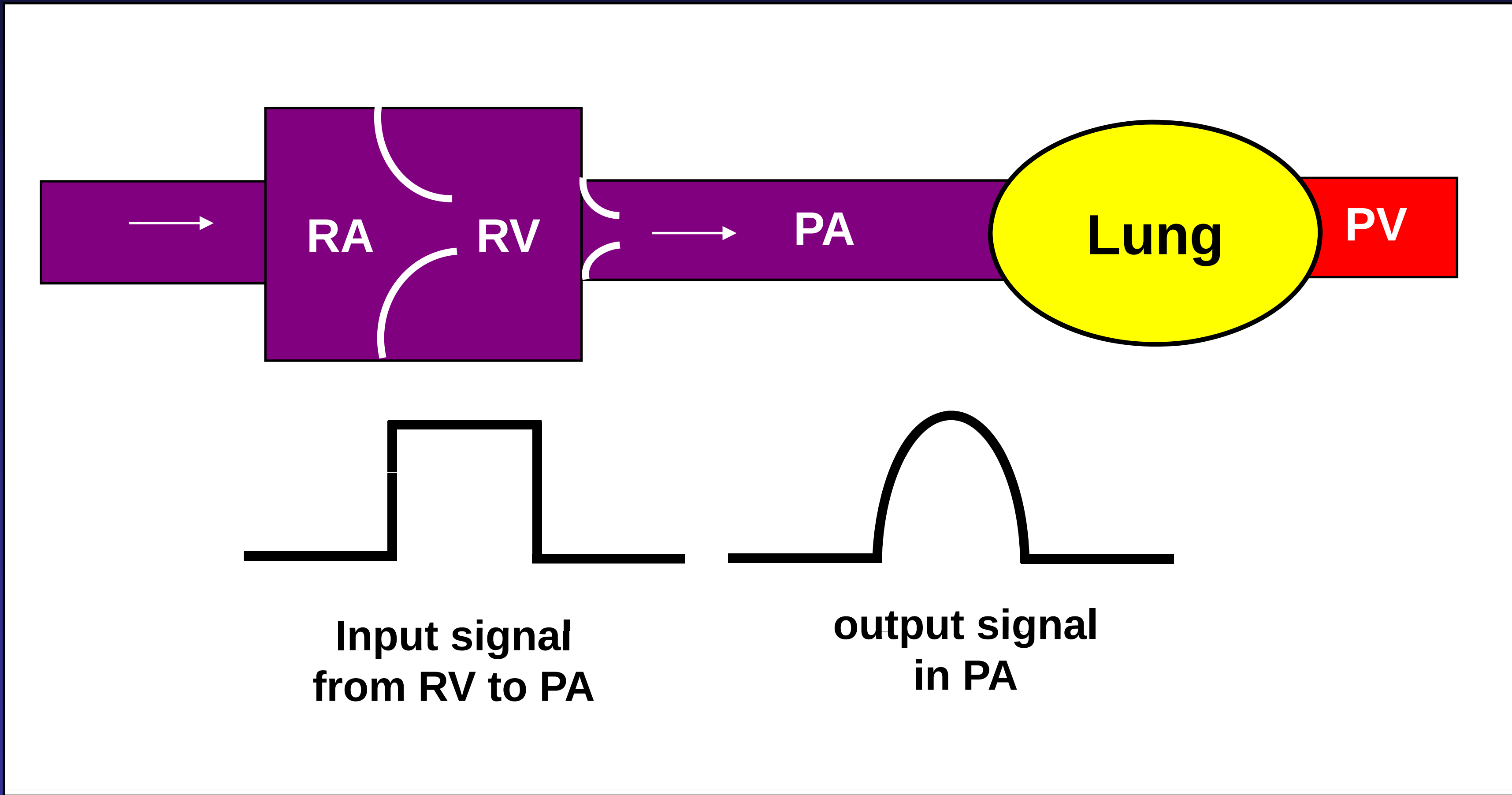
- Pressure, flow and Resistance -



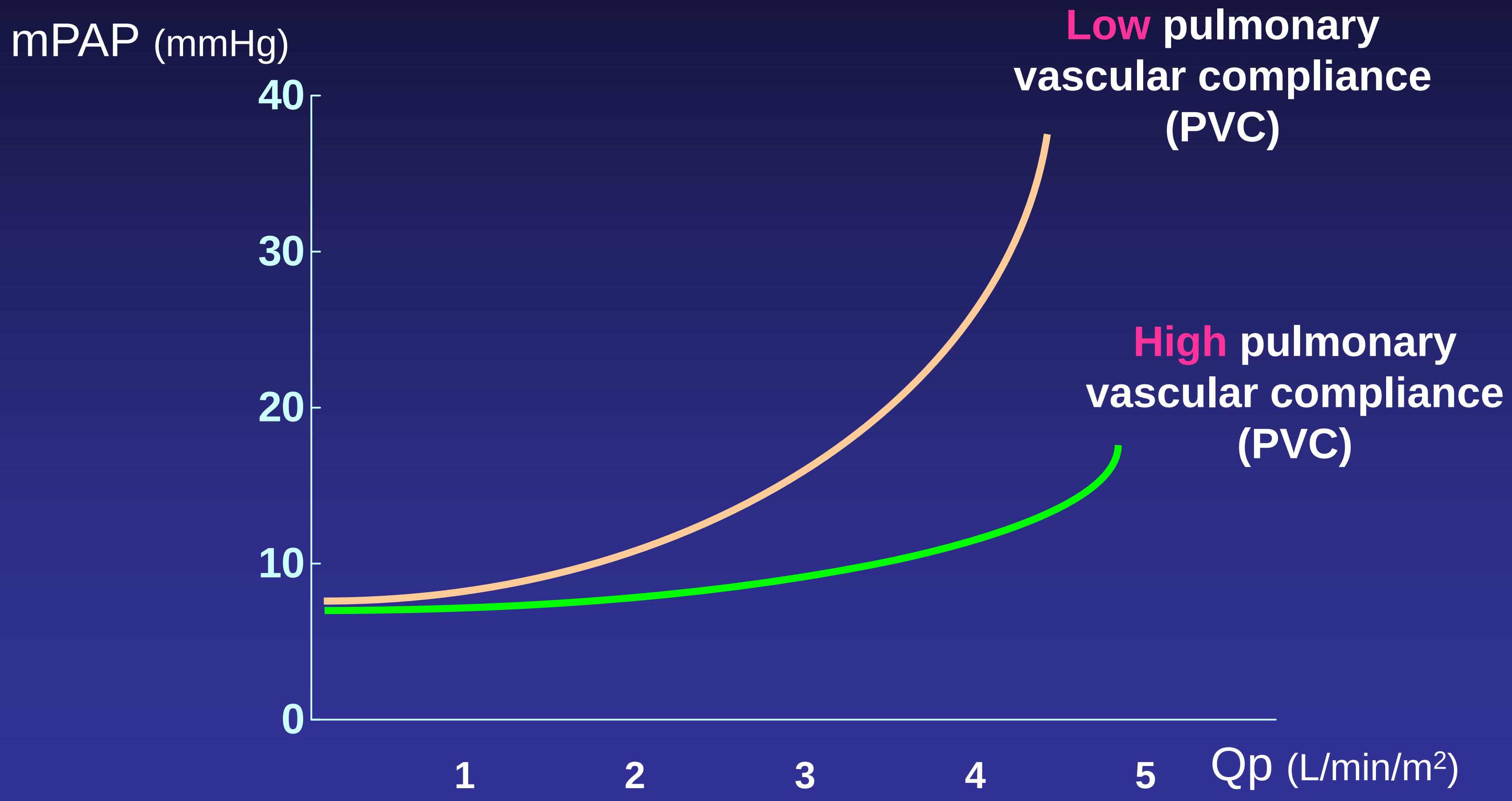
Qp vs. PAP



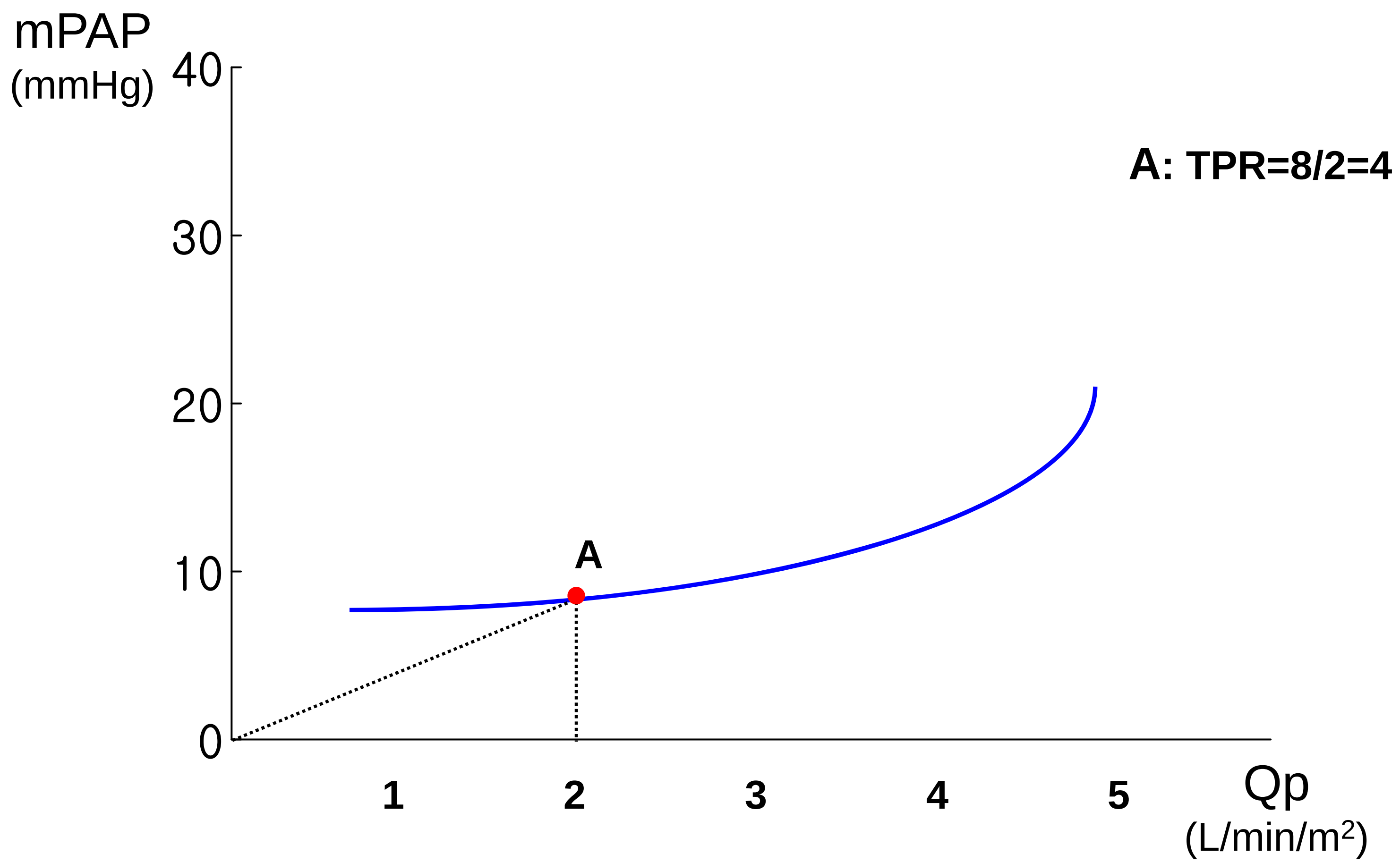
Output signal in PA



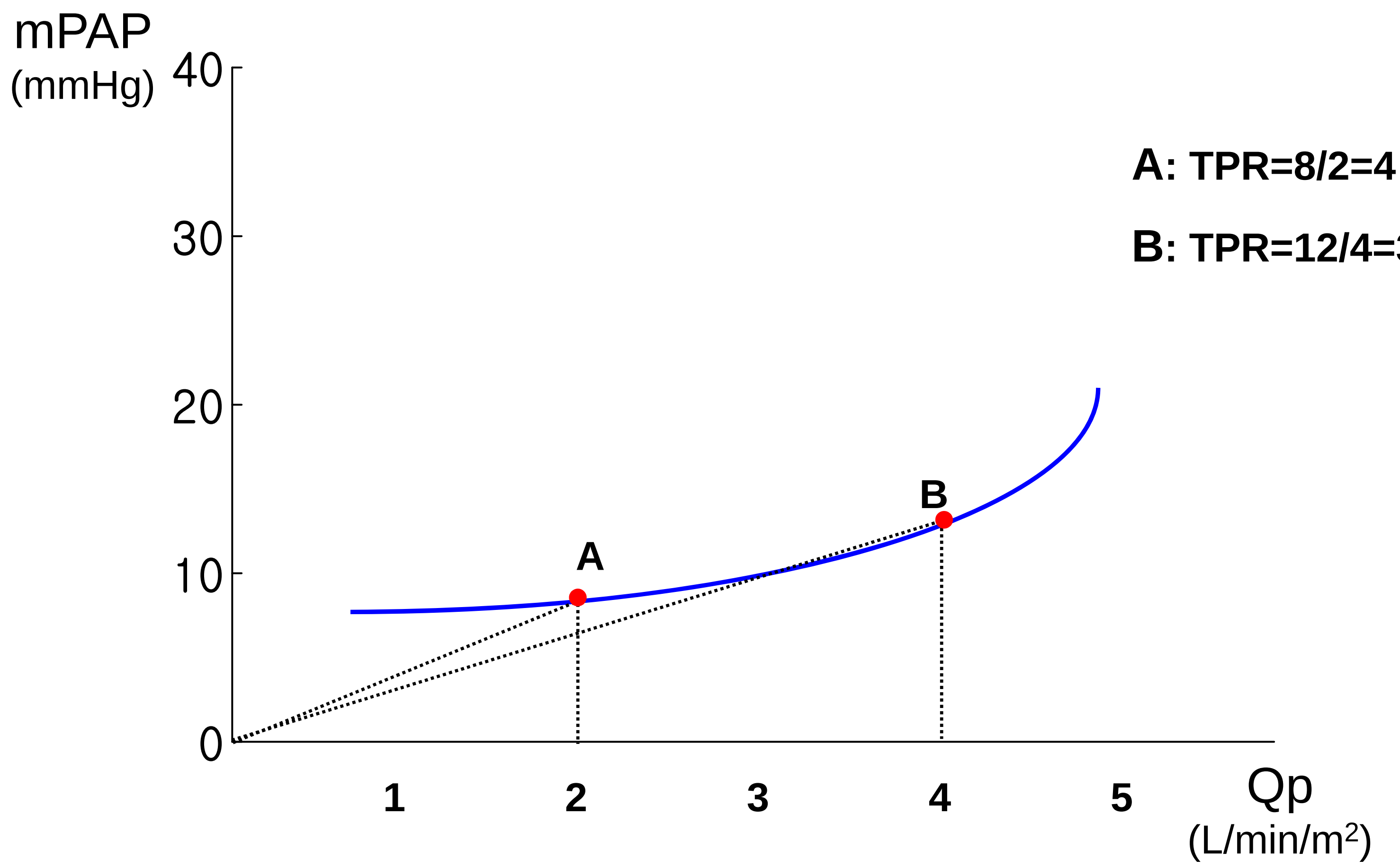
Qp vs. PAP


mPAP (mmHg)
40
30
20
10
0
1
2
3
4
5
Qp (L/min/m2)
Low pulmonary vascular compliance (PVC)
High pulmonary vascular compliance (PVC)

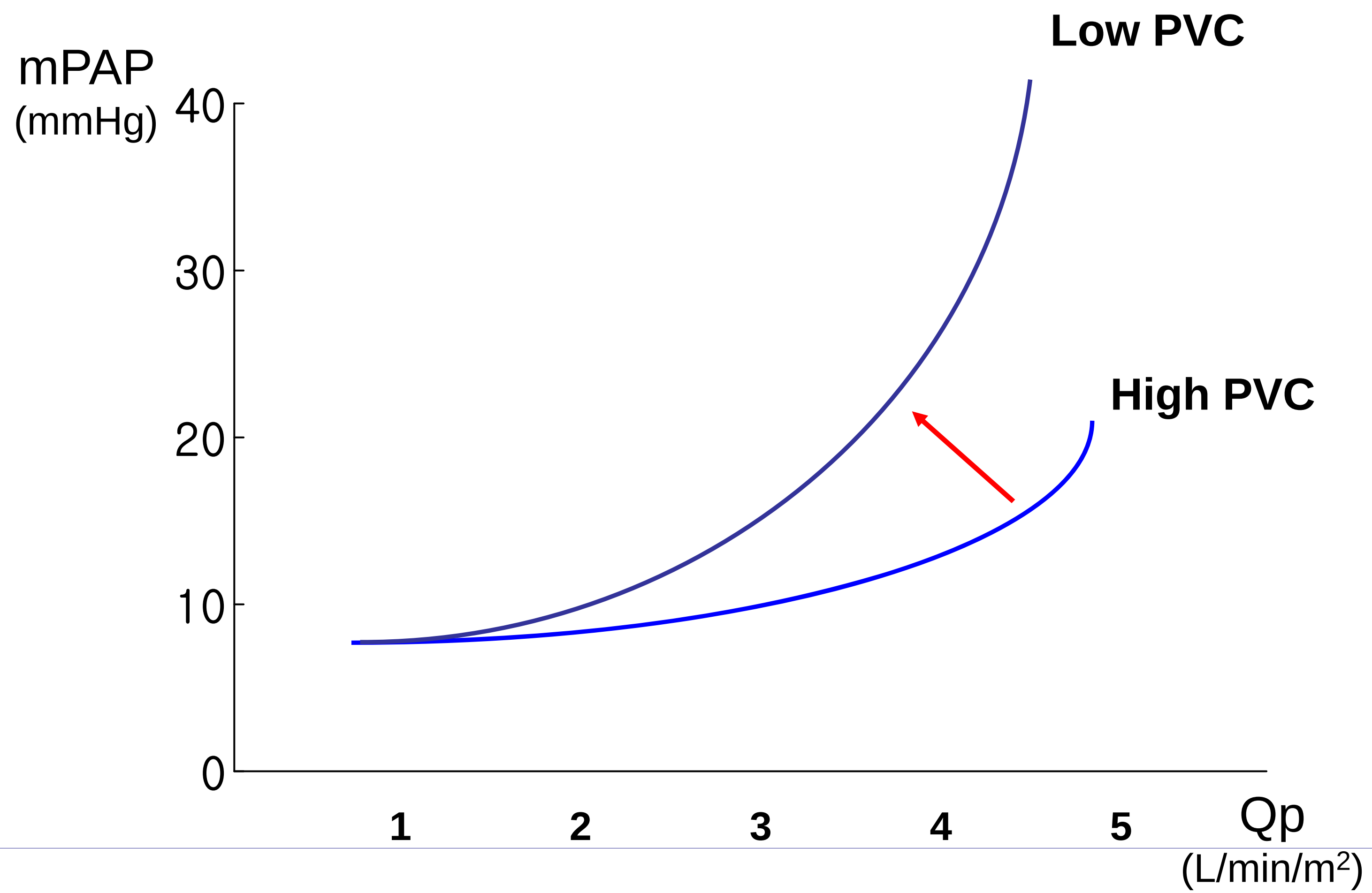
High PVC Fontan Candidates



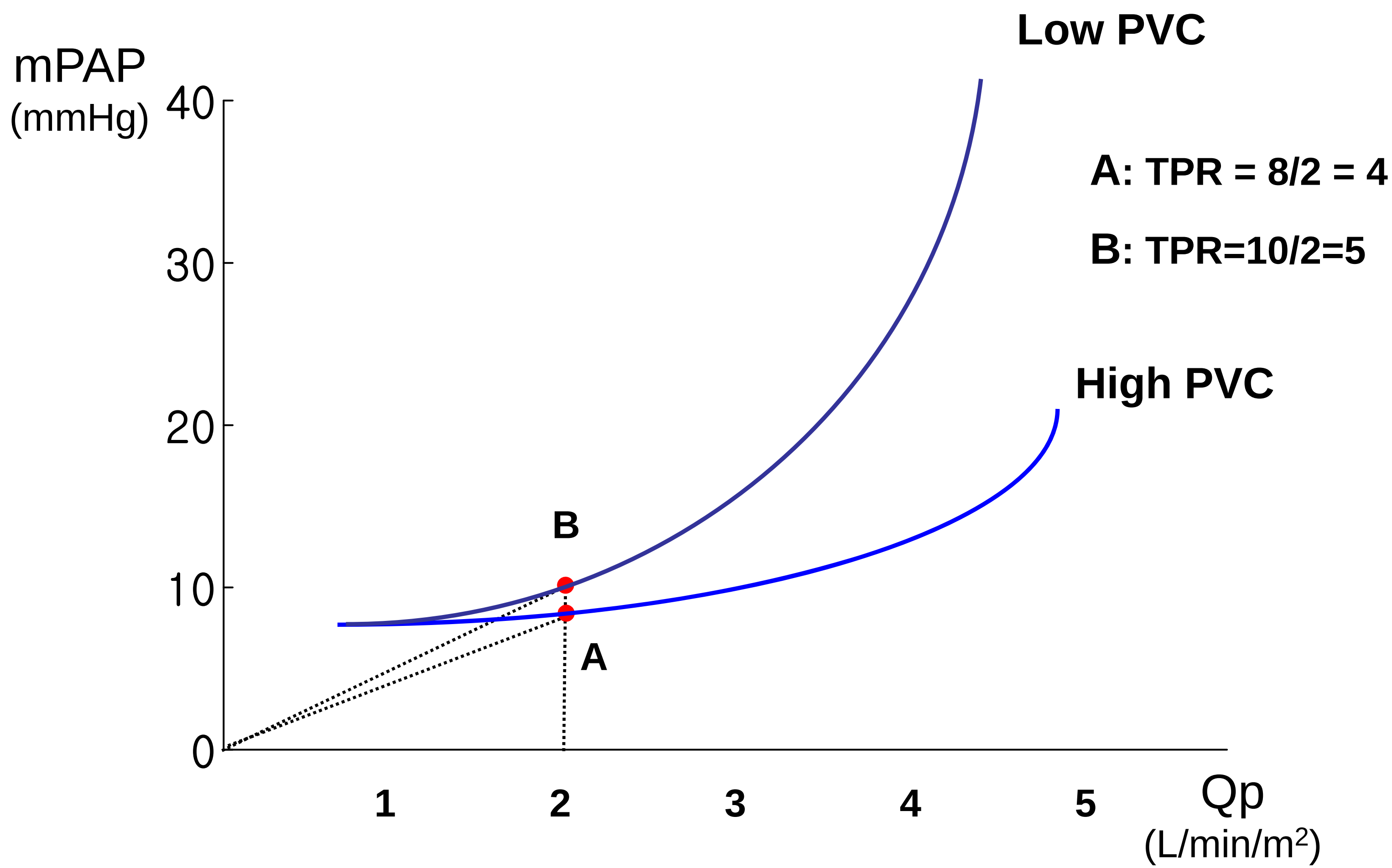
High PVC Fontan Candidates



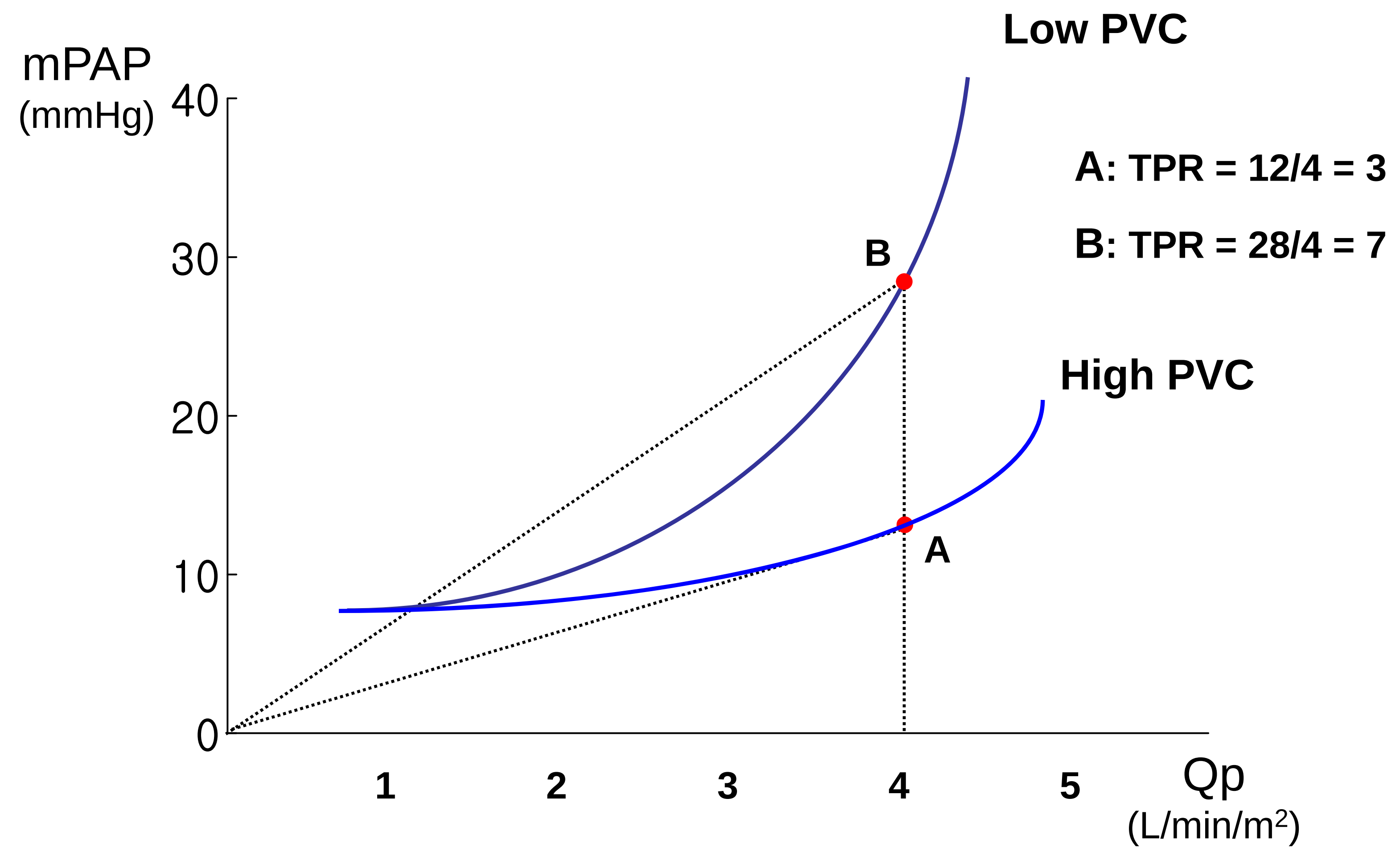
Low PVC Fontan Candidates



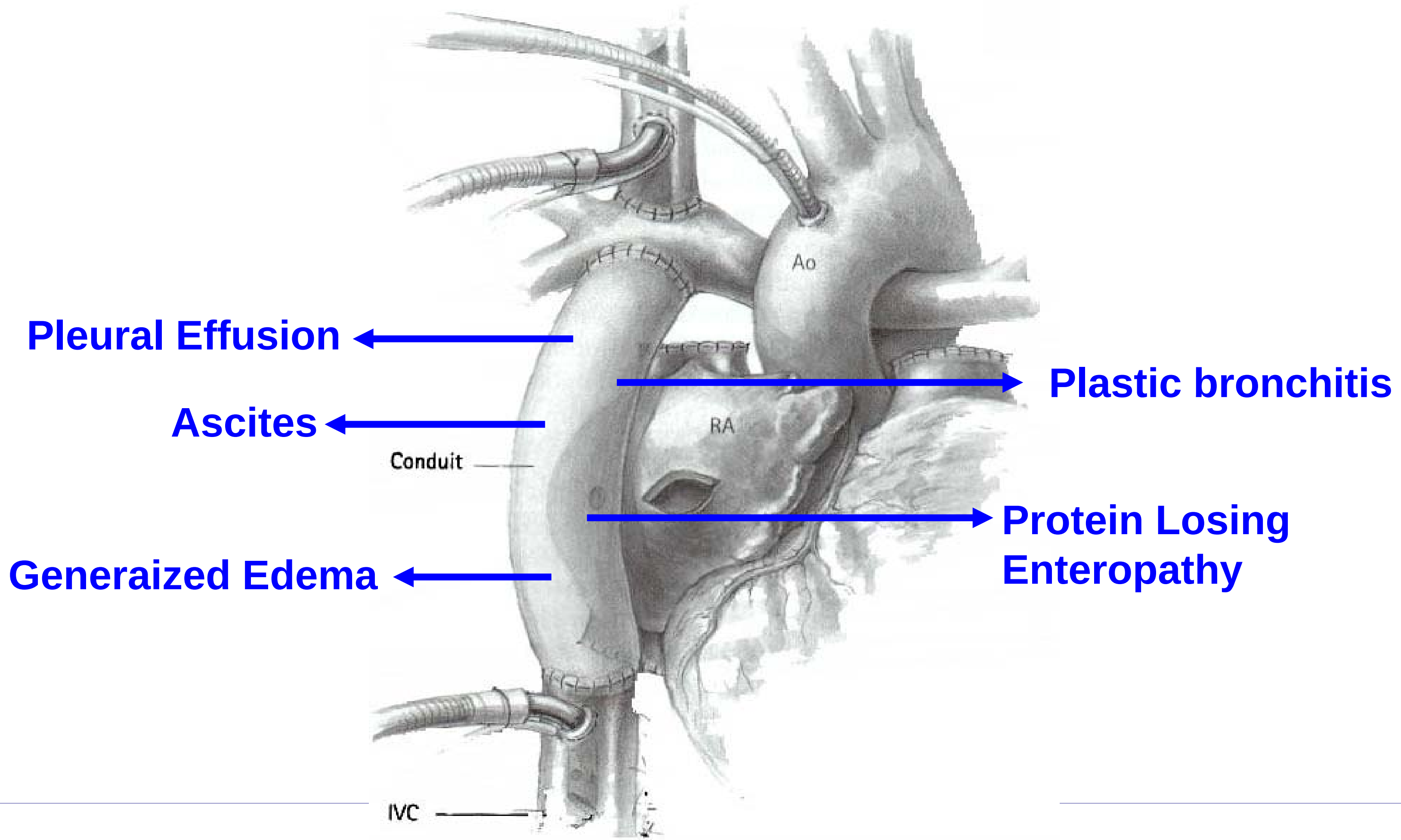
Low PVC Fontan Candidates



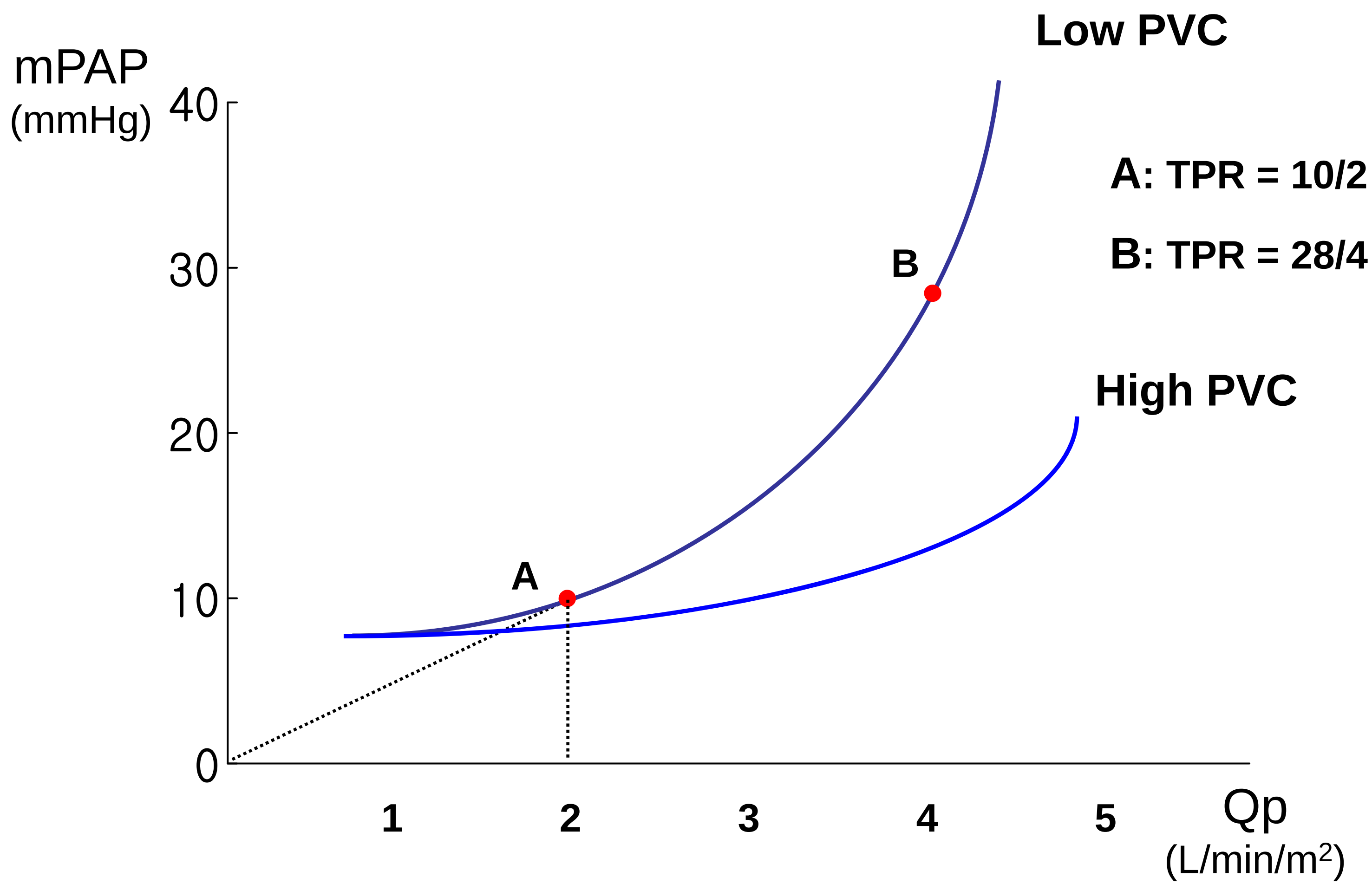
Low PVC Fontan Candidates



Low CVP = Good Fontan ?



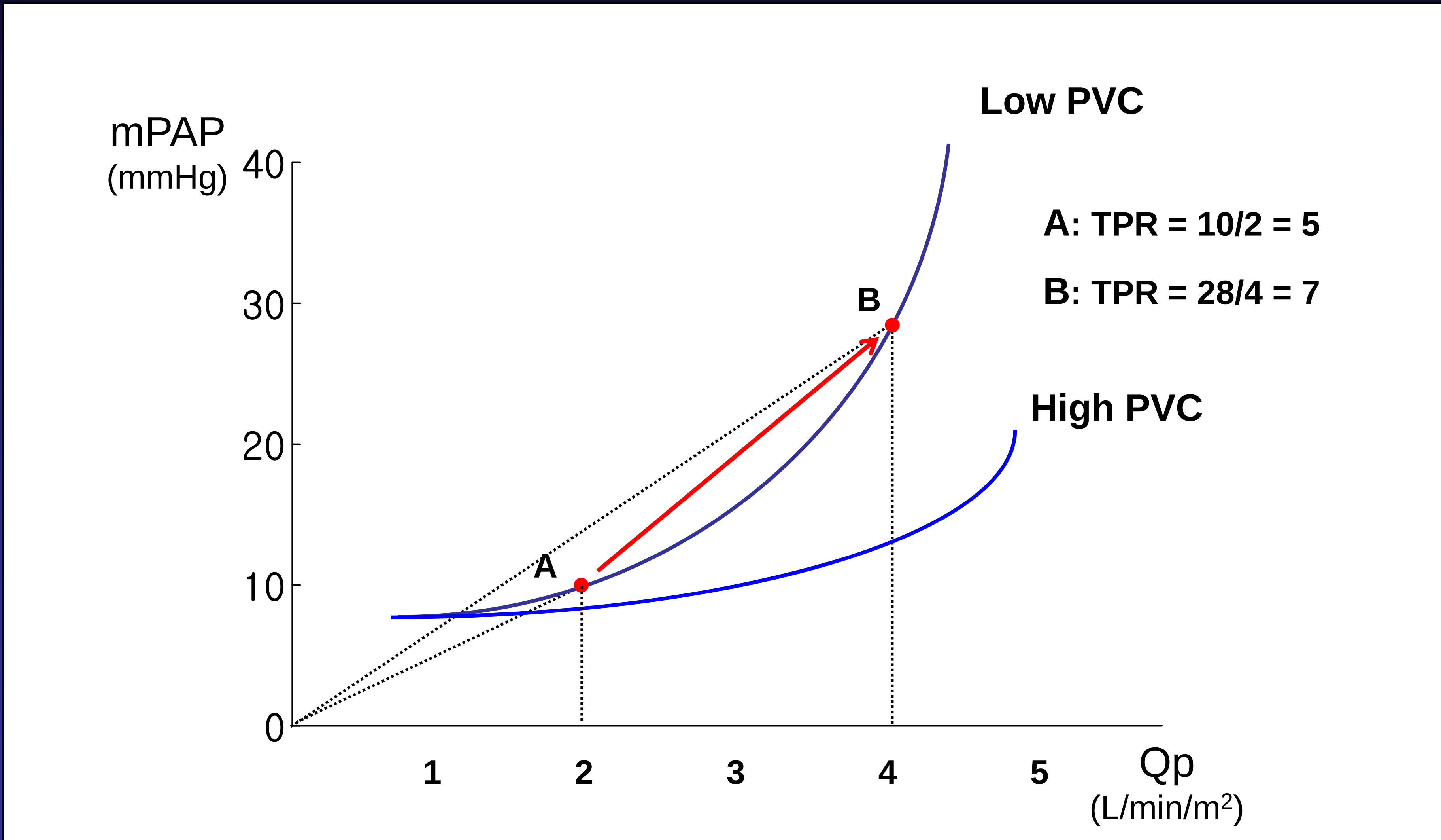
Fontan Failure



A: TPR = 10/2 = 5

B: TPR = 28/4 = 7

Heart Tx for Fontan Failure

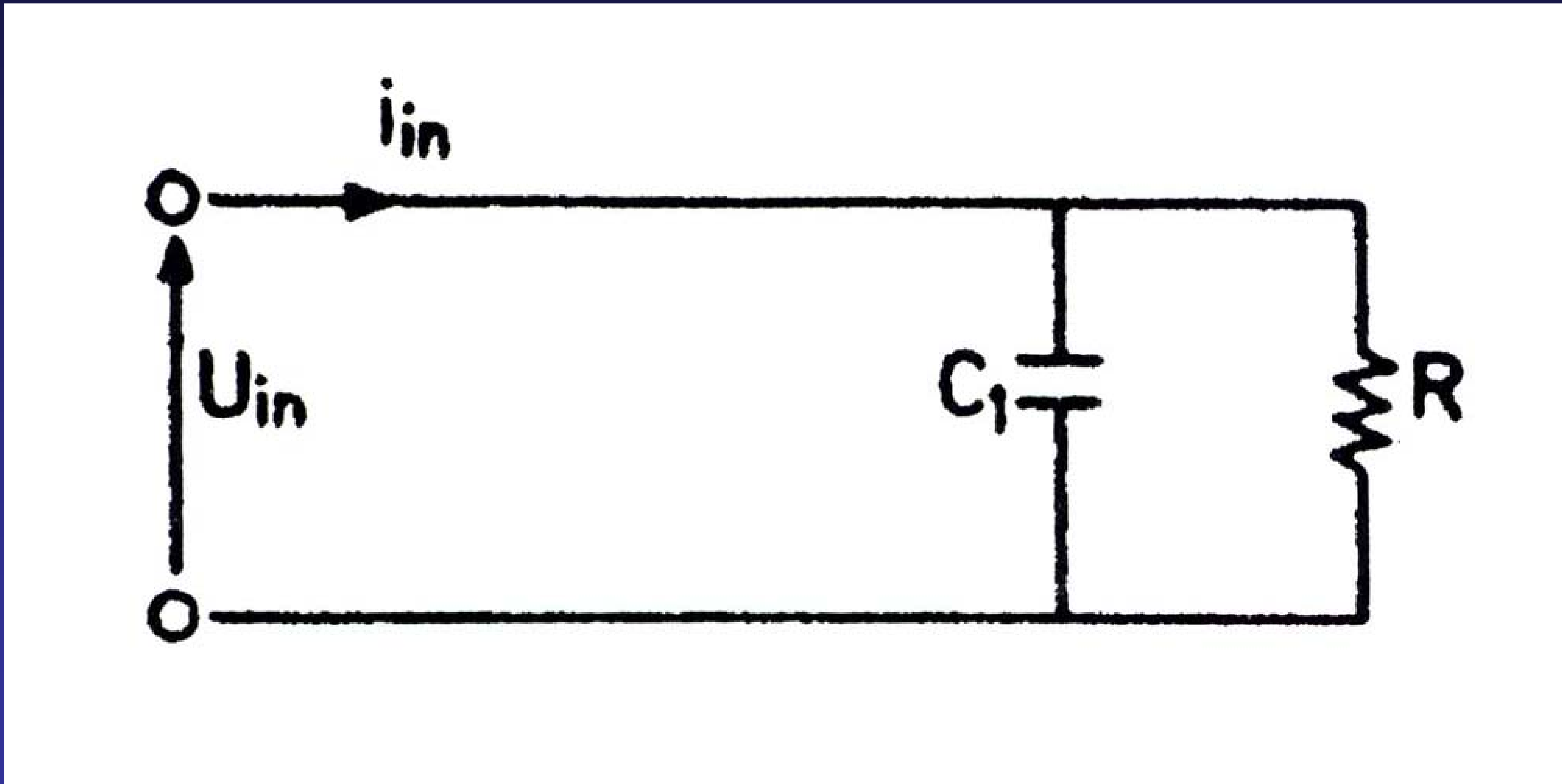


Methods for PVC Measurement

- Electrical circuit modeling
- Intra-op flow study
- Pulsed-wave Doppler

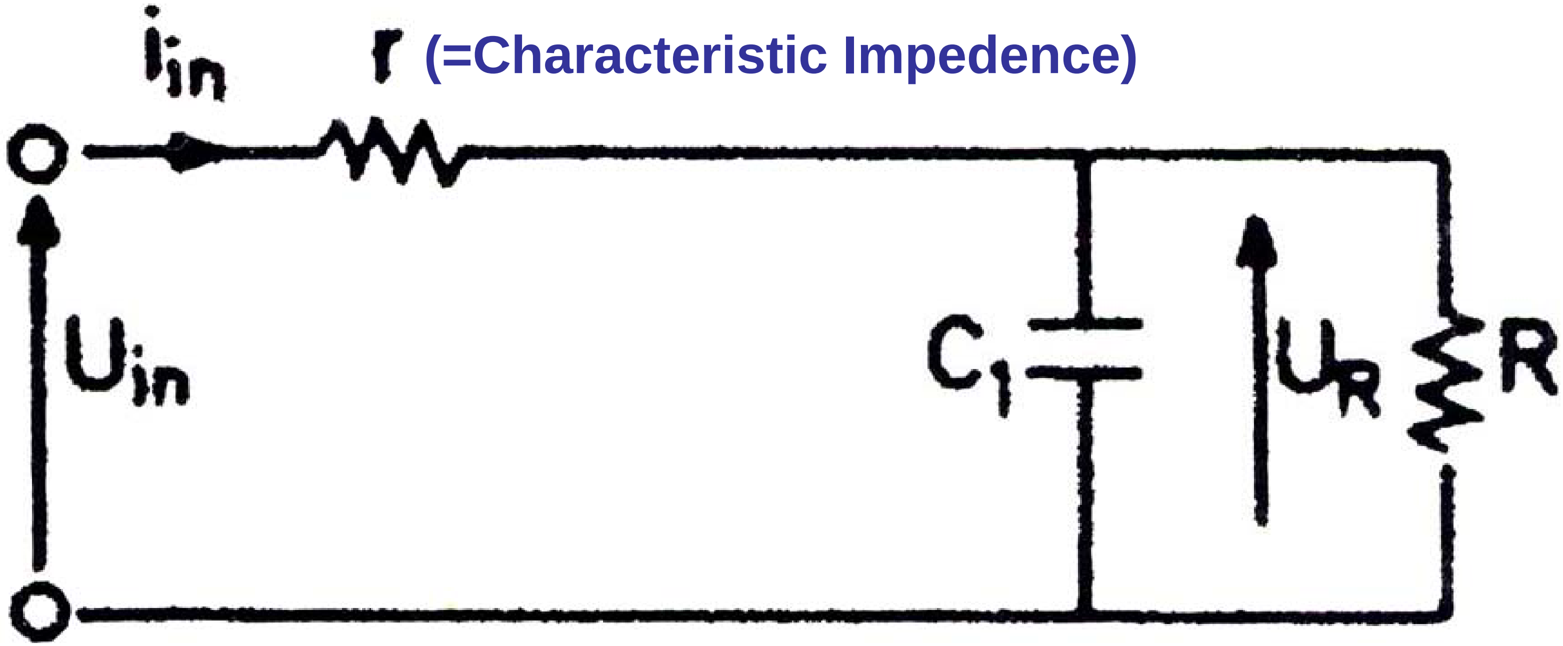
Electricl Circuit Models

- Windkessel (Frank, 1899) -



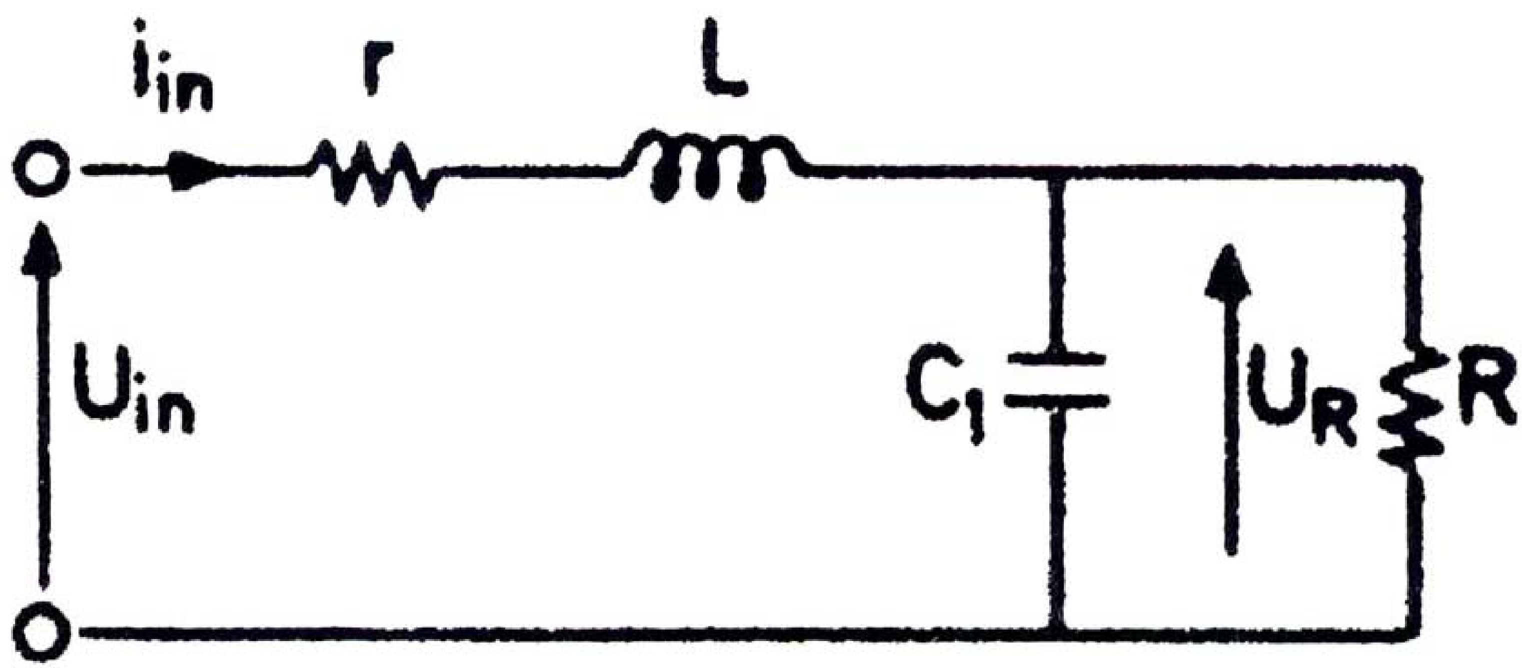
Electricl Circuit Models

- Landers (1943) and Westerhof (1968) -



Electricl Circuit Models

- Landers (1943) and Deswysen (1980)-



Electricl Circuit Models

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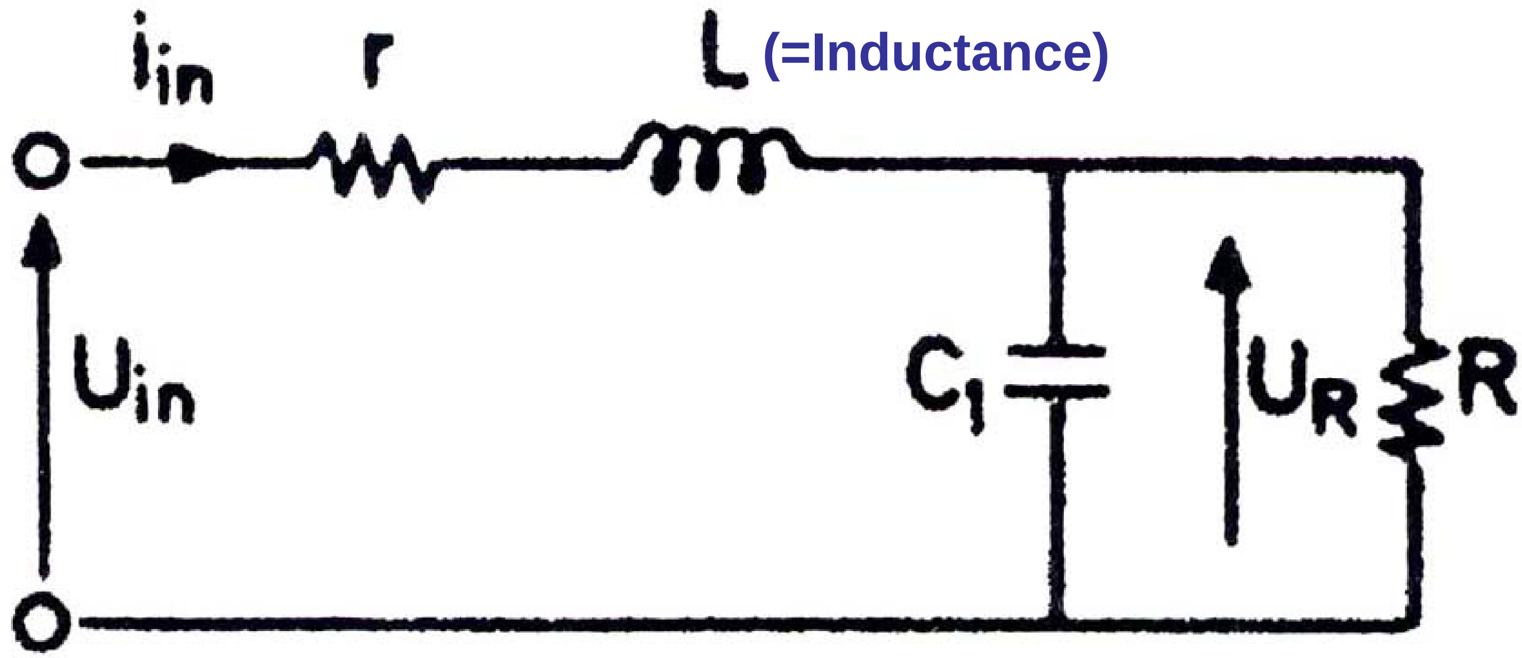

Electricl Circuit Models

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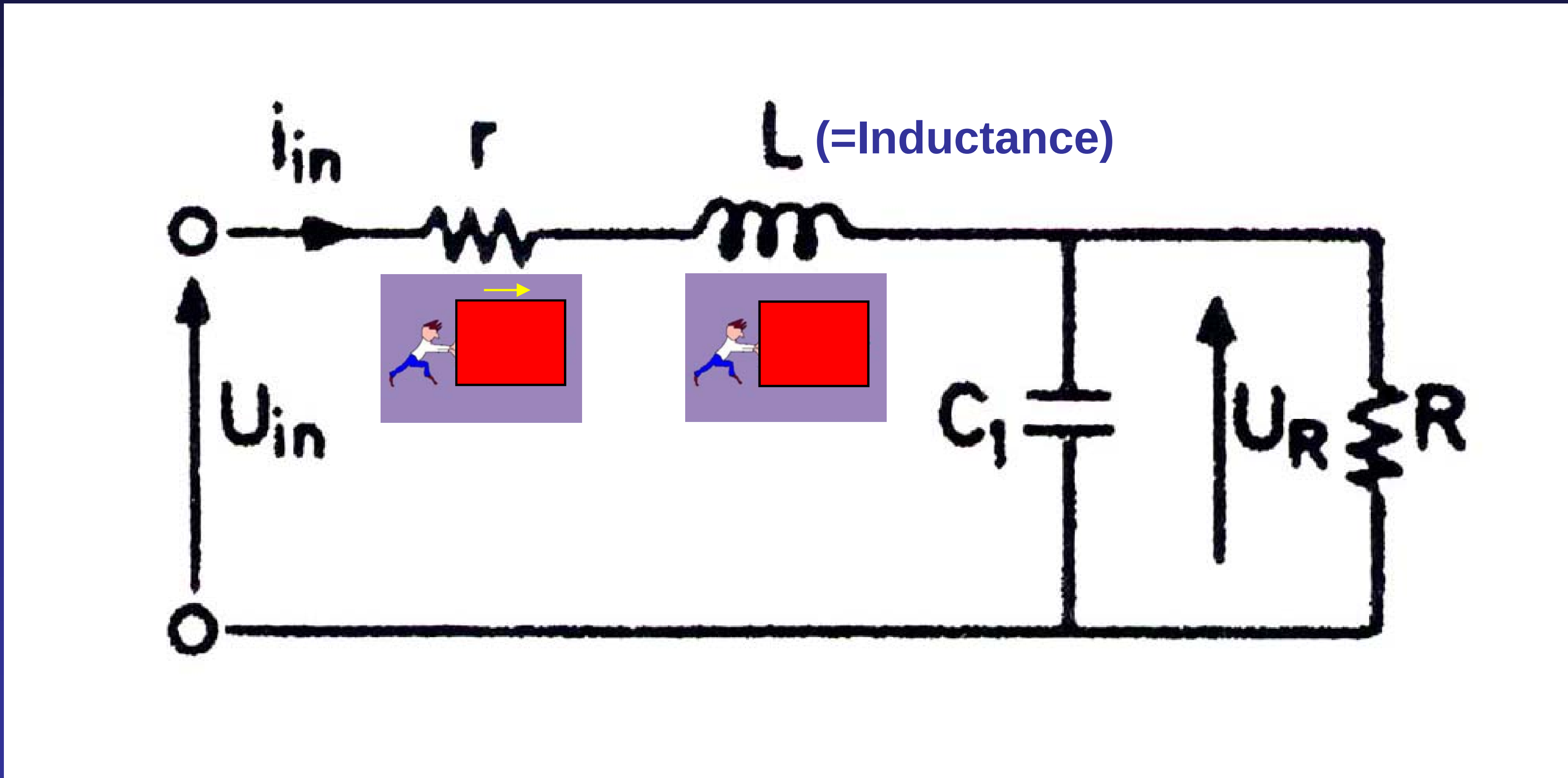
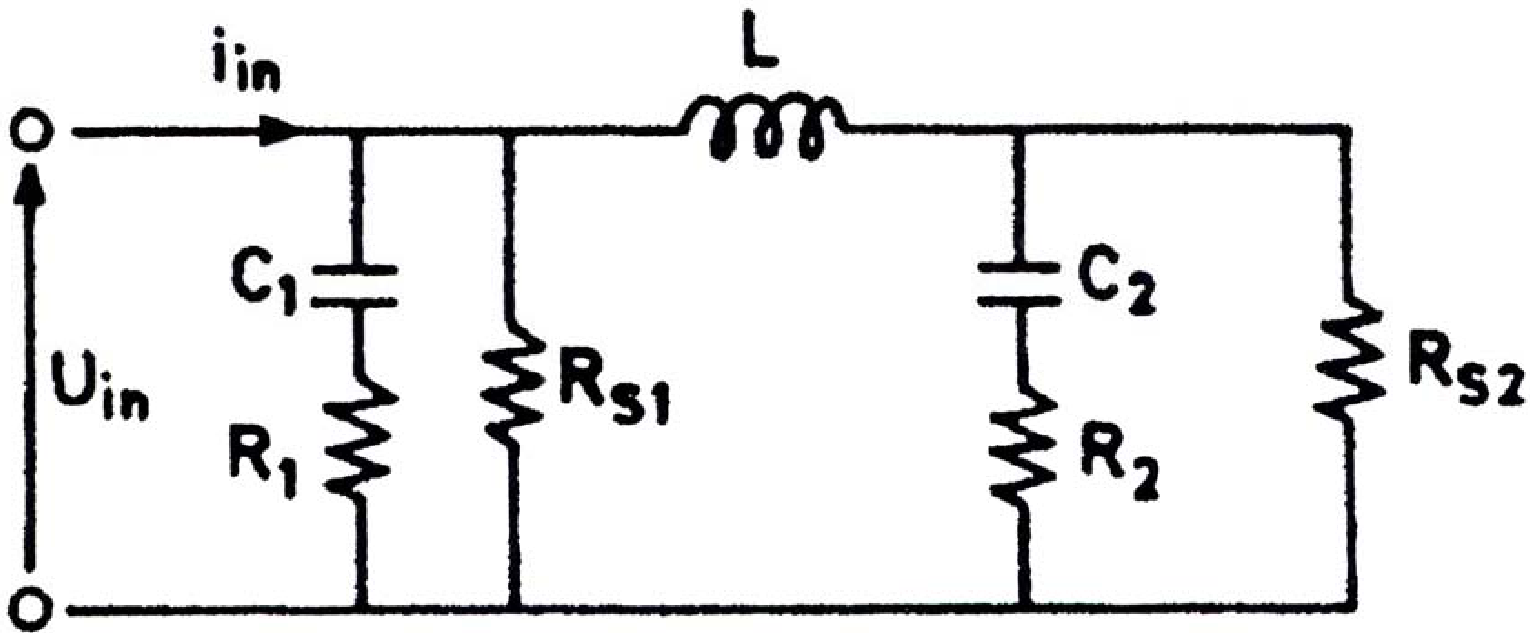


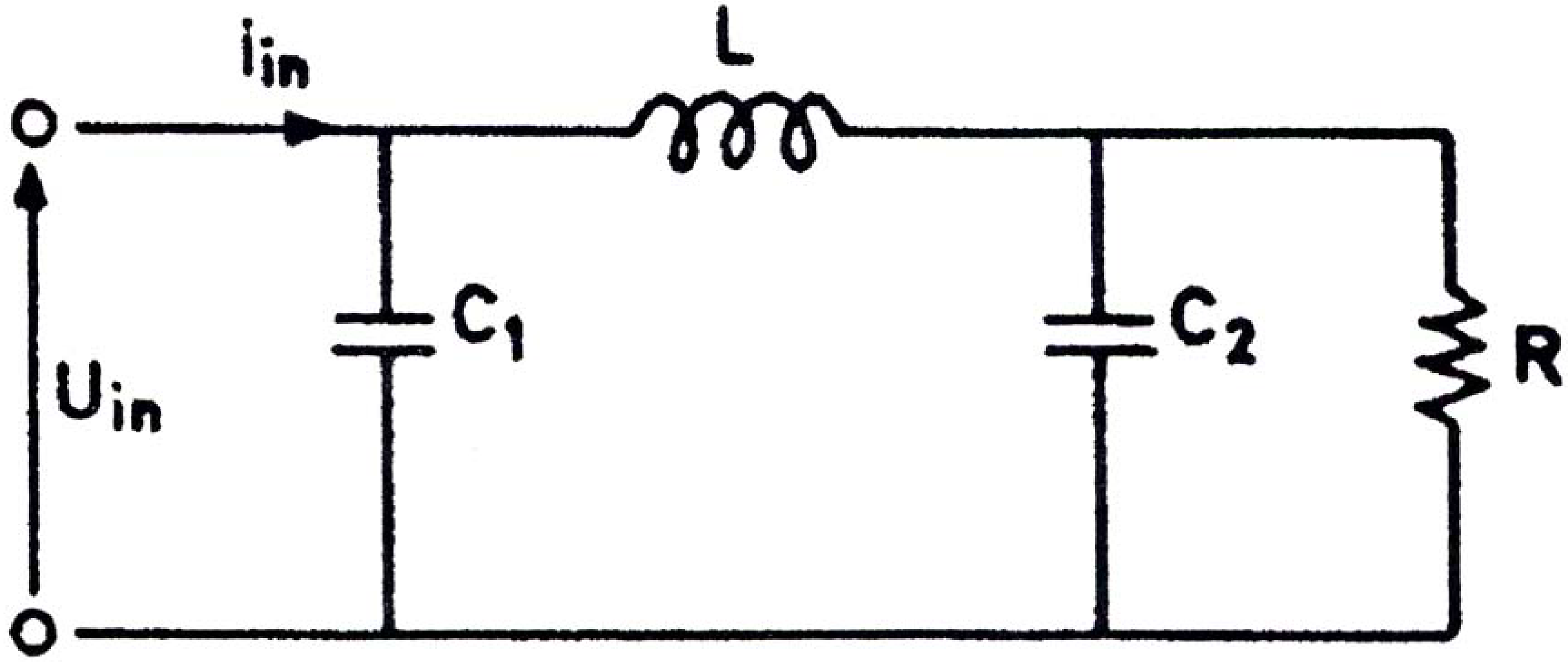
Electricl Circuit Models

- Spencer and Denison (1963) -



Electricl Circuit Models

- Goldwyn and Watt (1967) -



Electricl Circuit Models

- Chang (1973) and Sims (1972) -

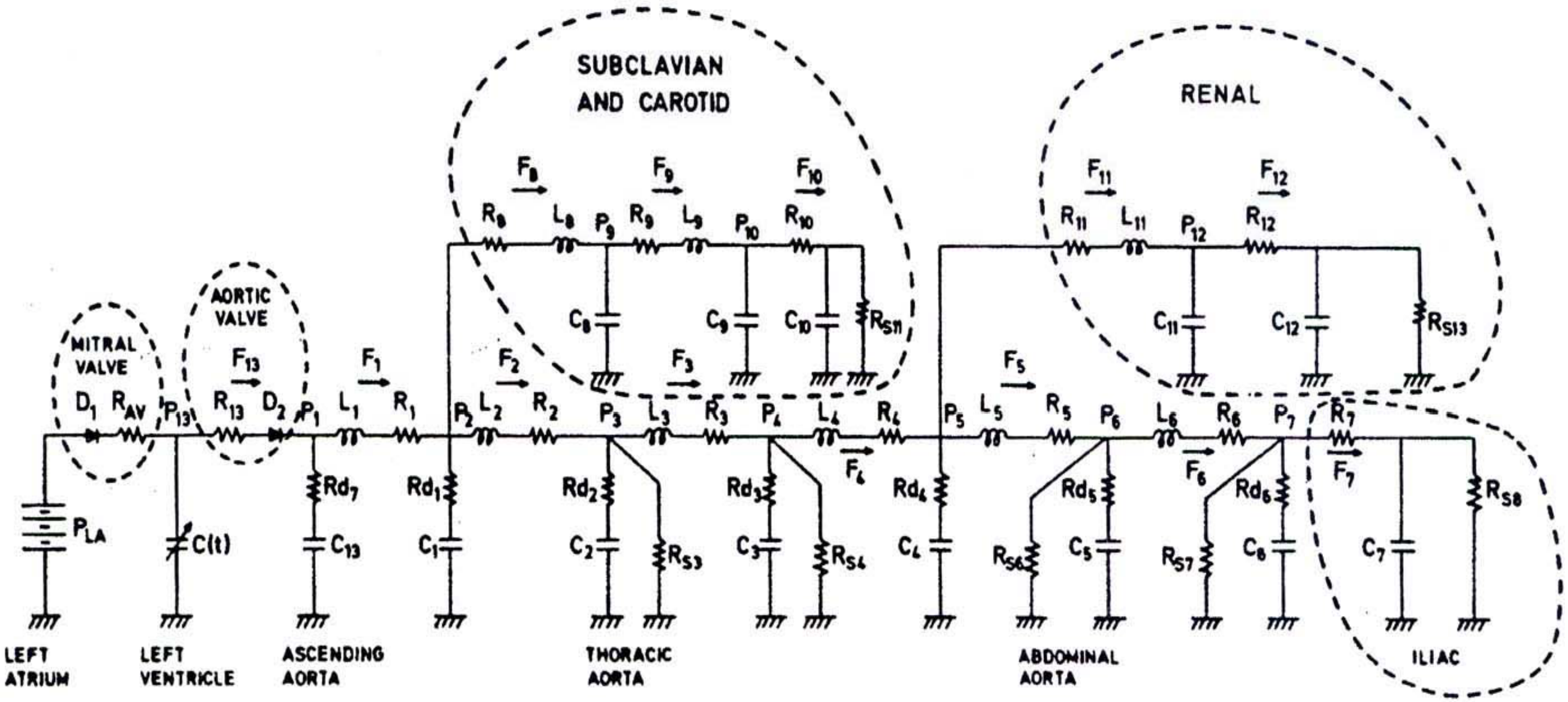
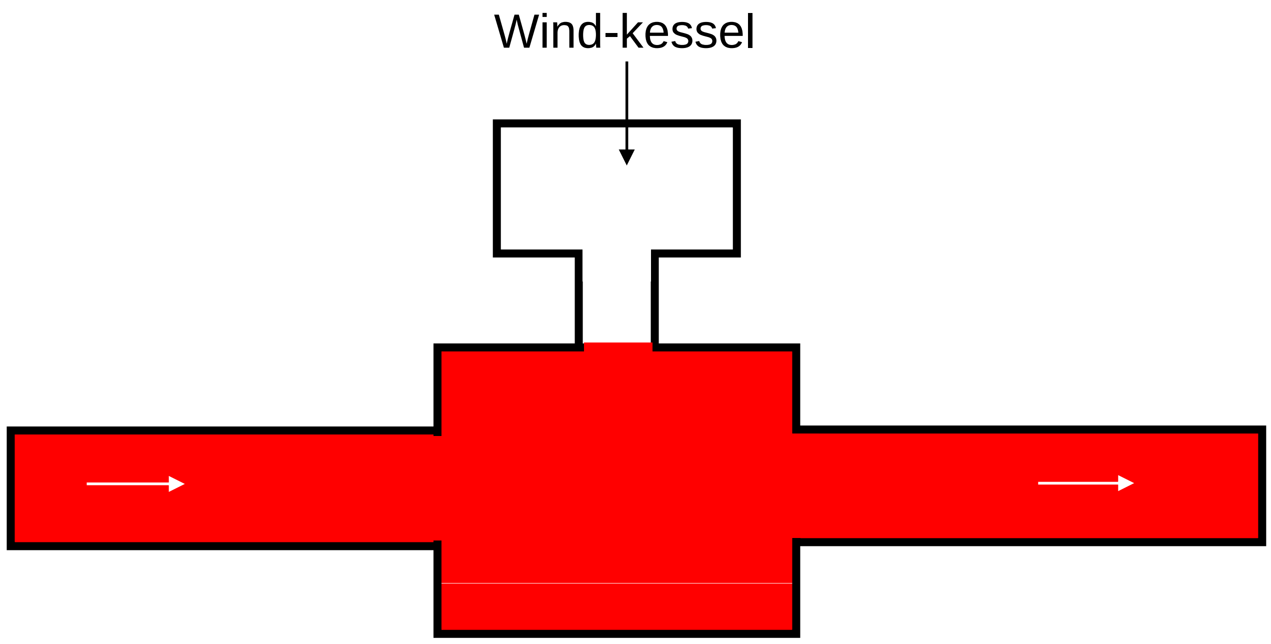
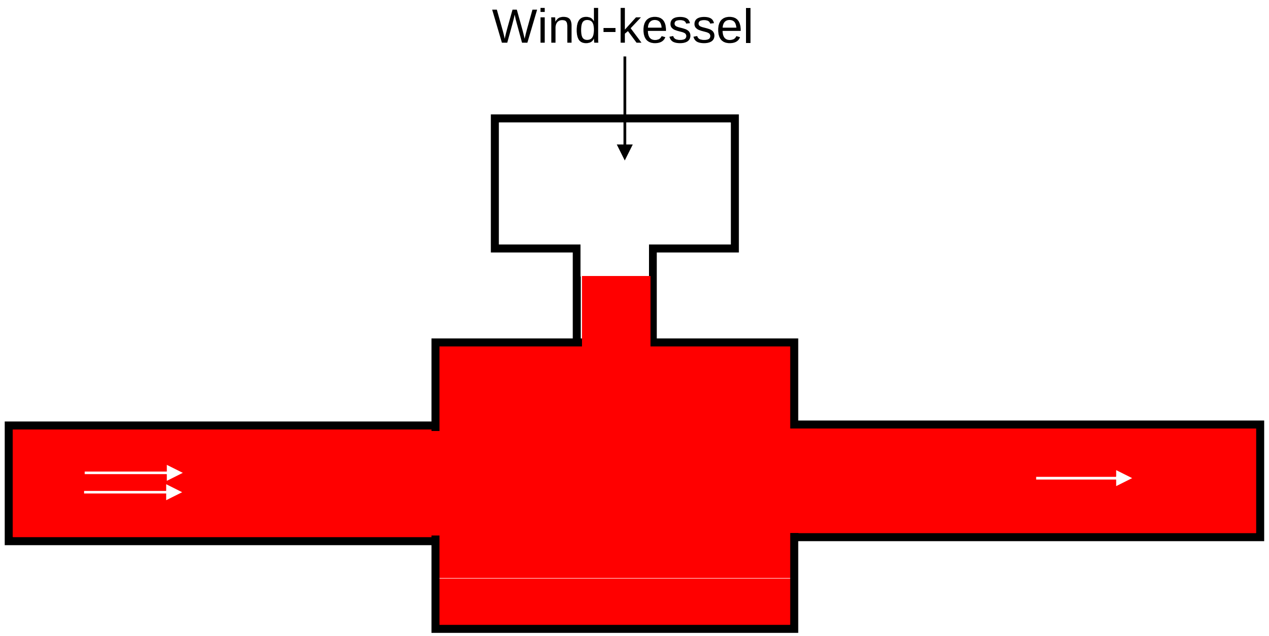


Fig. 2 Complex model of the systemic circulation (Chang, 1973; Sims, 1972)

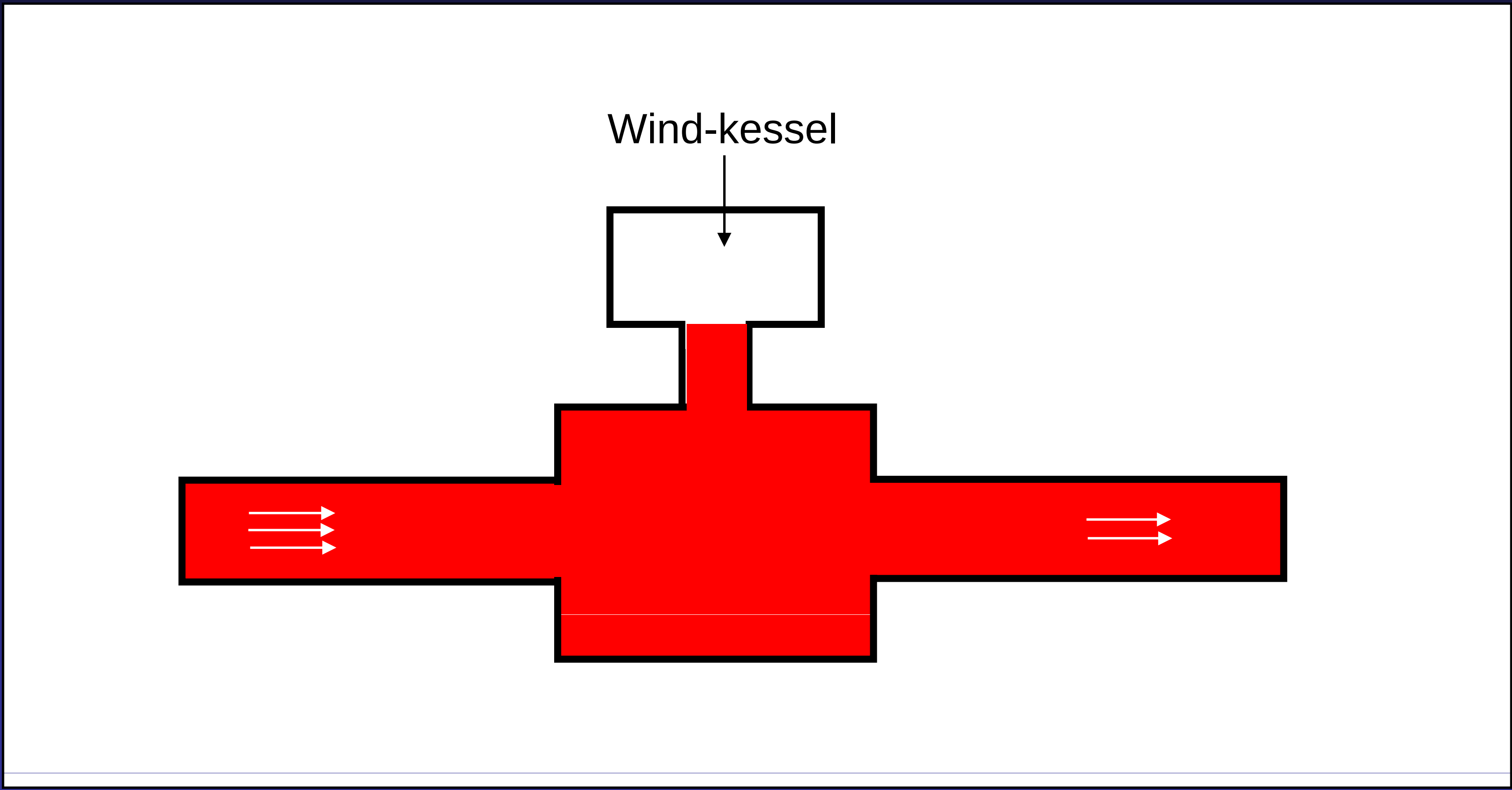
Wind-kessel = Air-chamber



Wind-kessel = Air-chamber



Wind-kessel = Air-chamber



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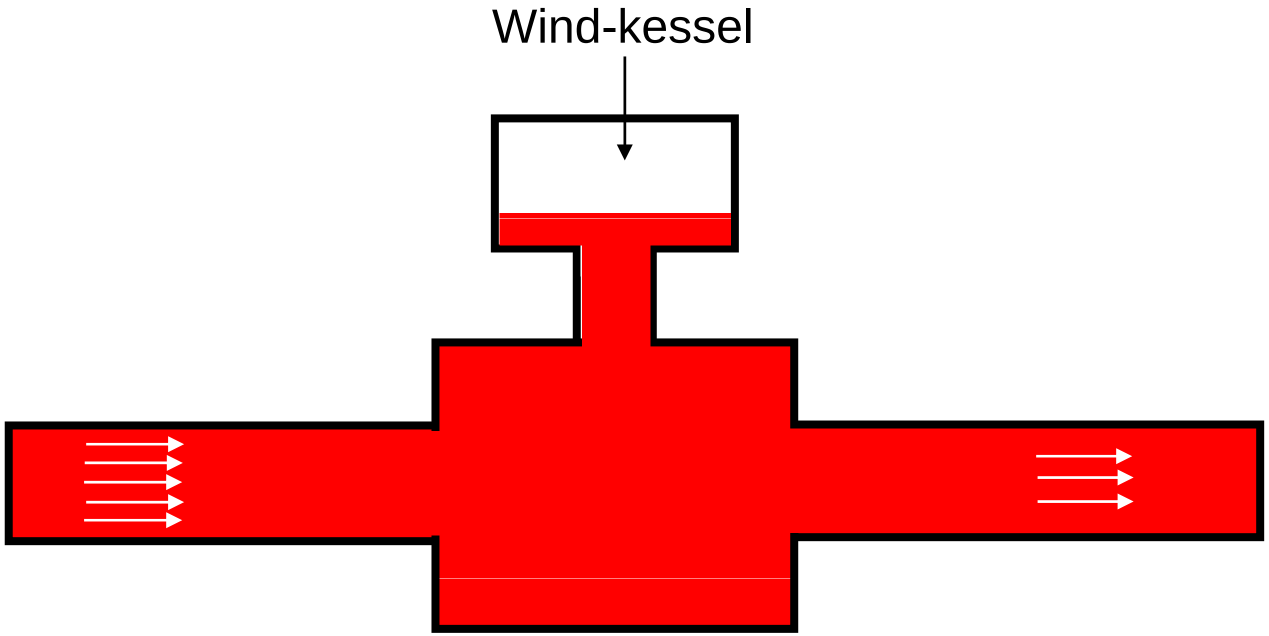
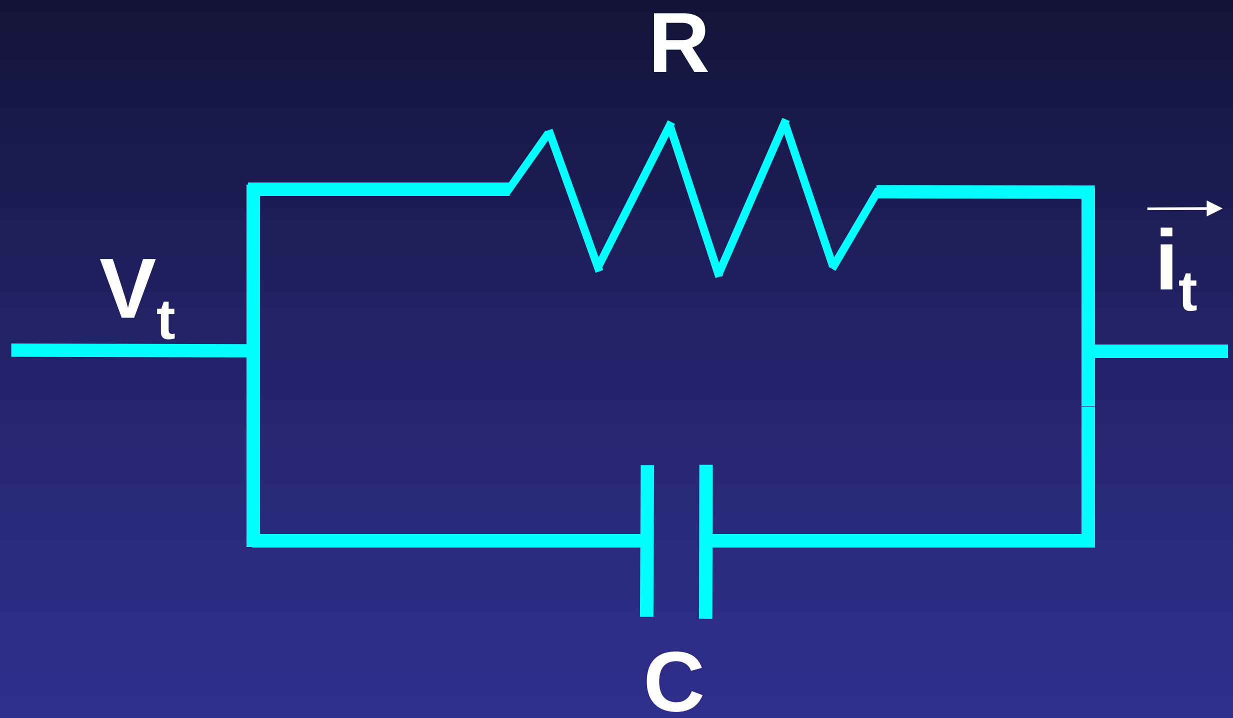
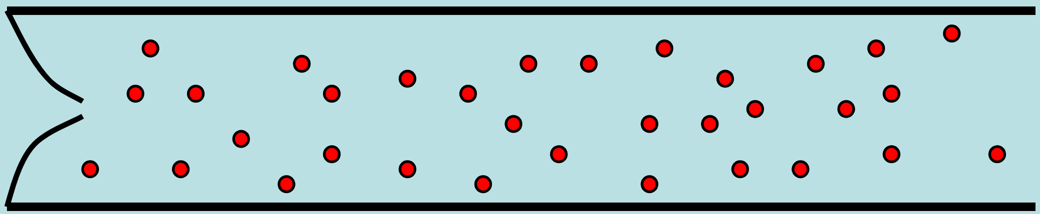
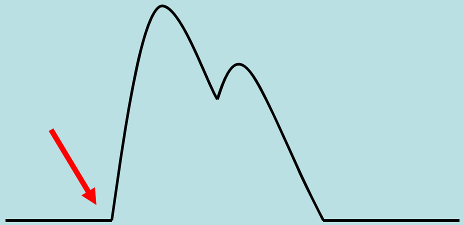


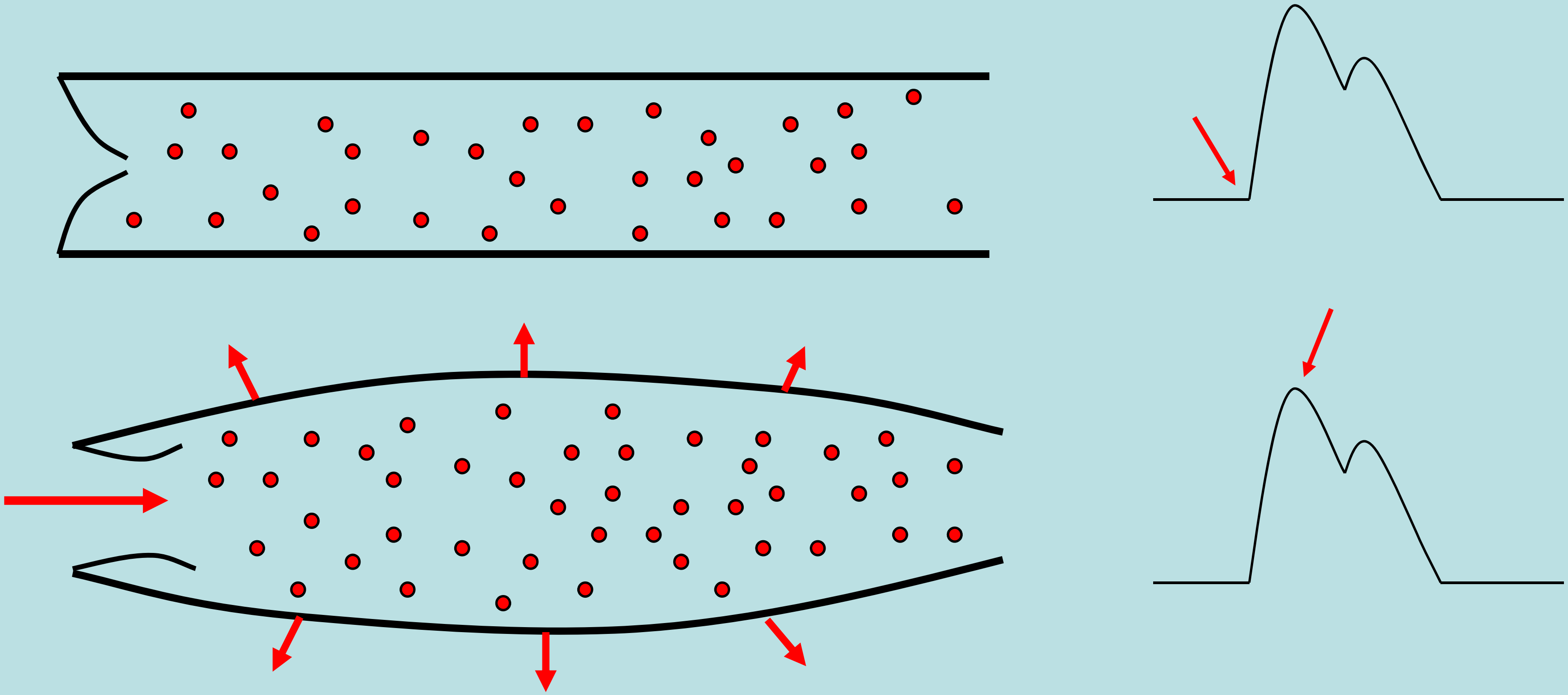
Windkessel Model for pulsatile flow

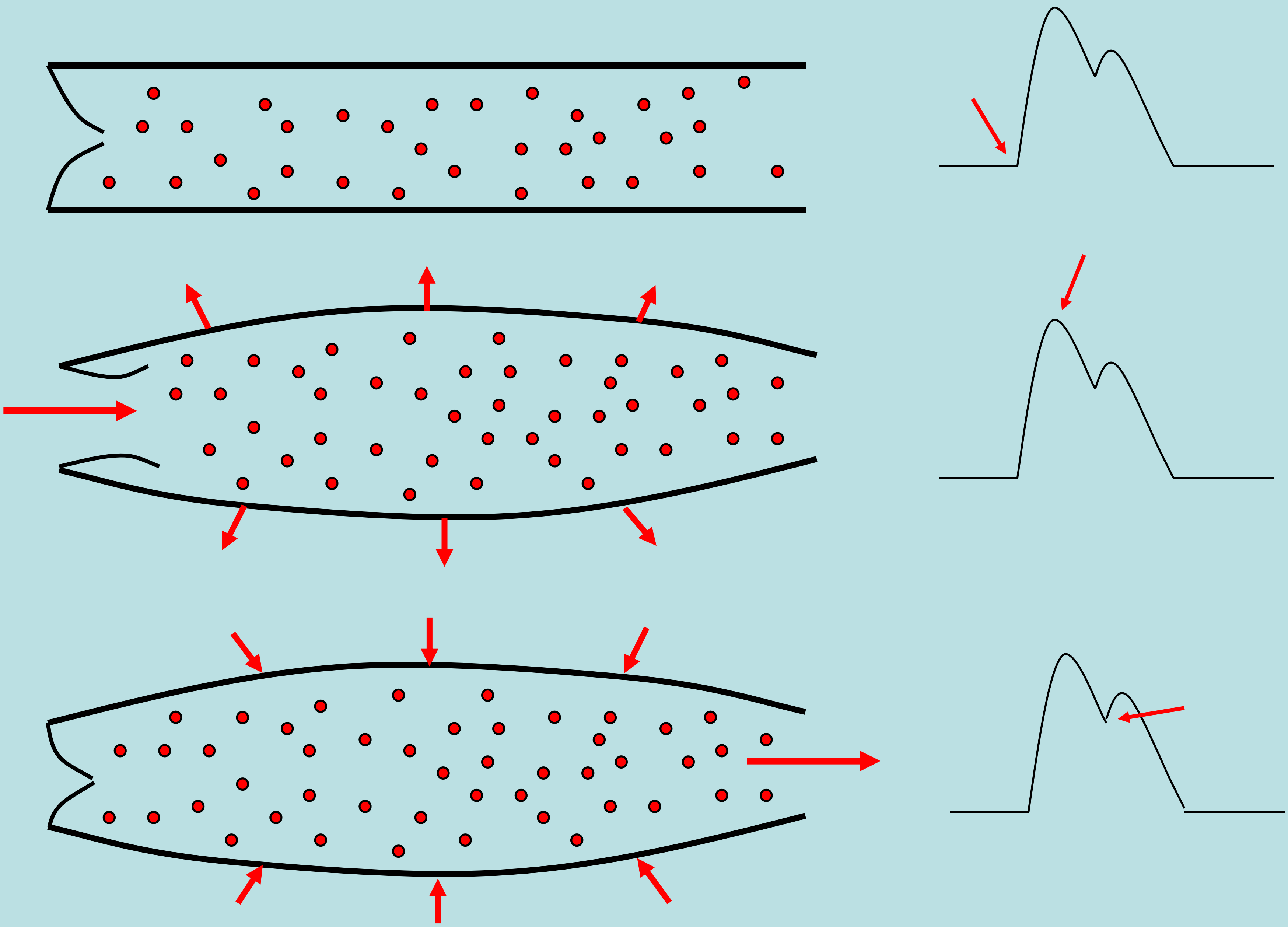


$$i_t = \frac{V_t}{R} + C\frac{dV_t}{dt}$$



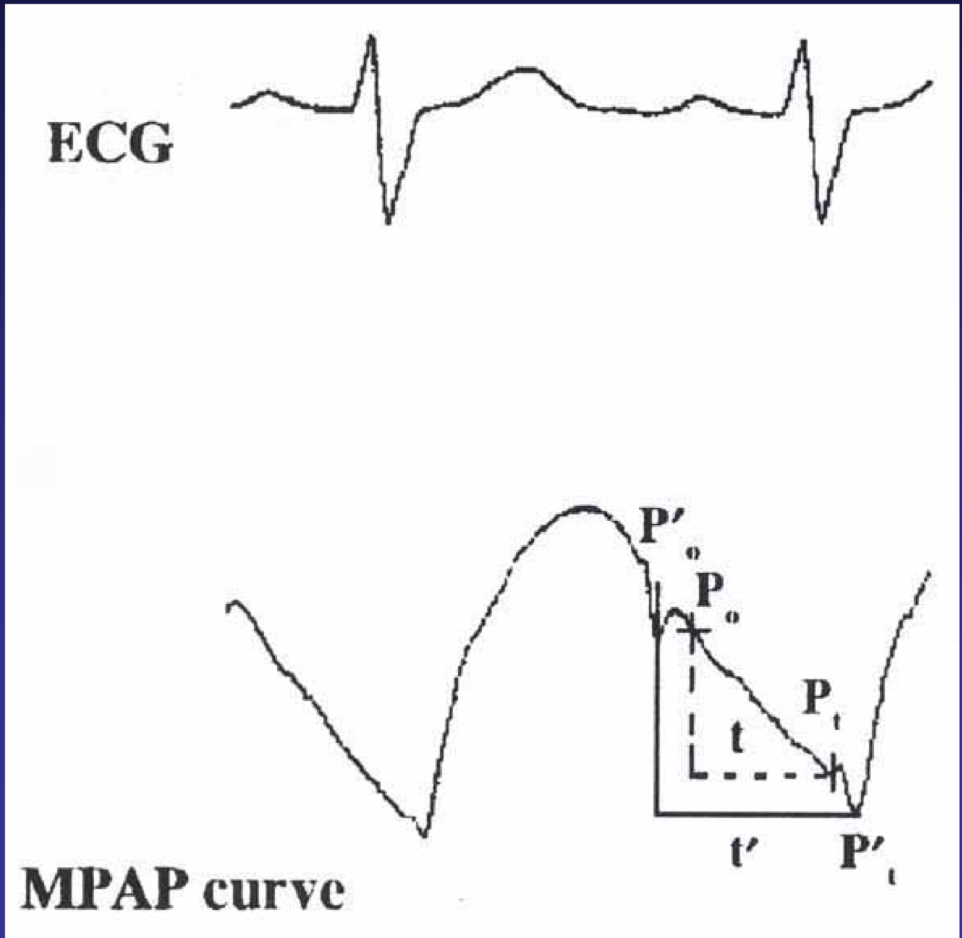






Windkessel Model for pulsatile flow

- Diastolic time constant (Reuben, 1971) -



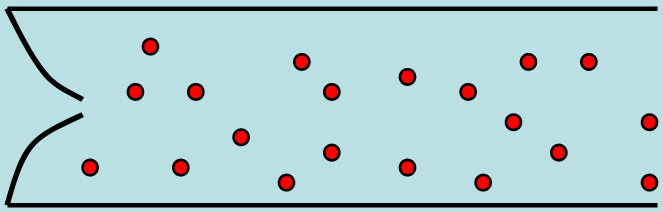
$$i_t = \frac{Pt}{R} + C\frac{dPt}{dt}$$

$$It_0 = \frac{P_0}{R} + C\frac{dPt}{dt} = 0$$

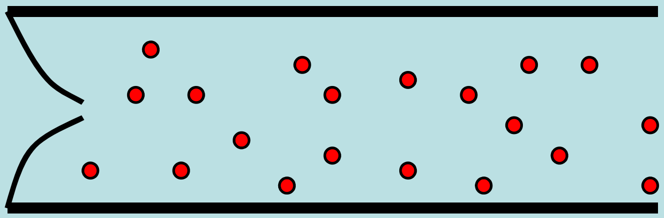
$$P_t = P_0\, e^{-t/RC}$$

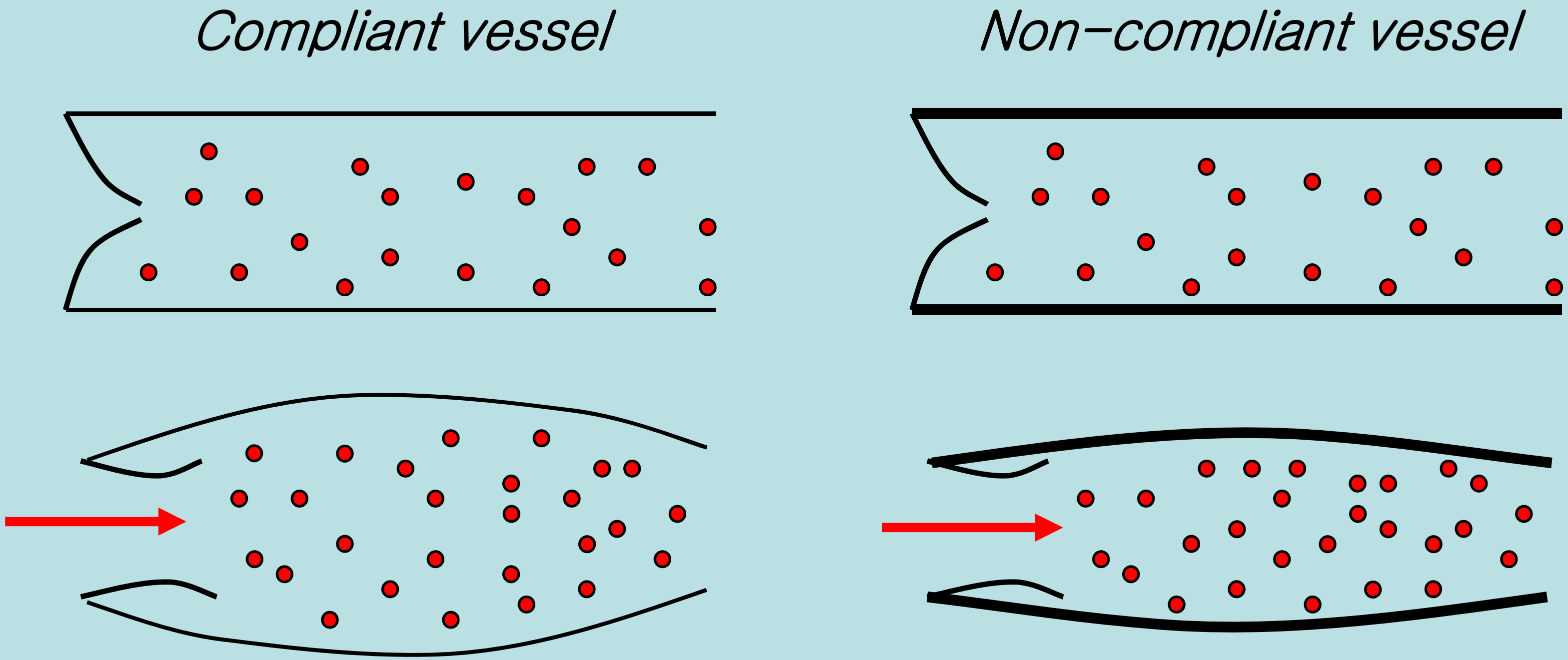
$$C_p = \frac{t}{R_p \bullet \log\,(P_0/P_t)}$$

Compliant vessel

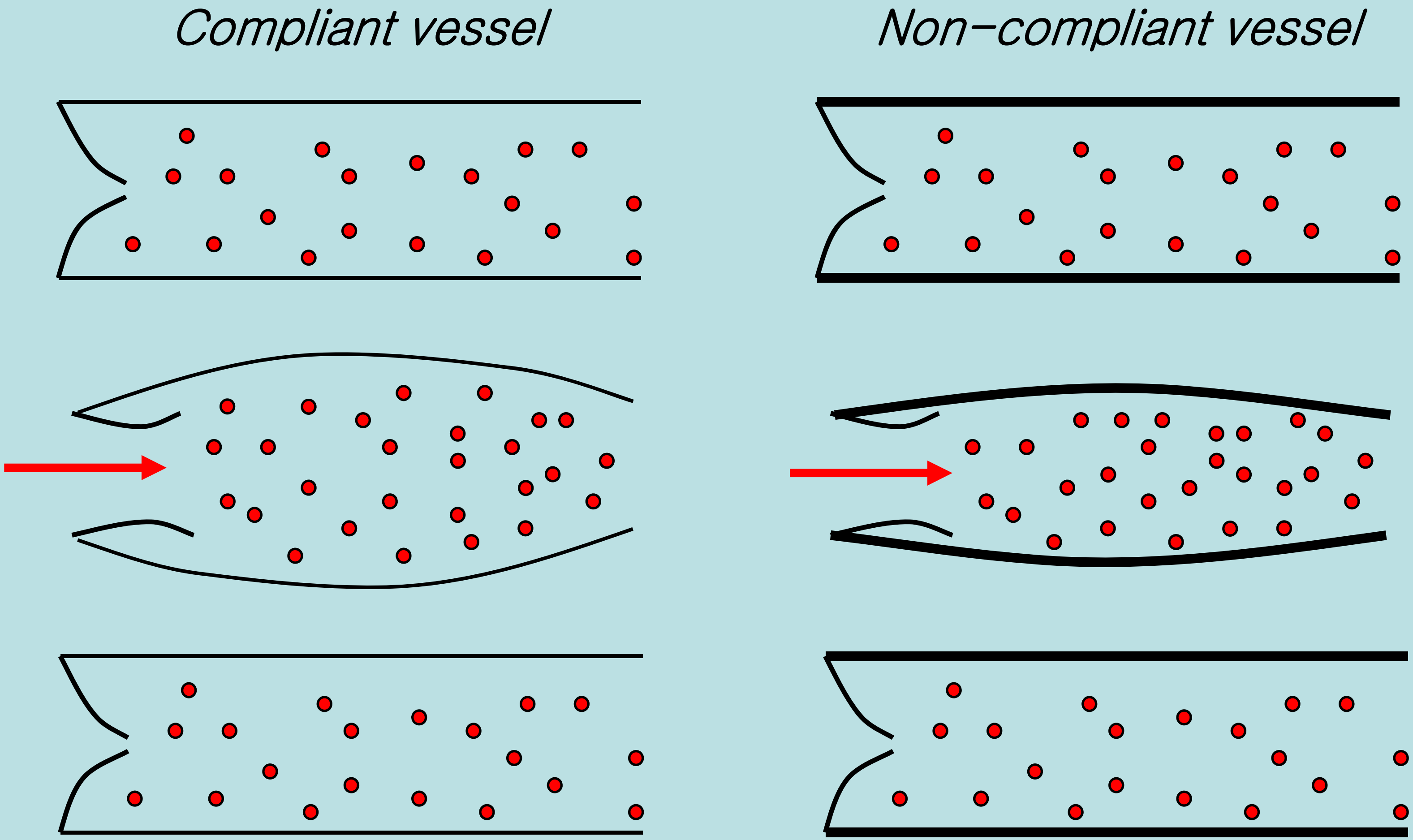


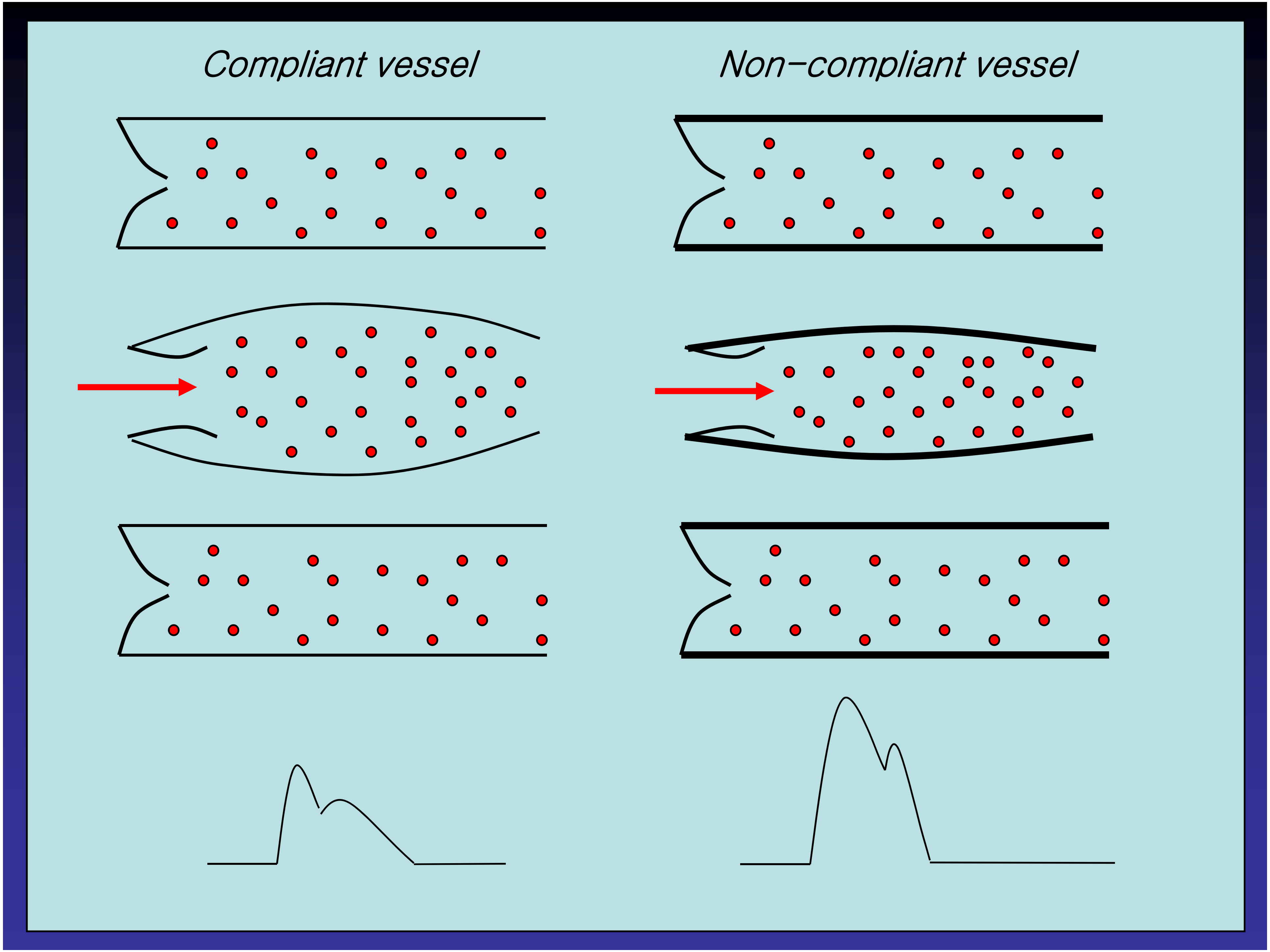
Non-compliant vessel

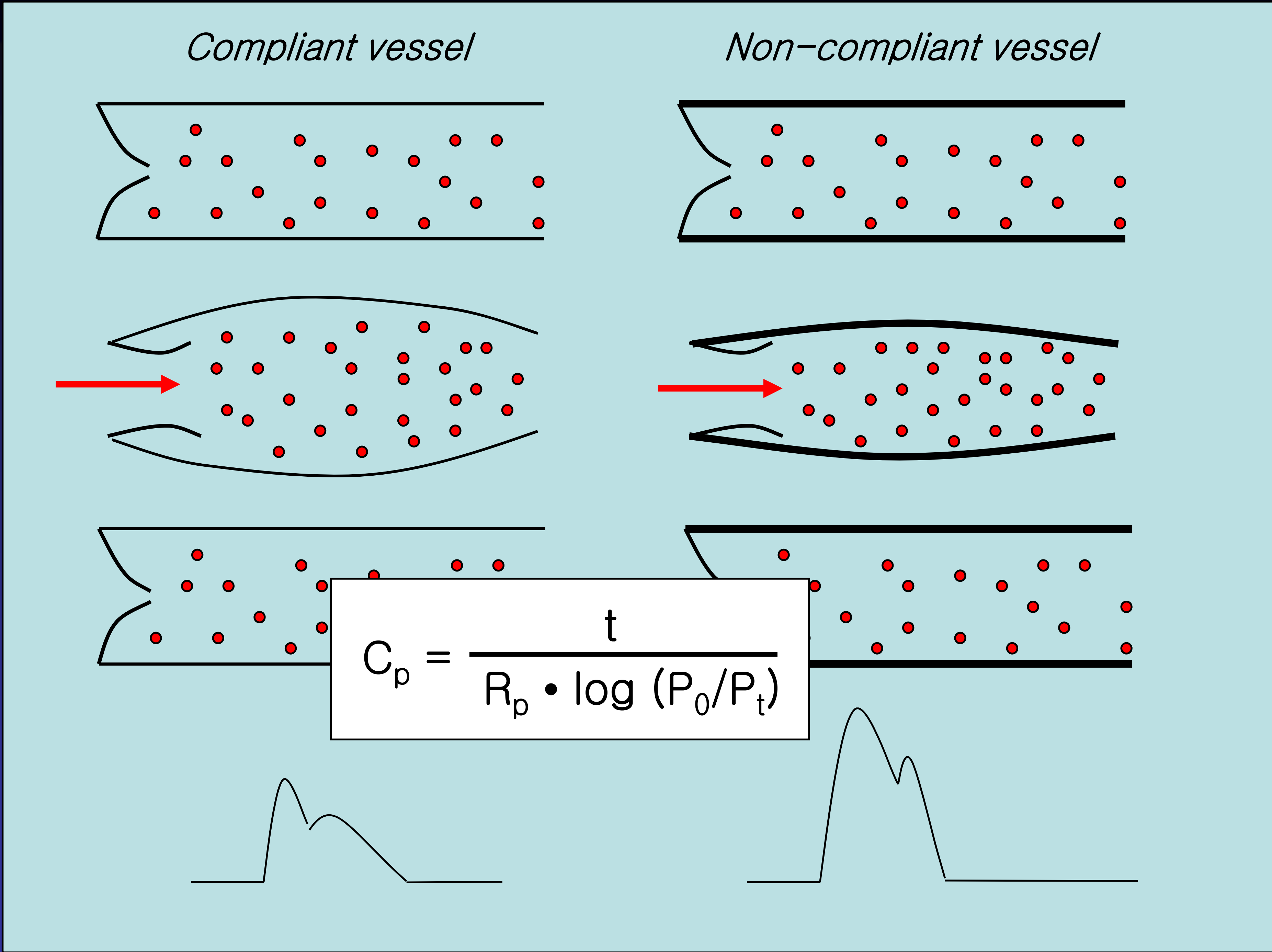




Compliant vessel
Non-compliant vessel

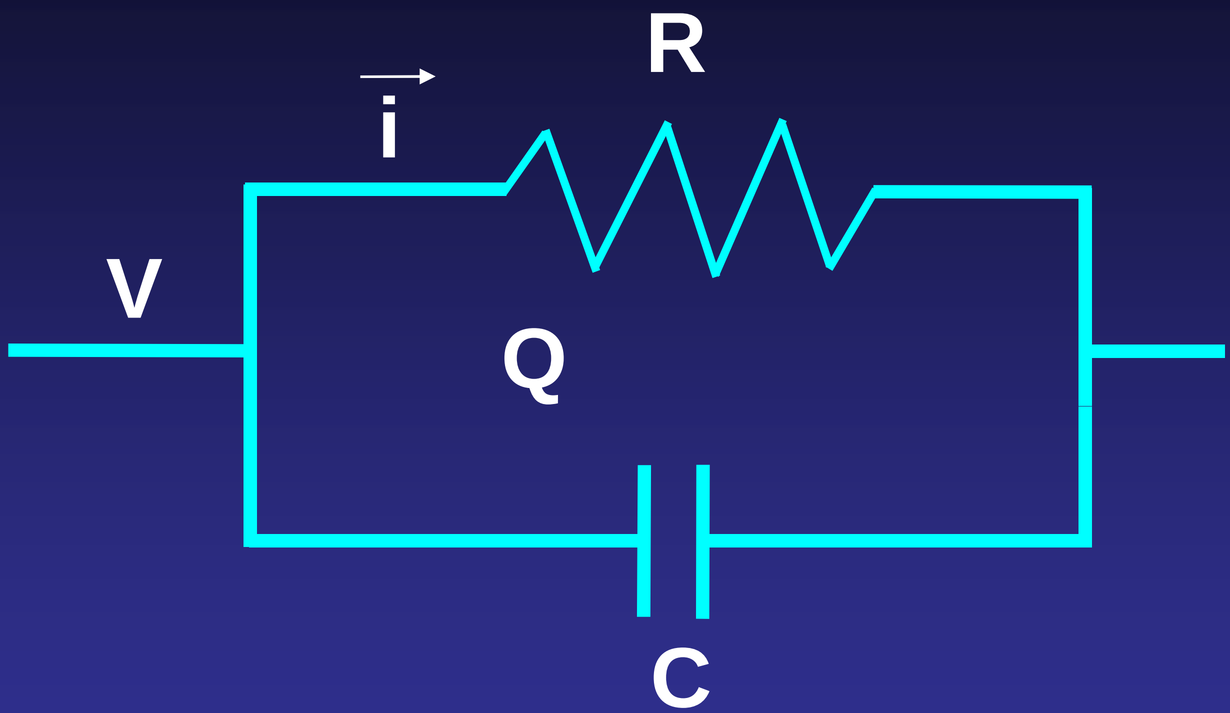

Compliant vessel
Non-compliant vessel


Compliant vessel
Non-compliant vessel



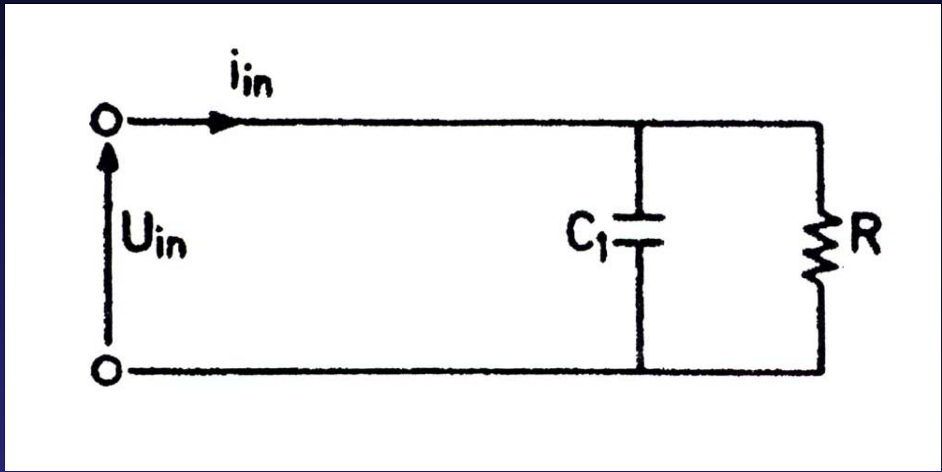
$$C_p = \frac{t}{R_p \bullet \log\,(P_0/P_t)}$$

Windkessel Model for steady flow



$V = iR \quad Q = VC = iRC \quad C = \frac{Q}{iR}$

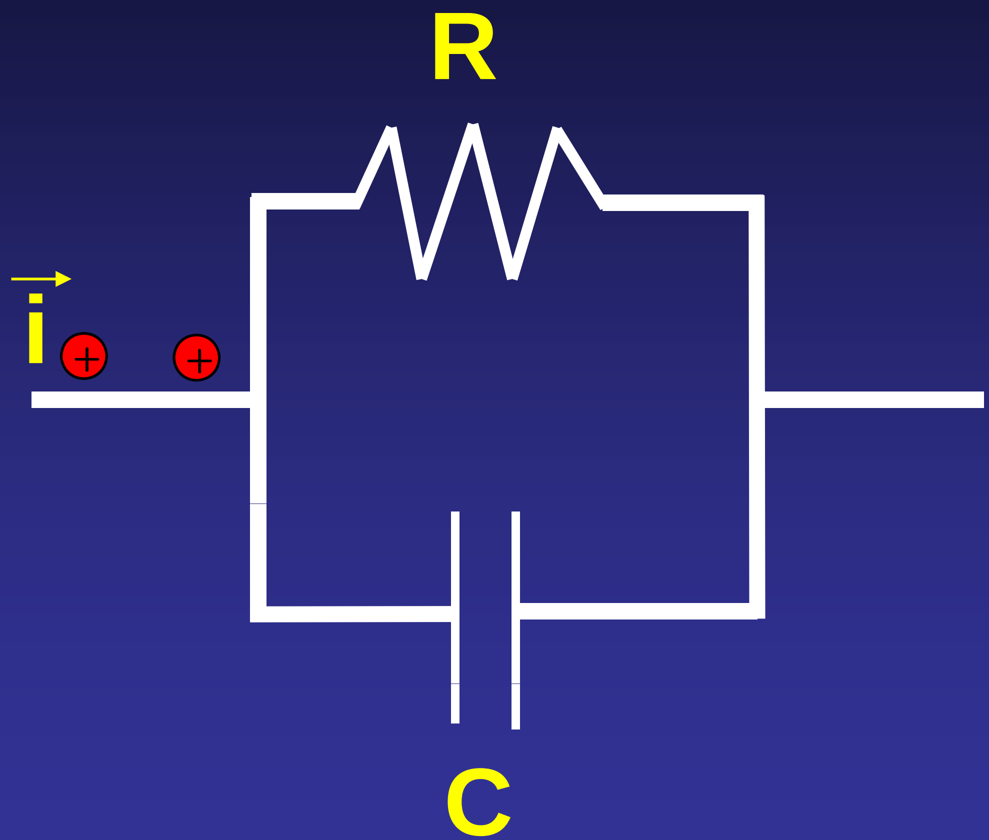
Windkessel model for Pulmonary Circulation

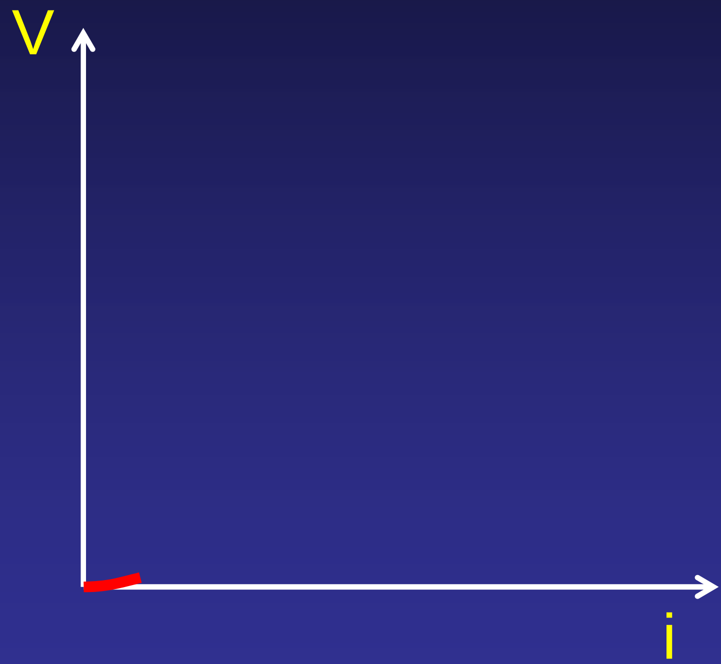


Best fit for Fontan hemodynamics !

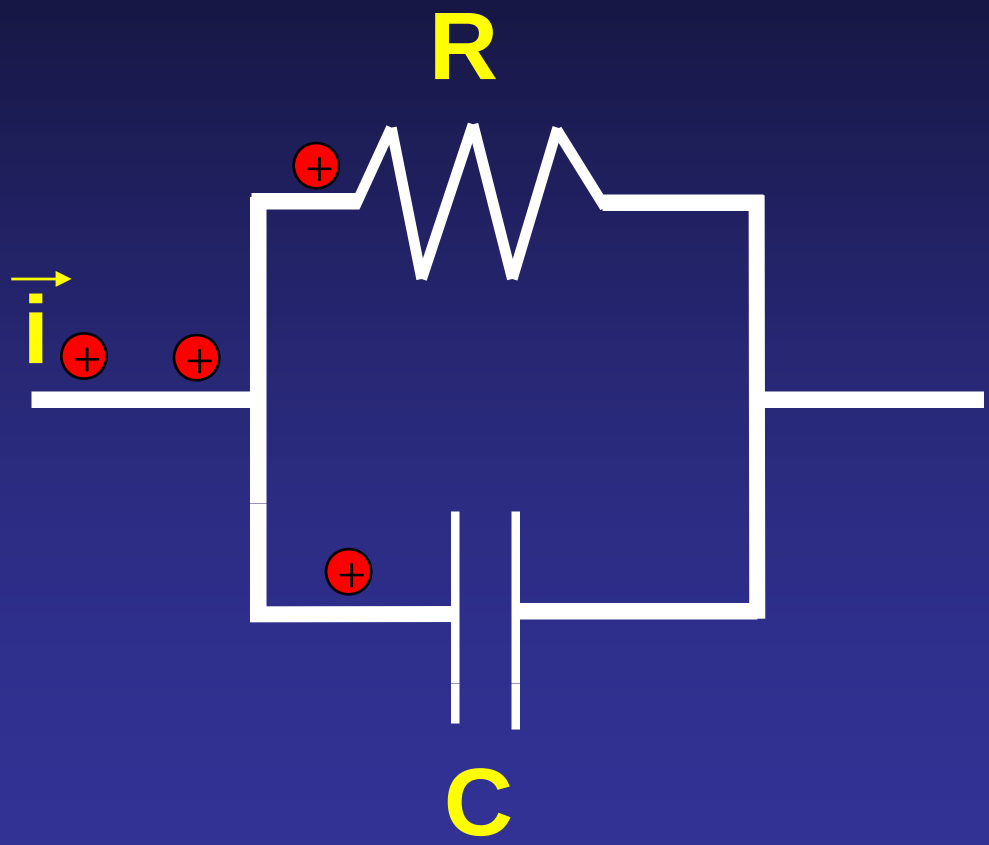
- Pulmonary circulation is simple (PA-lung-PV)
- Single organ: Uniform vascular bed
- Pulmonary vasculature is highly compliant
- Fontan: Non-pulsatile steady flow hemodynamics

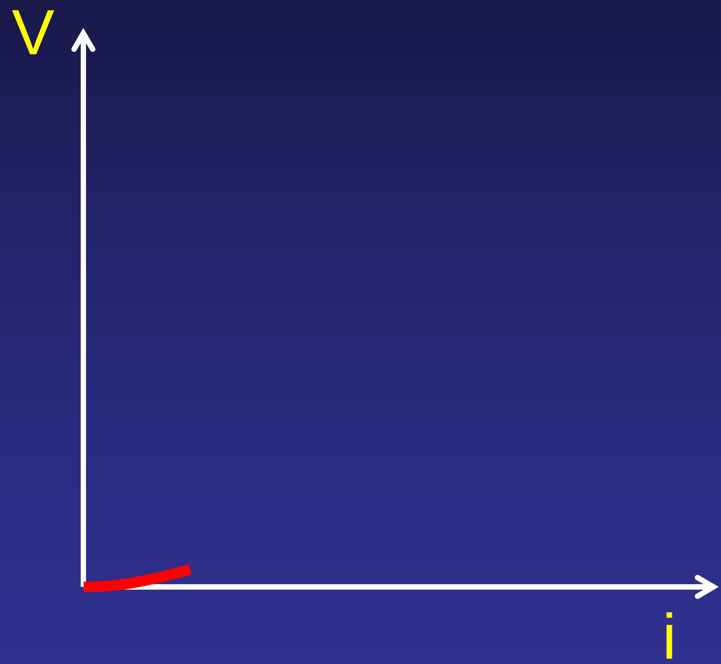
Windkessel model



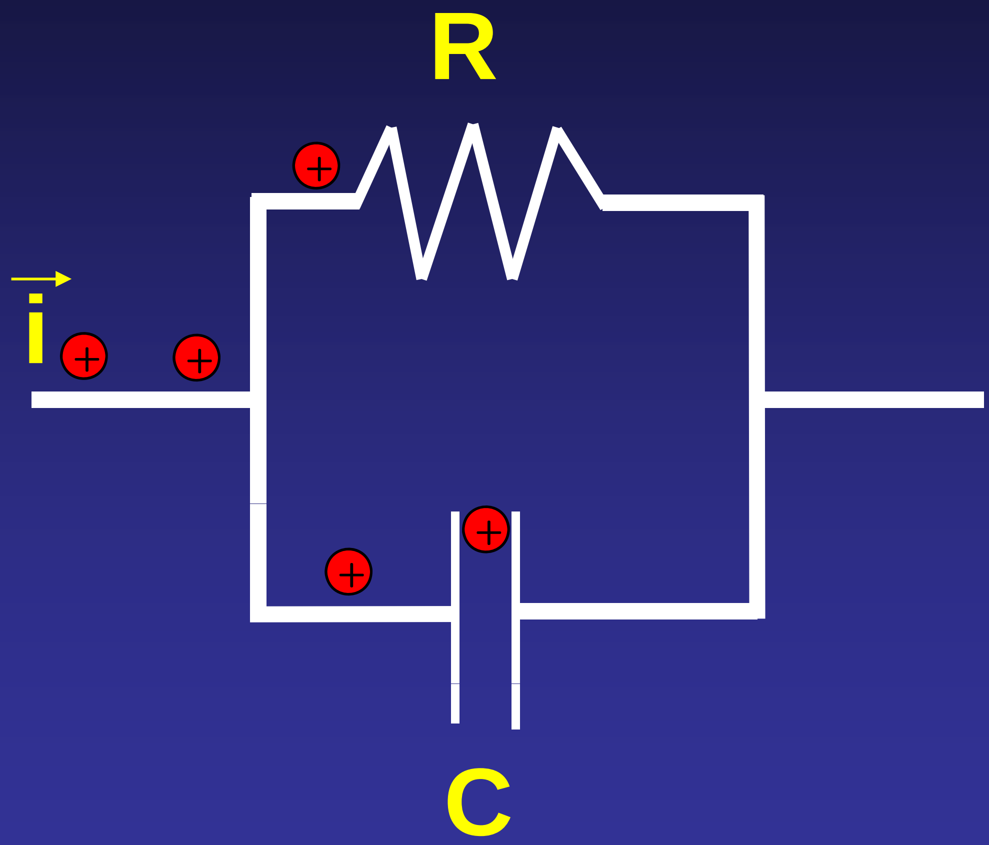


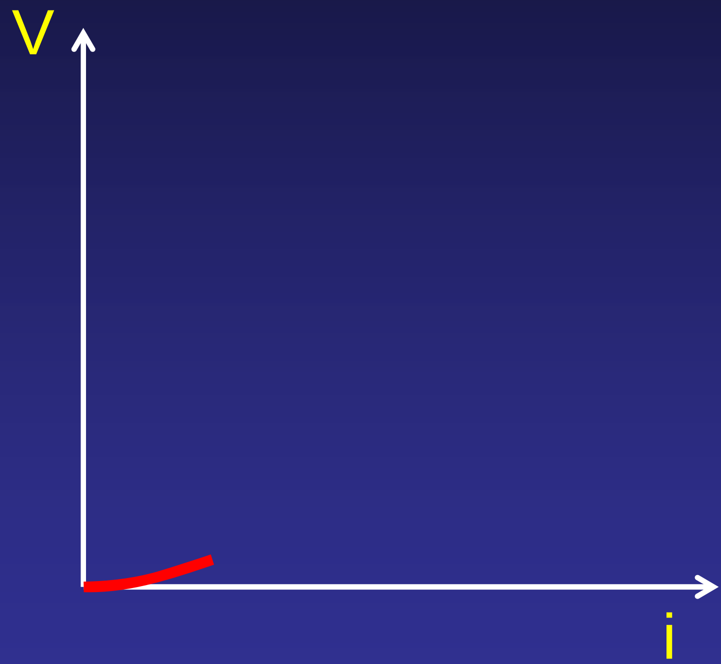
Windkessel model



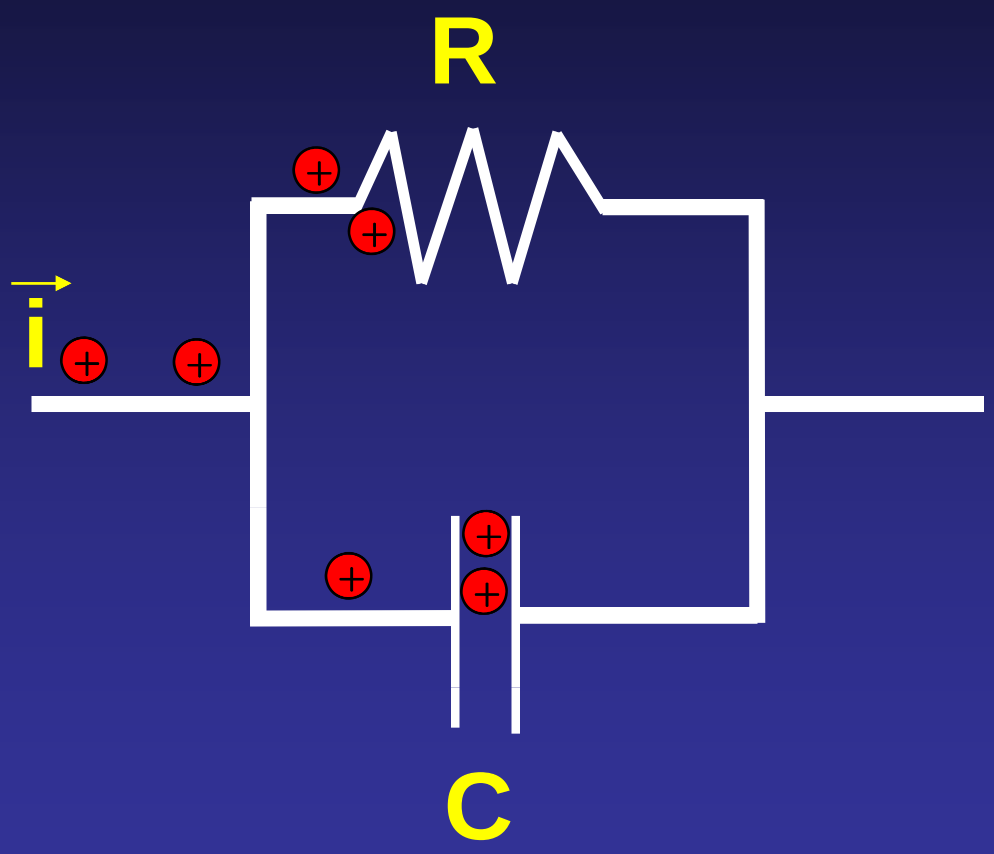


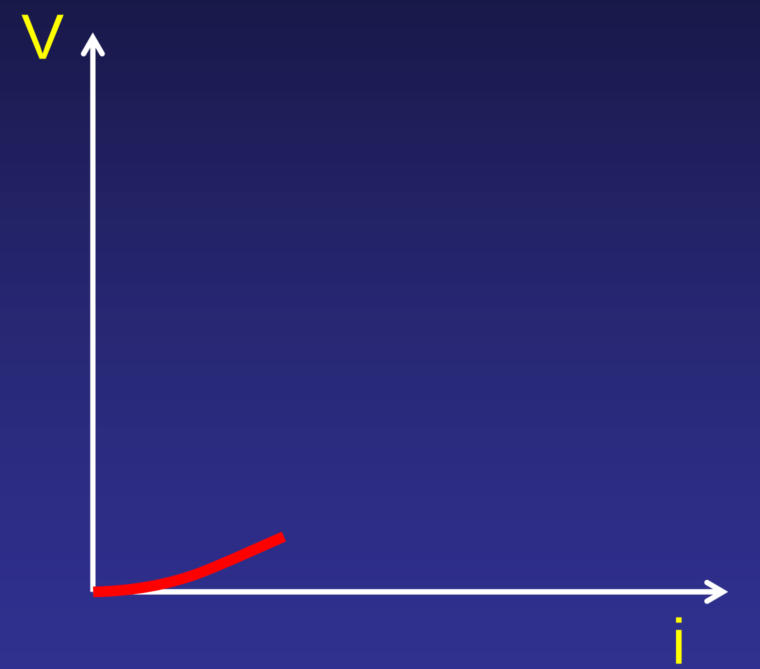
Windkessel model



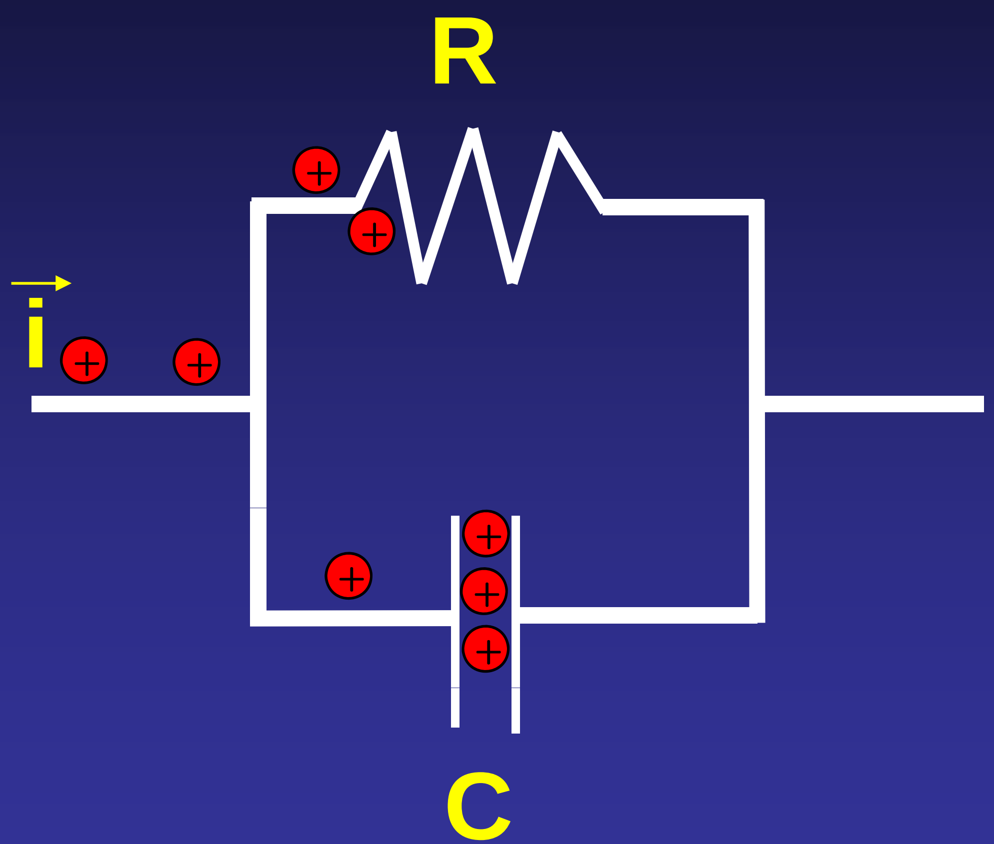


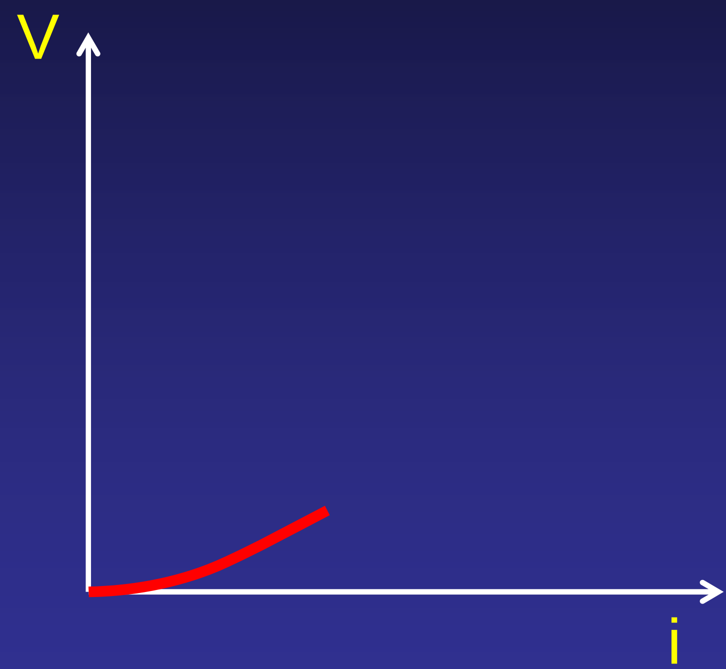
Windkessel model



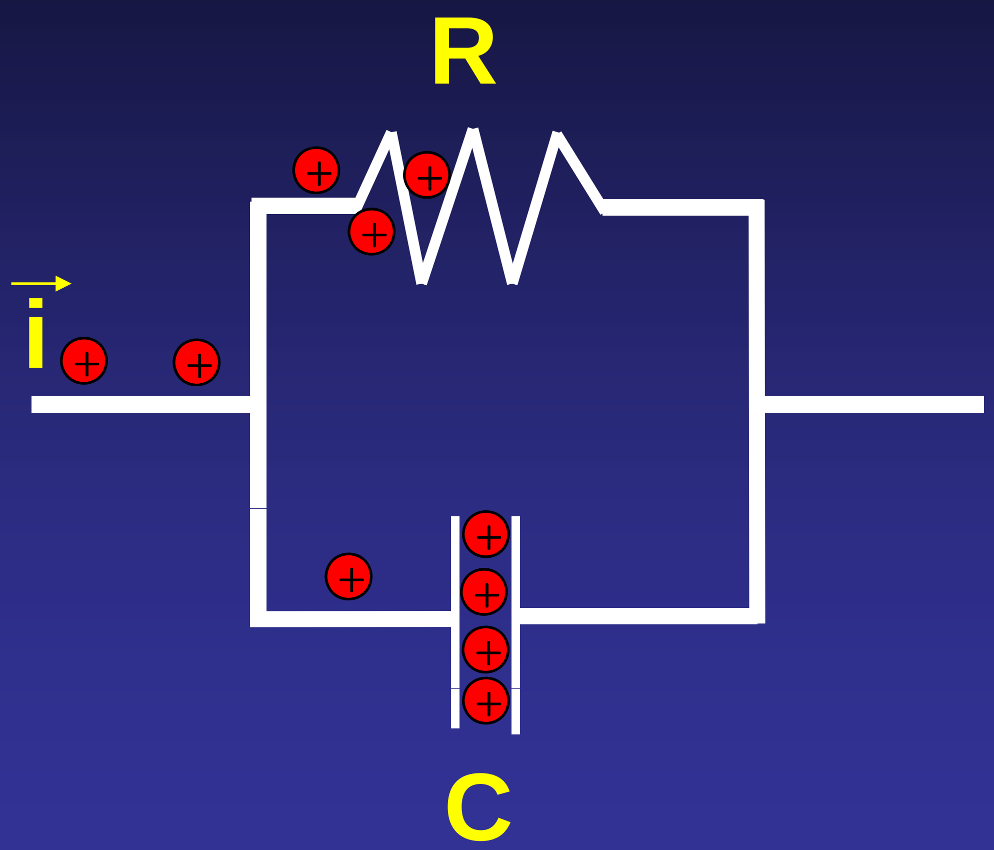


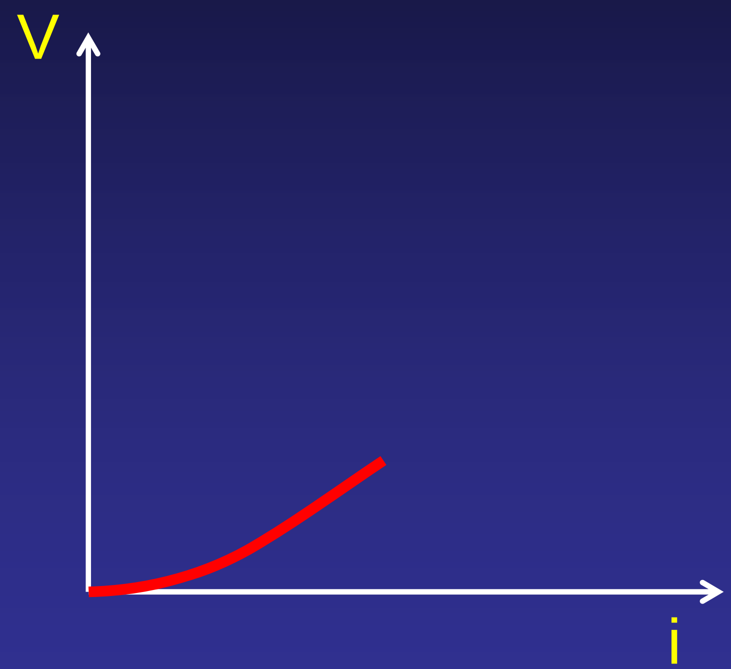
Windkessel model



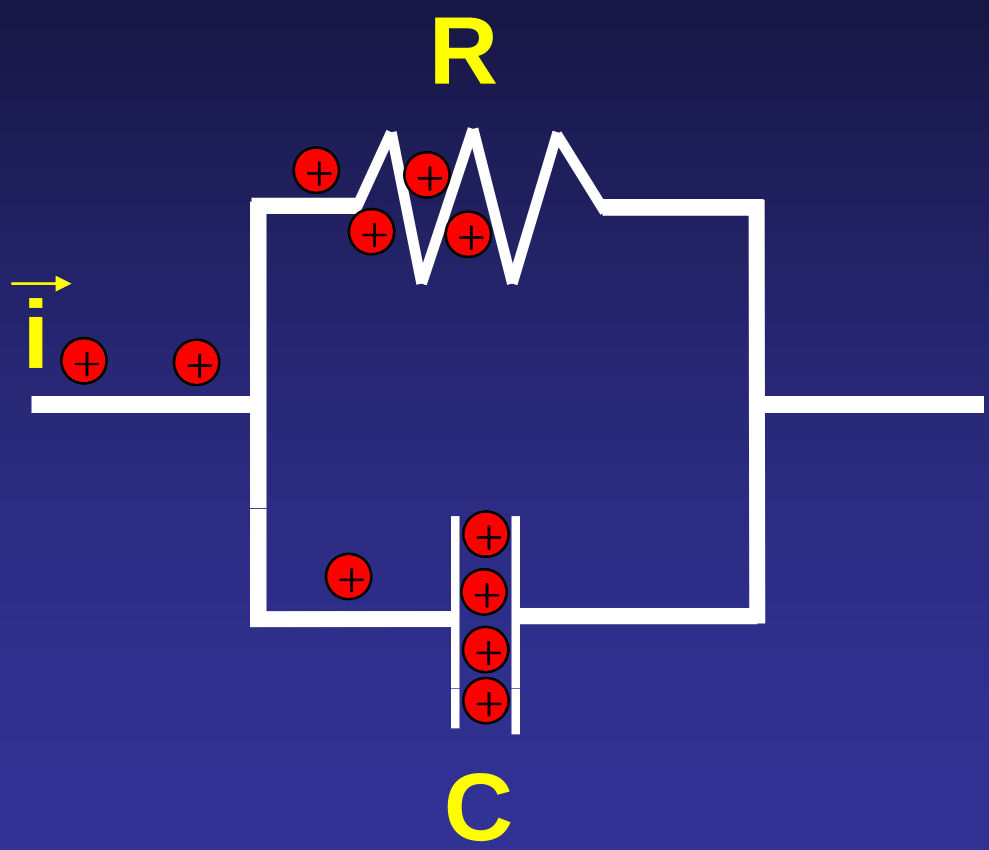


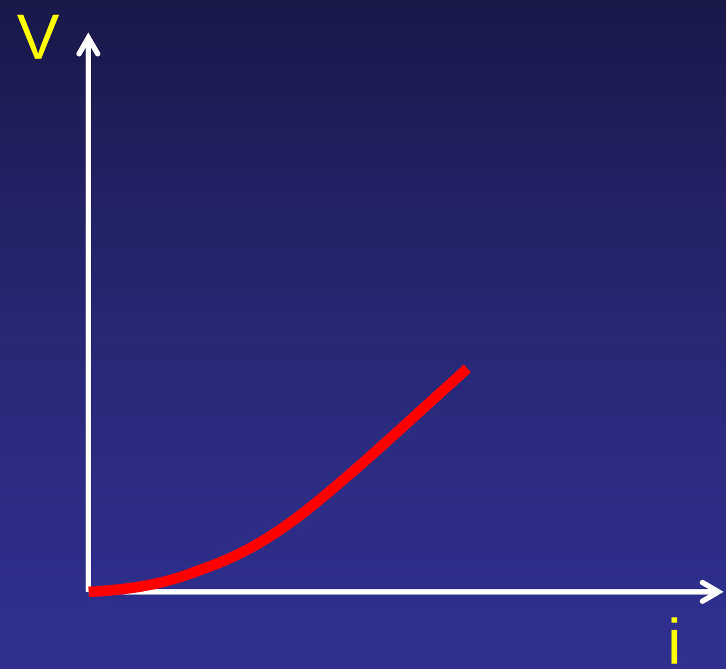
Windkessel model



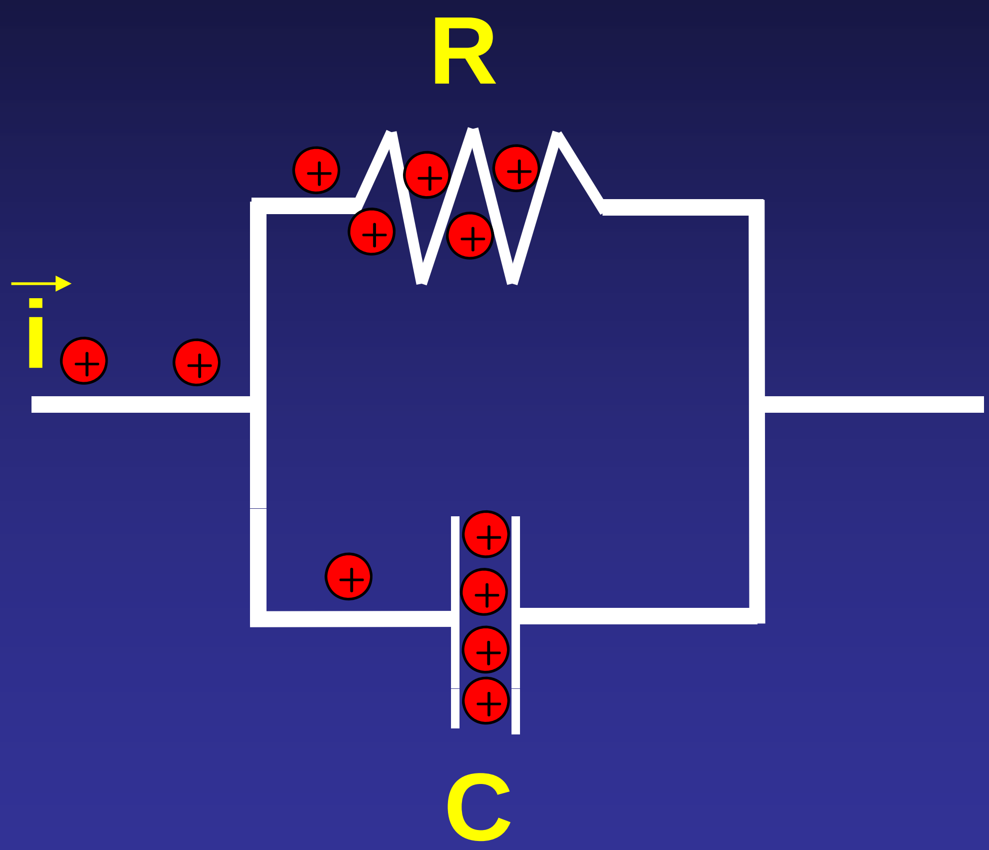


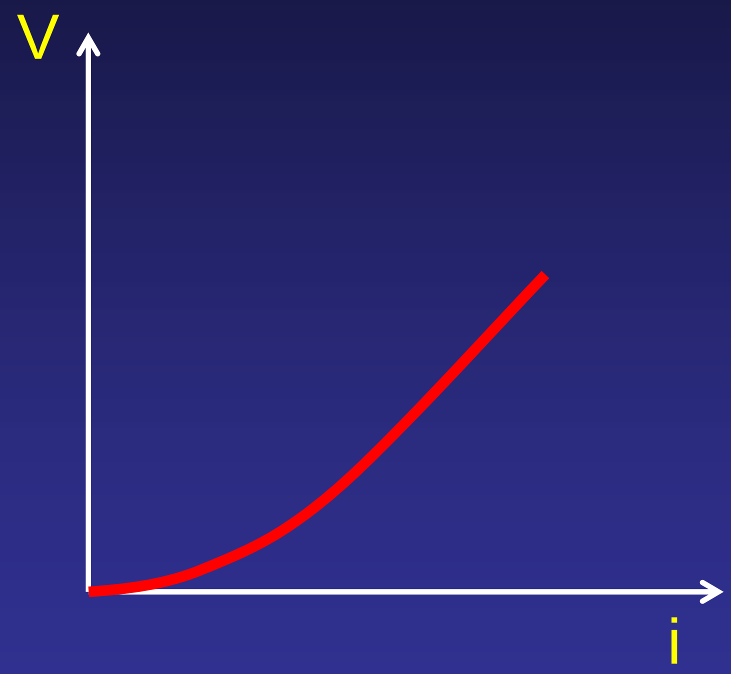
Windkessel model



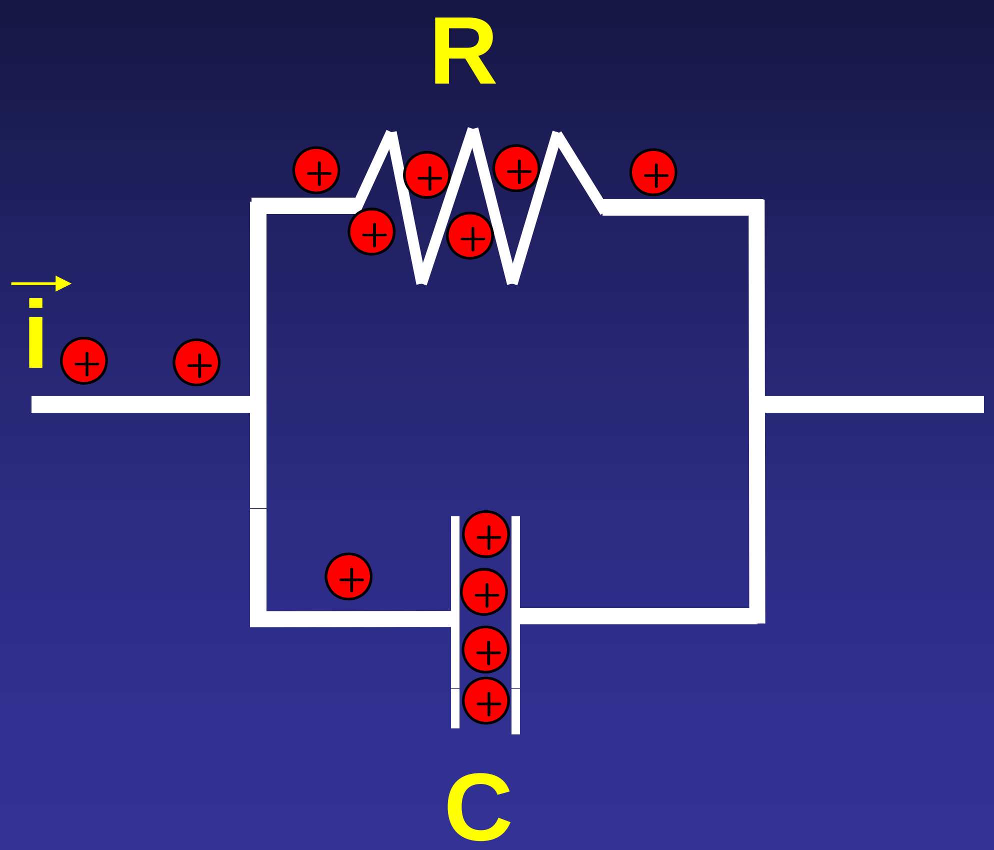


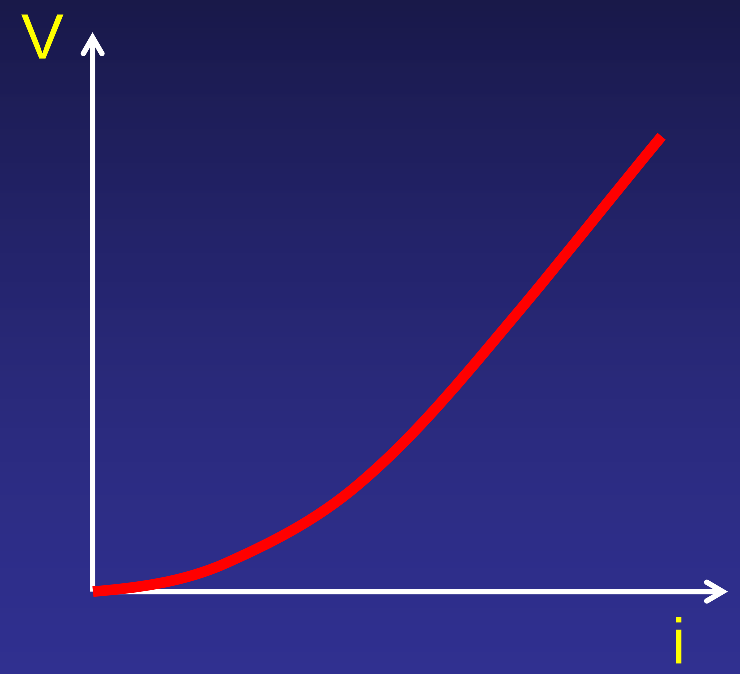
Windkessel model



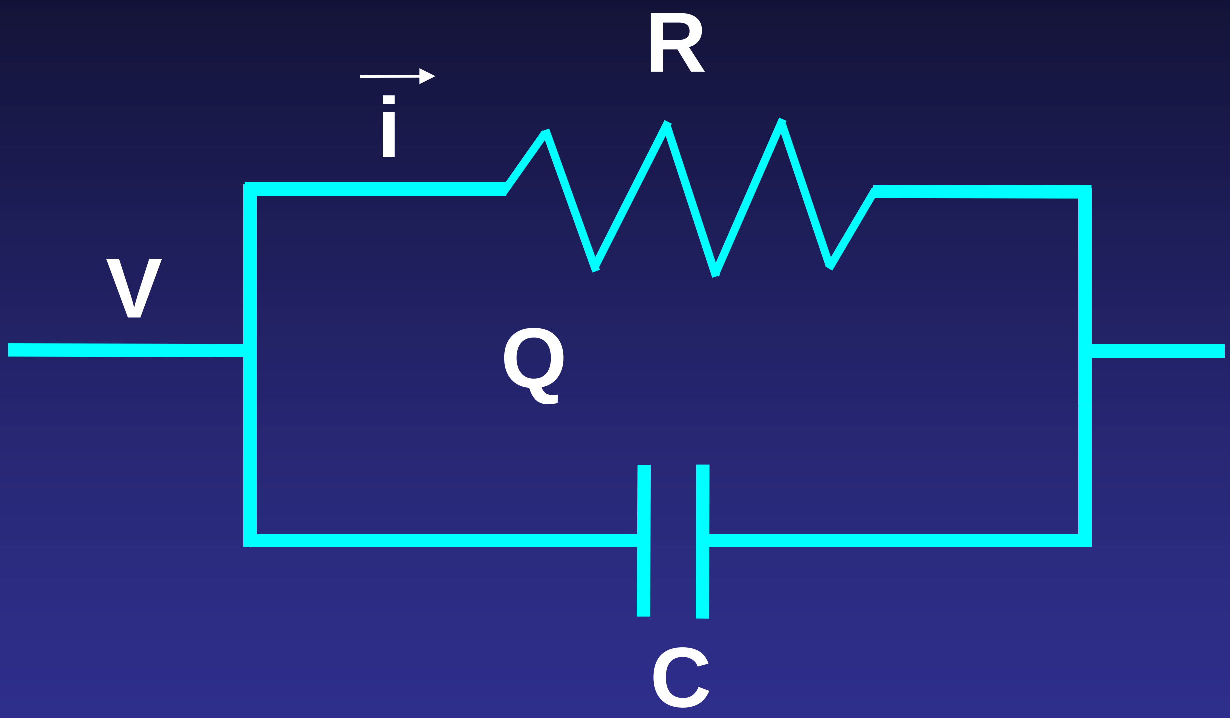


Windkessel model



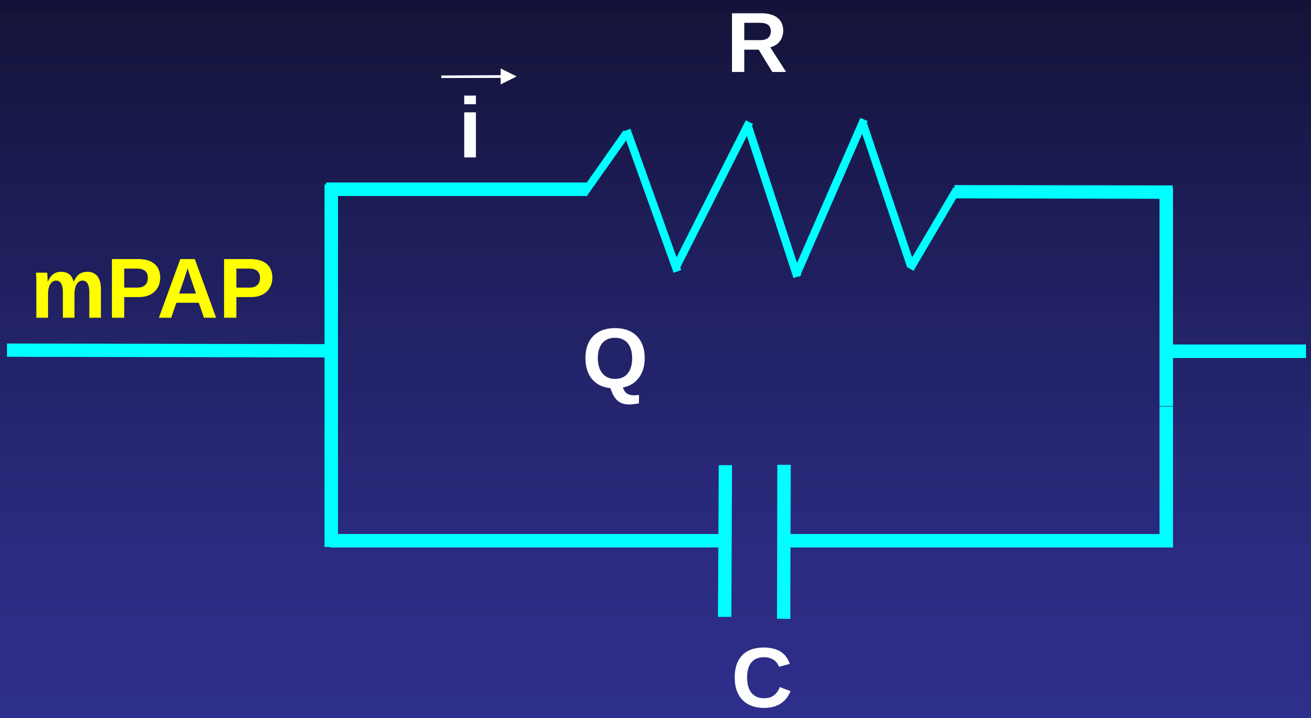


PVC from windkessel Model



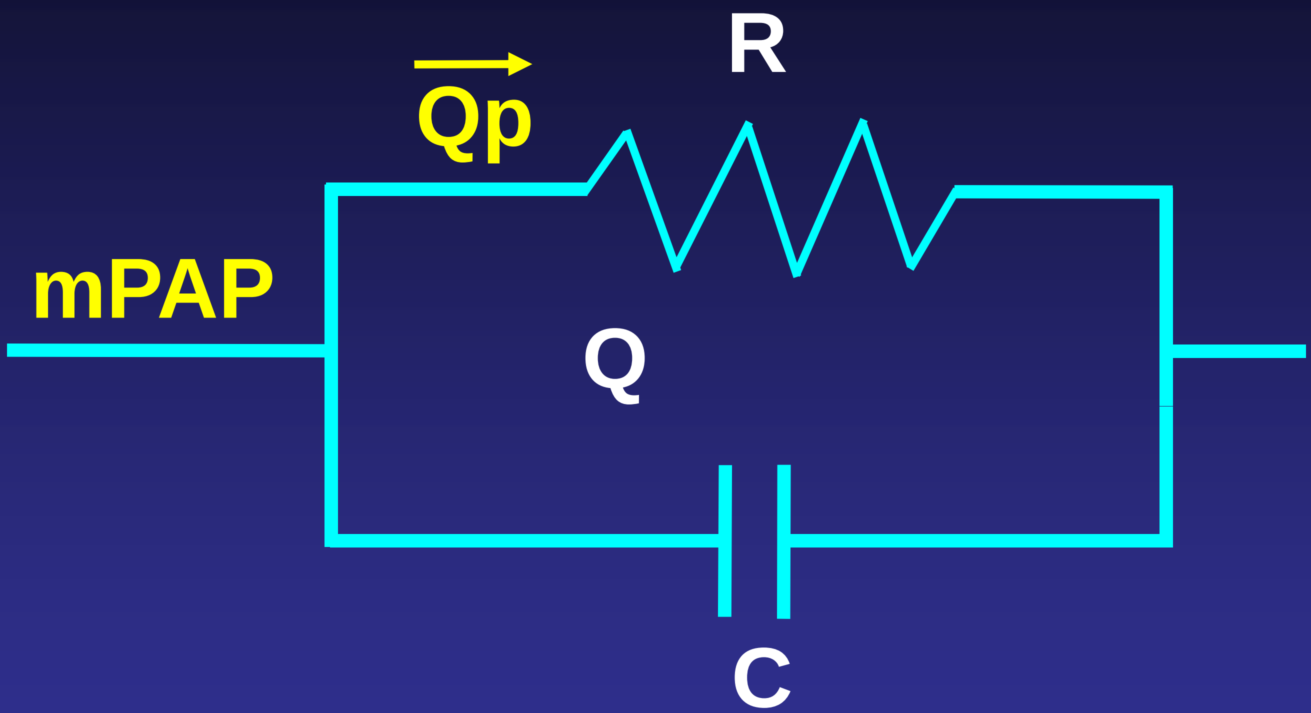
$V = iR \quad Q = VC = iRC \quad C = \frac{Q}{iR}$

PVC from windkessel model



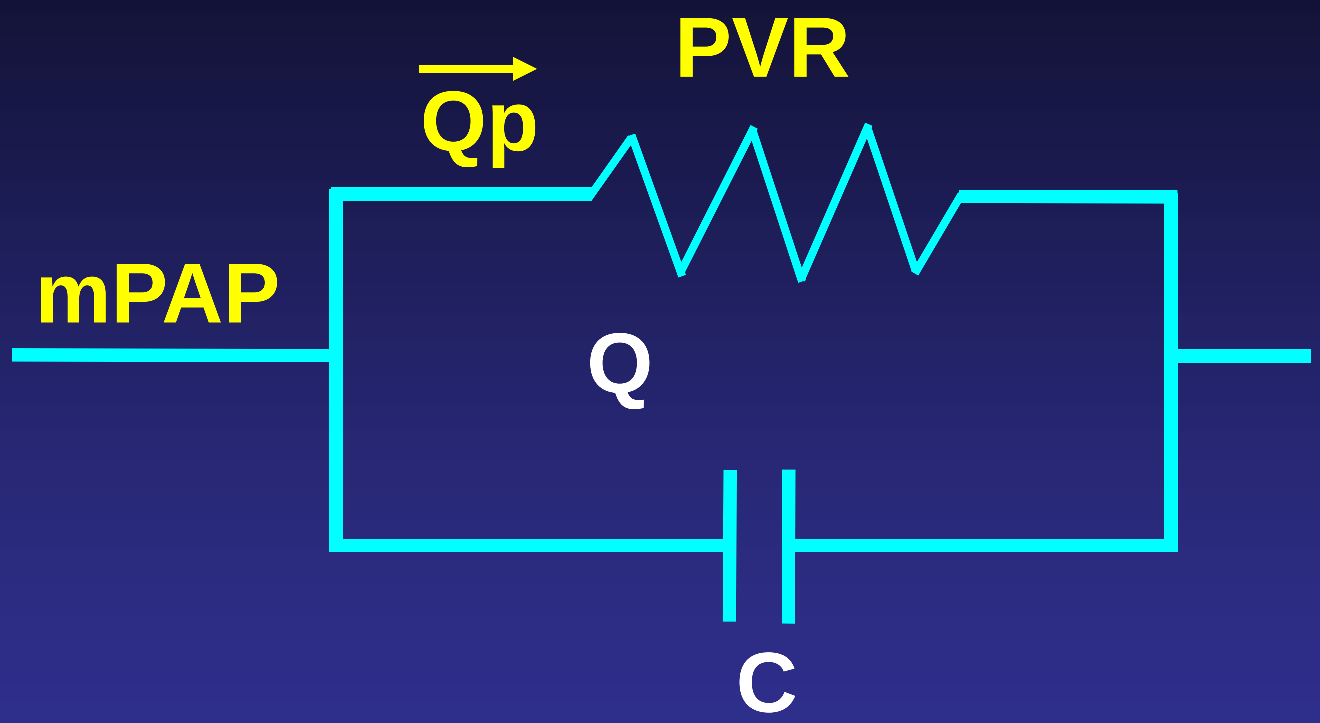
$V = iR \quad Q = VC = iRC \quad C = \dfrac{Q}{iR}$

PVC from windkessel model



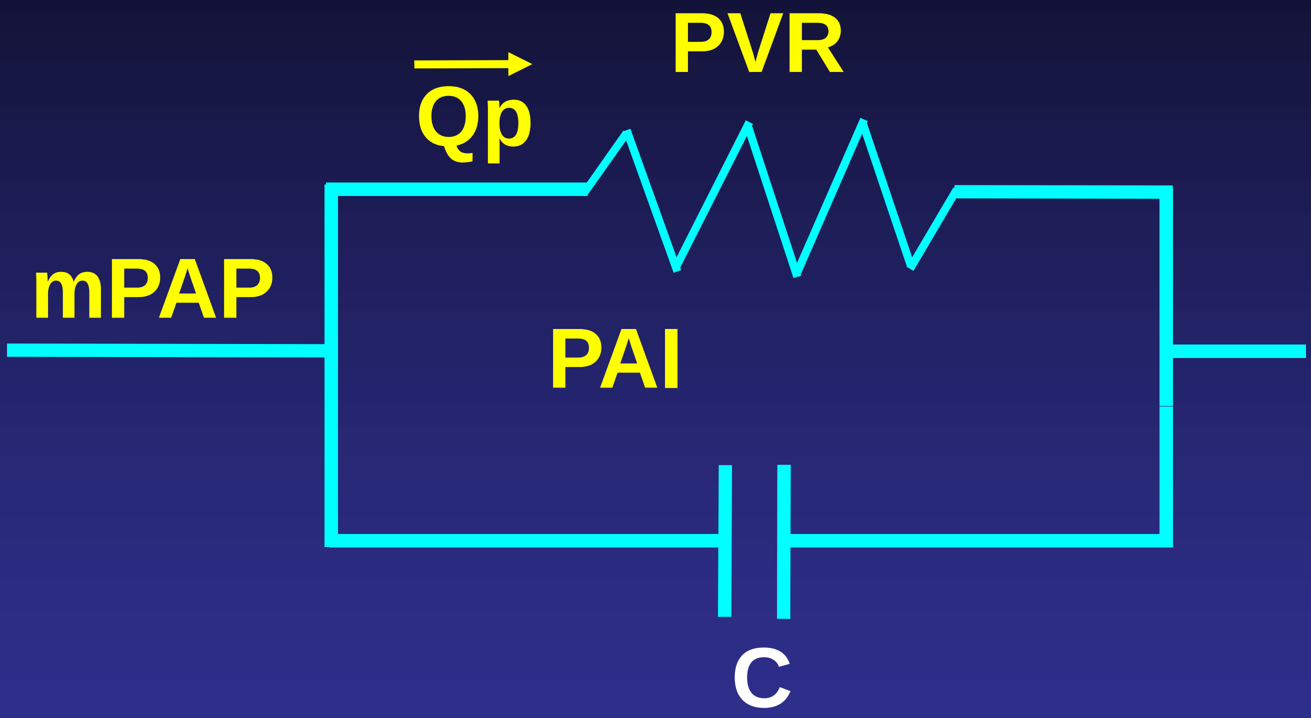
$$V = iR \qquad Q = VC = iRC \qquad C = \frac{Q}{iR}$$

PVC from windkessel model



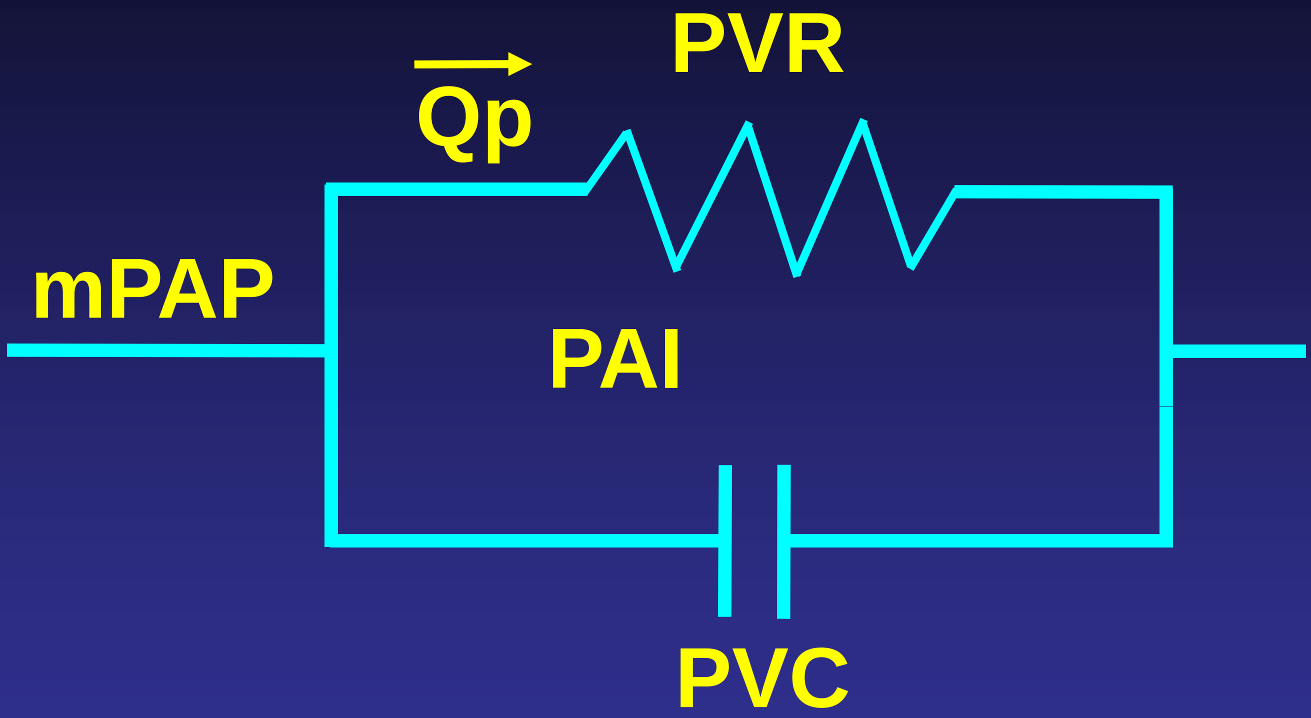
$V = iR \quad Q = VC = iRC \quad C = \dfrac{Q}{iR}$

PVC from windkessel model



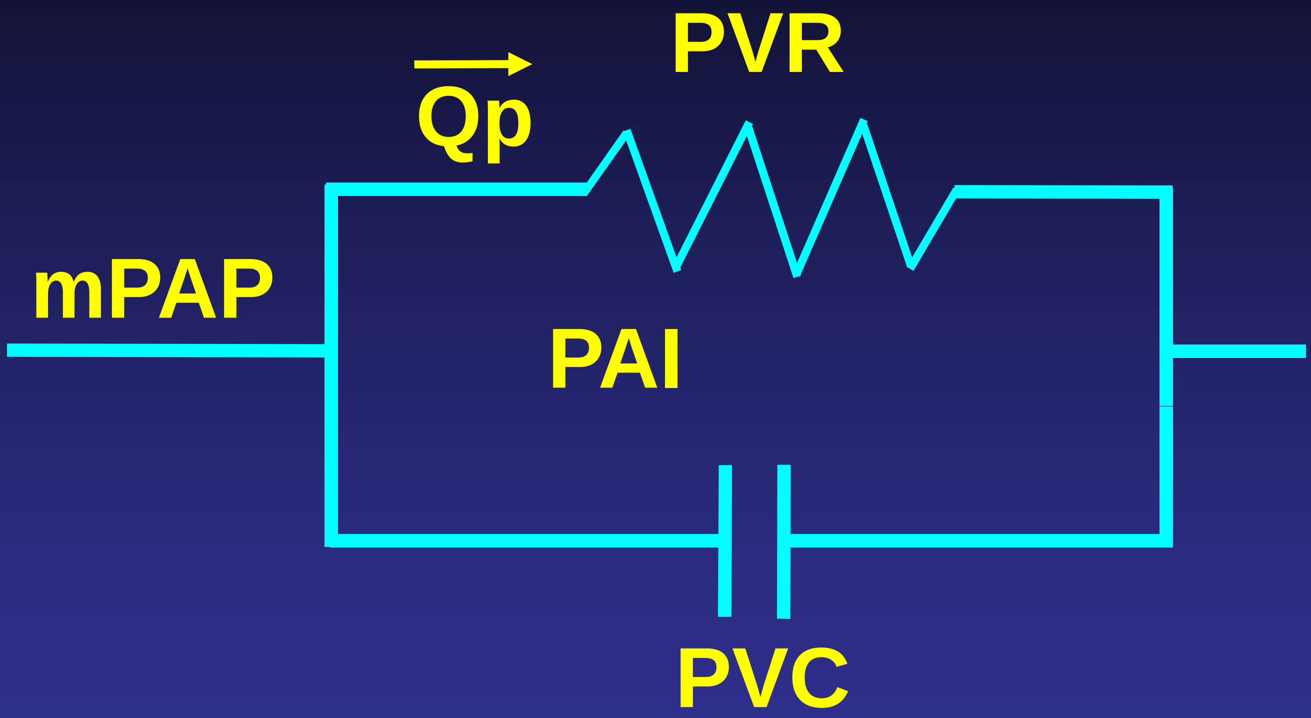
$V = iR \quad Q = VC = iRC \quad C = \frac{Q}{iR}$

PVC from windkessel model



$$V = iR \quad Q = VC = iRC \quad C = \frac{Q}{iR}$$

PVC from windkessel model



$$PVC = \frac{PAI}{Qp * PVR}$$

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Pulmonary vascular compliance and pleural effusion duration after the Fontan procedure

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Abstract

Background: Preoperative risk analysis for Fontan candidates is still less than optimal in that patients with apparently low risks may have a poor outcome, such as prolonged pleural drainage, protein-losing enteropathy, pulmonary thromboembolism and death. We hypothesized that low pulmonary vascular compliance (PVC) is a risk factor for persistent pleural effusion after the Fontan operation.
Methods: A retrospective review of 85 patients who underwent the extracardiac Fontan procedures (median age: 3.87 years) was performed. Fontan risk score (FRS) was calculated from 12 categorized preoperative anatomical and physiological variables. PVC ($mm^2/m^2 \cdot mmHg$) was defined as pulmonary artery index (mm^2/m^2) divided by total pulmonary resistance ($Wood\ Unit \cdot m^2$) and pulmonary blood flow ($L/min/m^2$), based on the electrical circuit analogy of the pulmonary circulation. Chest tube indwelling time was log-transformed (log indwelling time, LIT) to fit normal distribution, and the relationship between perioperative predictors and LIT was analyzed by multiple linear regression.
Results: Preoperative PVC, chest tube indwelling time and LIT ranged from 6 to 94.8 $mm^2/mmHg/m^2$ (median: 24.8), 3 to 268 days (median: 20 days), and 1.1 to 5.6 (mean: 2.9, standard deviation: 0.8), respectively. FRS, PVC, cardiopulmonary bypass time (CPB) and central venous pressure at postoperative 12 h were correlated with LIT by univariable analyses. By multiple linear regression, PVC ($p = 0.002$) and CPB ($p = 0.003$) independently predicted LIT, explaining 22% of the variation. The regression equation was $LIT = 2.744 - 0.016\,PVC + 0.007\,CPB$. Conclusion: Low pulmonary vascular compliance is an important risk factor for prolonged pleural effusion drainage after the extracardiac Fontan procedure.

Keywords: Fontan; Pleural effusion; Pulmonary vascular resistance; Pulmonary vascular compliance

Patients and methods (1)

- Single institution (AMC)
- Duration: Jan 2002 – Jun 2005
- 85 consecutive patients with ECC Fontan
  - ECC Fontan Op as a primary procedure
  - Exclusion of ECC Fontan revision
- Fenestration : 1/85
- F/U : 99% complete
- Early death: 0 / 85
- Late death: 4 / 85 (4.7%)

Patients and methods (2)

- **Outcome variable**

  Chest tube indwelling days

  Log transformation (log indwelling time, LIT)

- **Preoperative risk factors**

  1. Fontan risk score
  2. Pulmonary vasucular compliance (PVC)
  3. Miscellaneous

     Age at op, PA size (PAI), mPAP, PVR, Palliative op, AV valve regurgitation, Ventricular morphology, Ventricular function.

Patients a

Factor/score	0	1	2	3
1. Age(months)	>12	6-12		< 6
2. Ventricle	LV	RV		
3. Syst outflow obst		(+)		
4. PV obst			(+)	
5. PA hypoplasia	(-)	Mild	Moderate	Severe
McGoon ratio	>2	1.8-2.0	1.5-1.8	<1.5
Nakada index	>200	100-200	50-100	<50
Diameter(z)	-2 to +2	-2 to –3	-3 to –4	<-4
6. Mean PAP	<15	15-20	20-25	>25
7. PABS or distortion	(-)	disc-sing	disc-multi	diffuse
8. Rp unit	<2	2-3	3-4	>4
9. AVV regurg	(-)	Mild	Moderate	Severe
10. V syst dysfun	(-)	Mild	Moderate	Severe
EF(%)	>55	55-45	45-40	<40
SF(%)	>32	31-28	27-24	<231
11. V diast dysf				
VEDP(mmHg)	<10	10-12	12-14	>14
12. V hypertrophy	nl	Mild	Moderate	severe
mass(echo)	-2 to +2	-2 to -3	-3 to –4	<-4

* Fontan risk score : 0-3 (low risk), 4-5 (moderate risk), ≥6 or one item ≥3 (high risk)

- **Outcome variab**

  Chest tube indwell

  Log transformatio

- **Preoperative risk factors**

  1. Fontan risk score

  2. Pulmonary vasucular compliance (PVC)

  3. Miscellaneous

     Age at op, PA size (PAI), mPAP, PVR, Palliative op, AV valve regurgitation, Ventricular morphology, Ventricular function.

Patients and methods (2)

$$PVC = \frac{PAI}{Qp * PVR}$$

- **Outcome variable**

  Chest tube indwelling day

  Log transformation (log in ling time, LIT)

- **Preoperative risk fact s**

  1. Fontan risk score
  2. ***Pulmonary vasucular compliance (PVC)***
  3. Miscellaneous

     Age at op, PA size (PAI), mPAP, PVR, Palliative op, AV valve regurgitation, Ventricular morphology, Ventricular function.

Patients and methods (2)

- **Outcome variable**

  Chest tube indwelling days

  Log transformation (log indwelling time, LIT)

- **Preoperative risk factors**

  1. Fontan risk score
  2. Pulmonary vasucular compliance (PVC)
  3. ***Miscellaneous***

     Age at op, PA size (PAI), mPAP, PVR, Palliative op, AV valve regurgitation, Ventricular morphology, Ventricular function.

Result (1)

- **C-tube indwelling time: 3-268 d (median: 20 d)**

- **Log indwelling time: 1.1-5.59 (mean: 2.91)**

- **Risk factors for high LIT (Univariable analysis)**
  1. FRS
  2. Pulmonary vascular compliance (PVC)
  3. Cardiopulmonary bypass time (CPB)
  4. CVP at post-op. 12 hours

Result (2)

- **Multiple linear regression**

PVC (*p*=0.0018)

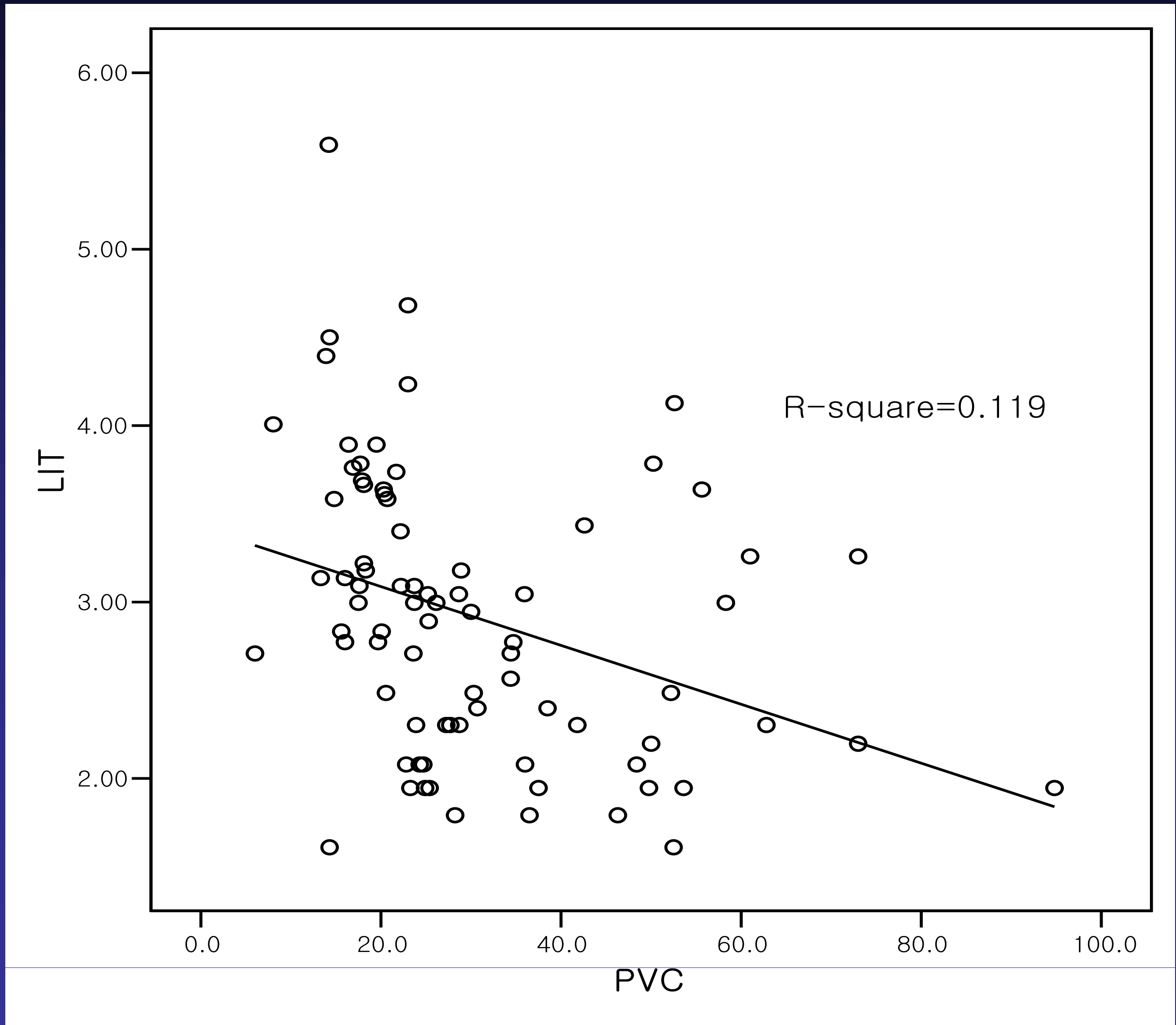
CPB (*p*=0.0024)

Explaining 21.7% of the LIT variation

Regression equation of LIT

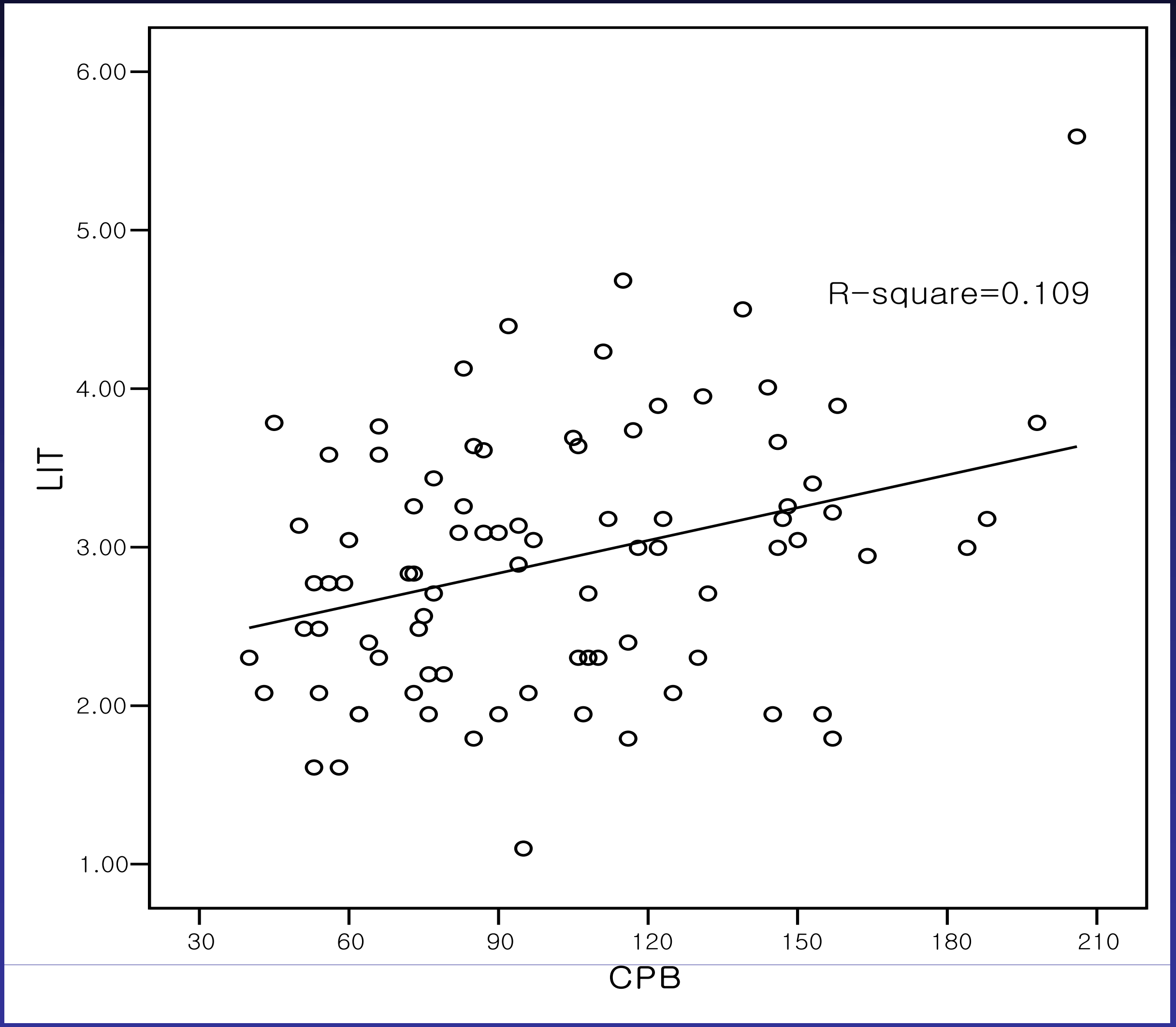
$$LIT = 2.74 - 0.0158 \times PVC + 0.00658 \times CPB$$

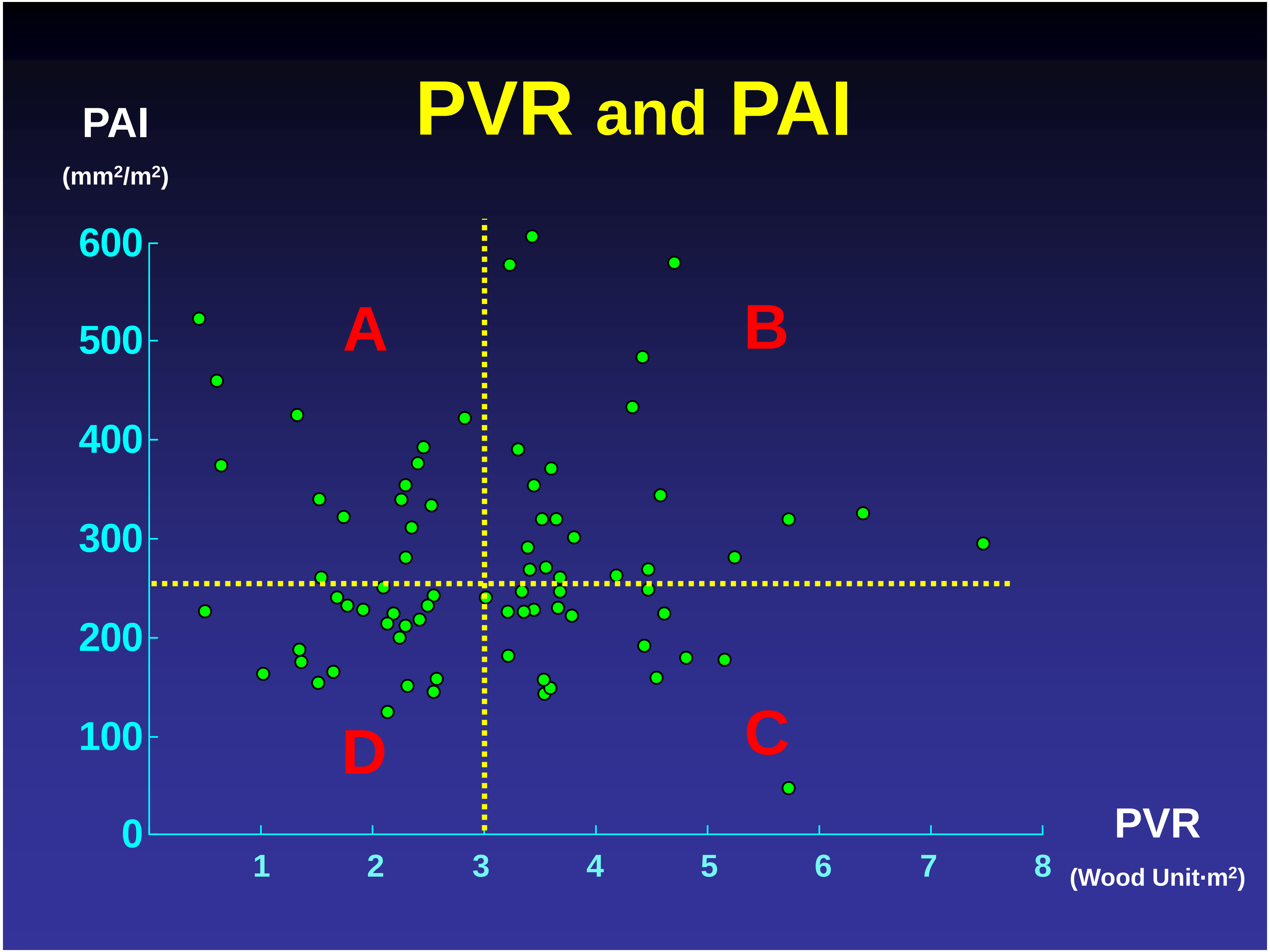
PVC and LIT

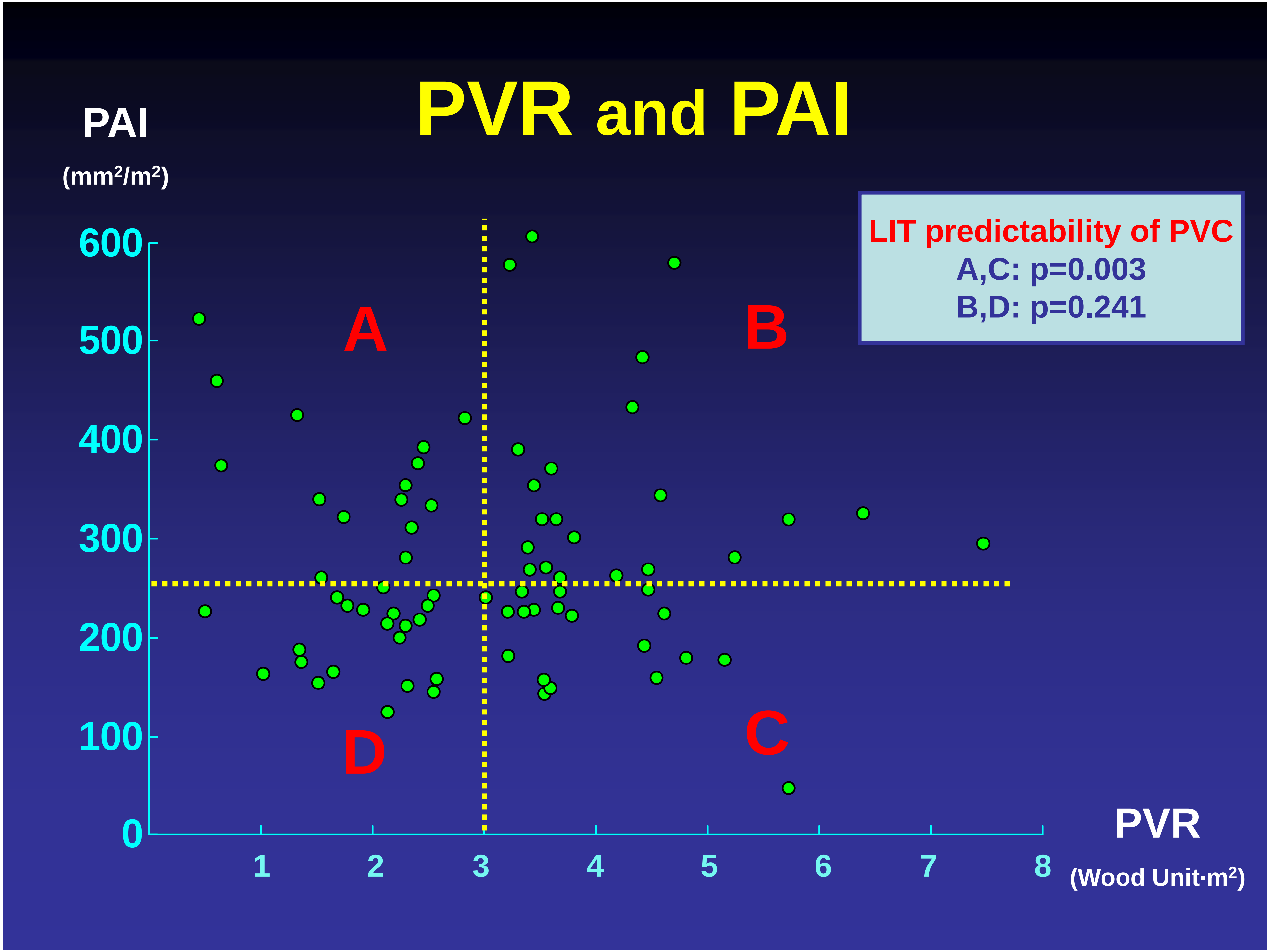


6.00
5.00
4.00
3.00
2.00
LIT
R-square=0.119
0.0
20.0
40.0
60.0
80.0
100.0
PVC

CPB time and LIT



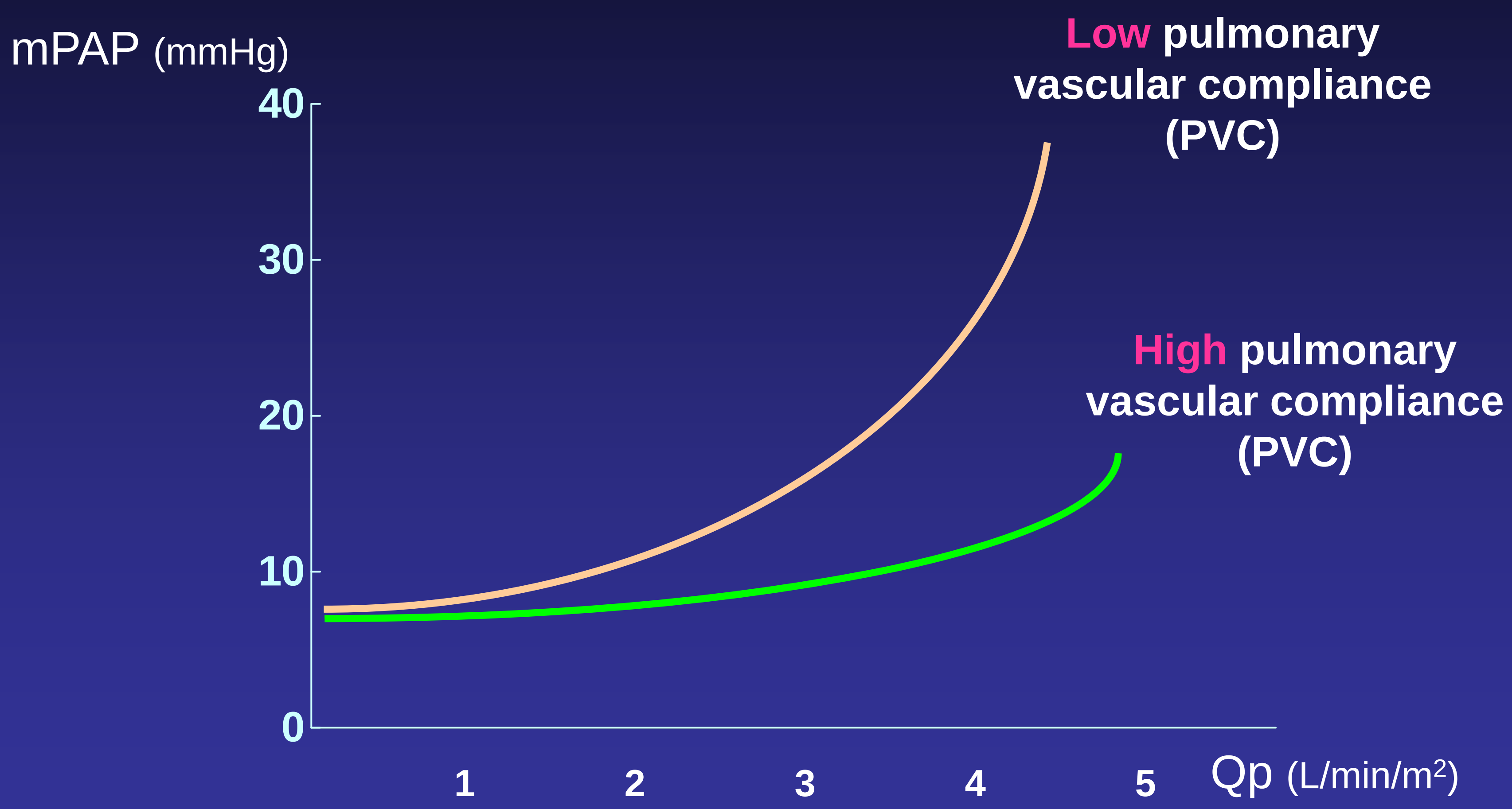

PVR and PAI
PAI
(mm²/m²)
600
500
400
300
200
100
0
A
B
C
D
1
2
3
4
5
6
7
8
PVR
(Wood Unit·m²)


PVR and PAI
PAI
(mm²/m²)
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
PVR
(Wood Unit·m²)
A
B
C
D
LIT predictability of PVC
A,C: p=0.003
B,D: p=0.241

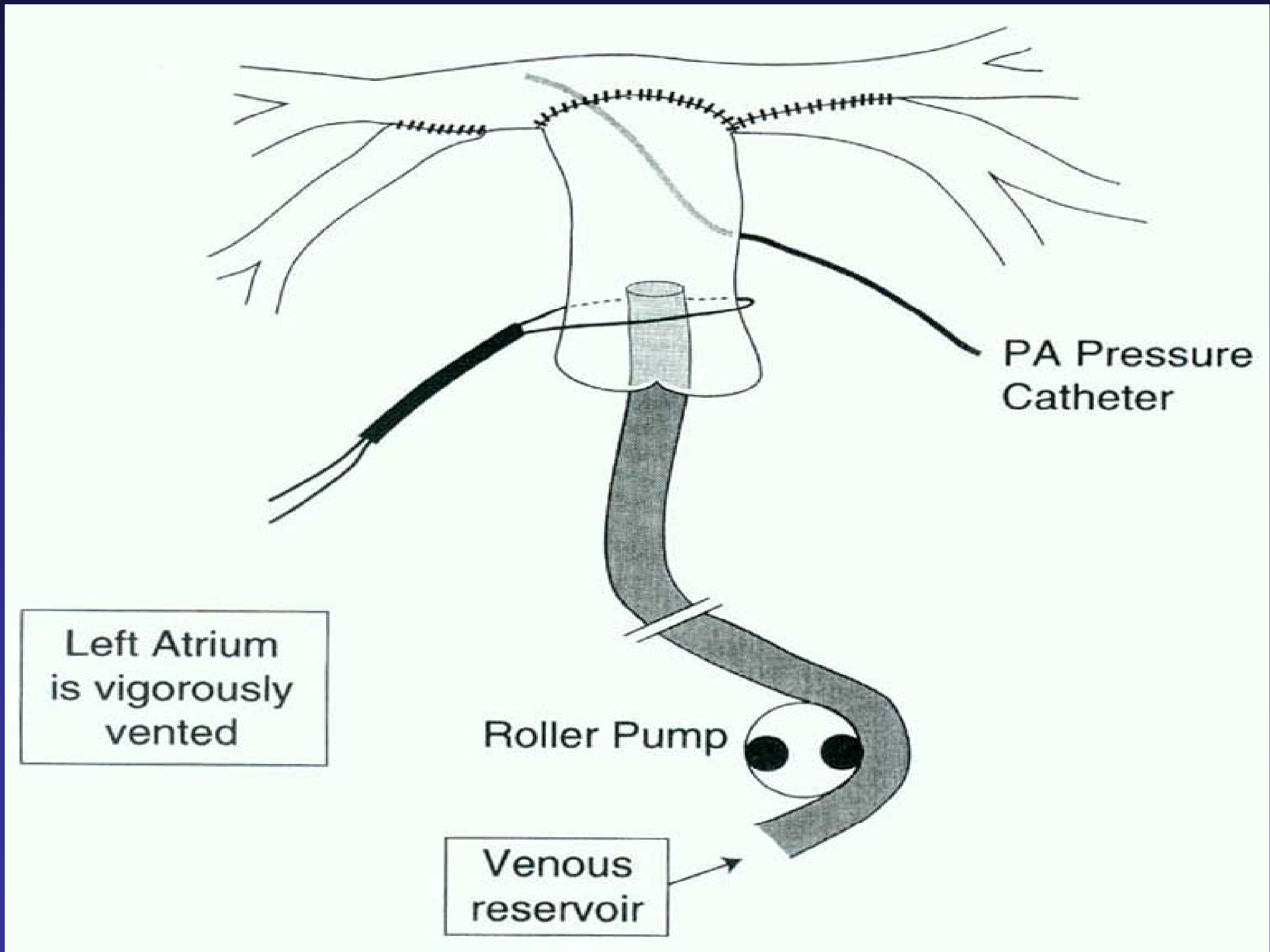
Limitations of the study

- LIT predictability of PVC is low !
- In the windkessel model, assumption of Q (total charge) = PAI may be wrong!

Qp vs. PAP

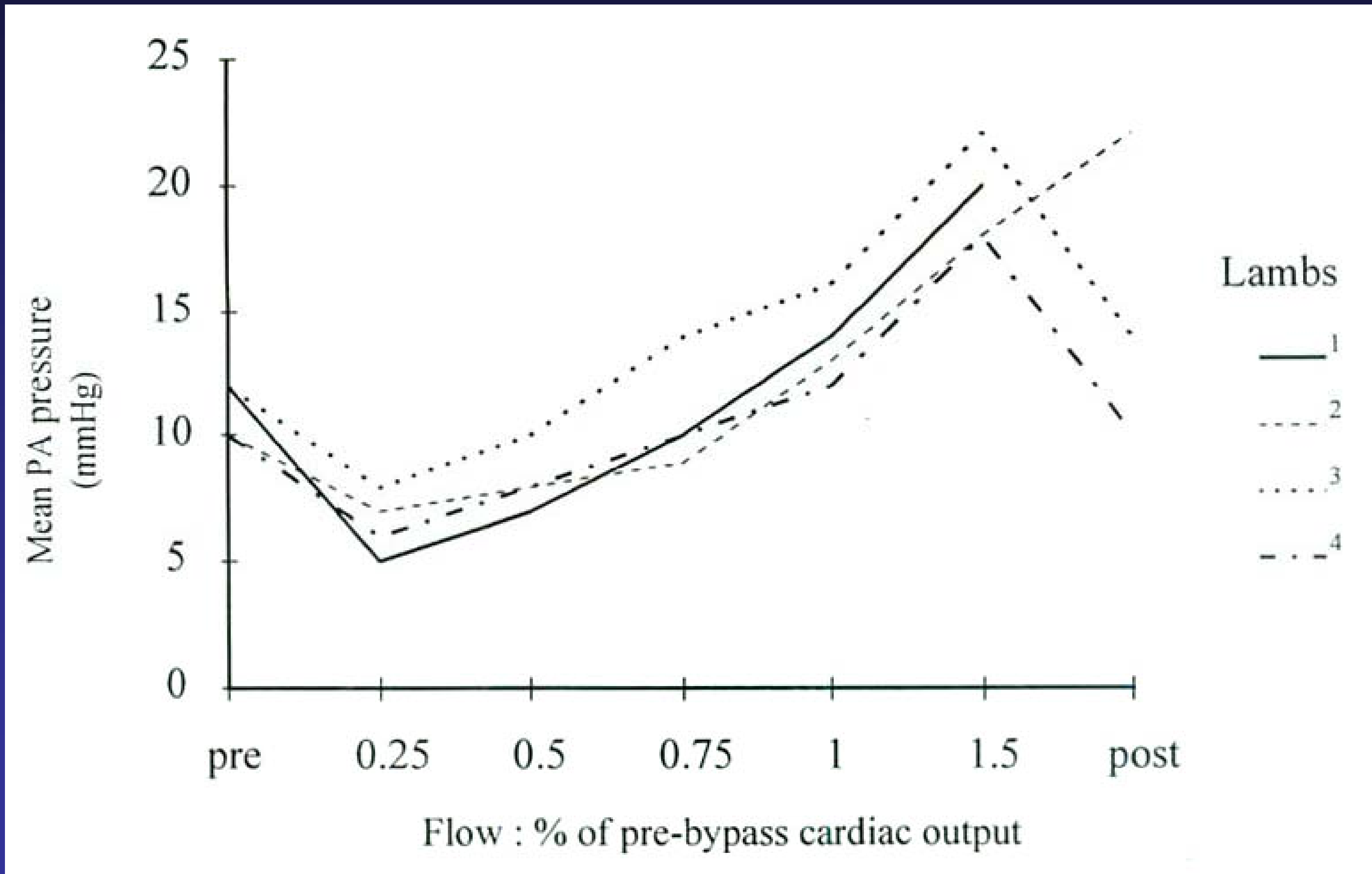

mPAP (mmHg)
40
30
20
10
0
1
2
3
4
5
Qp (L/min/m2)
Low pulmonary vascular compliance (PVC)
High pulmonary vascular compliance (PVC)

Flow study in PA,VSD,MAPCA
(Reddy et al, 1997)

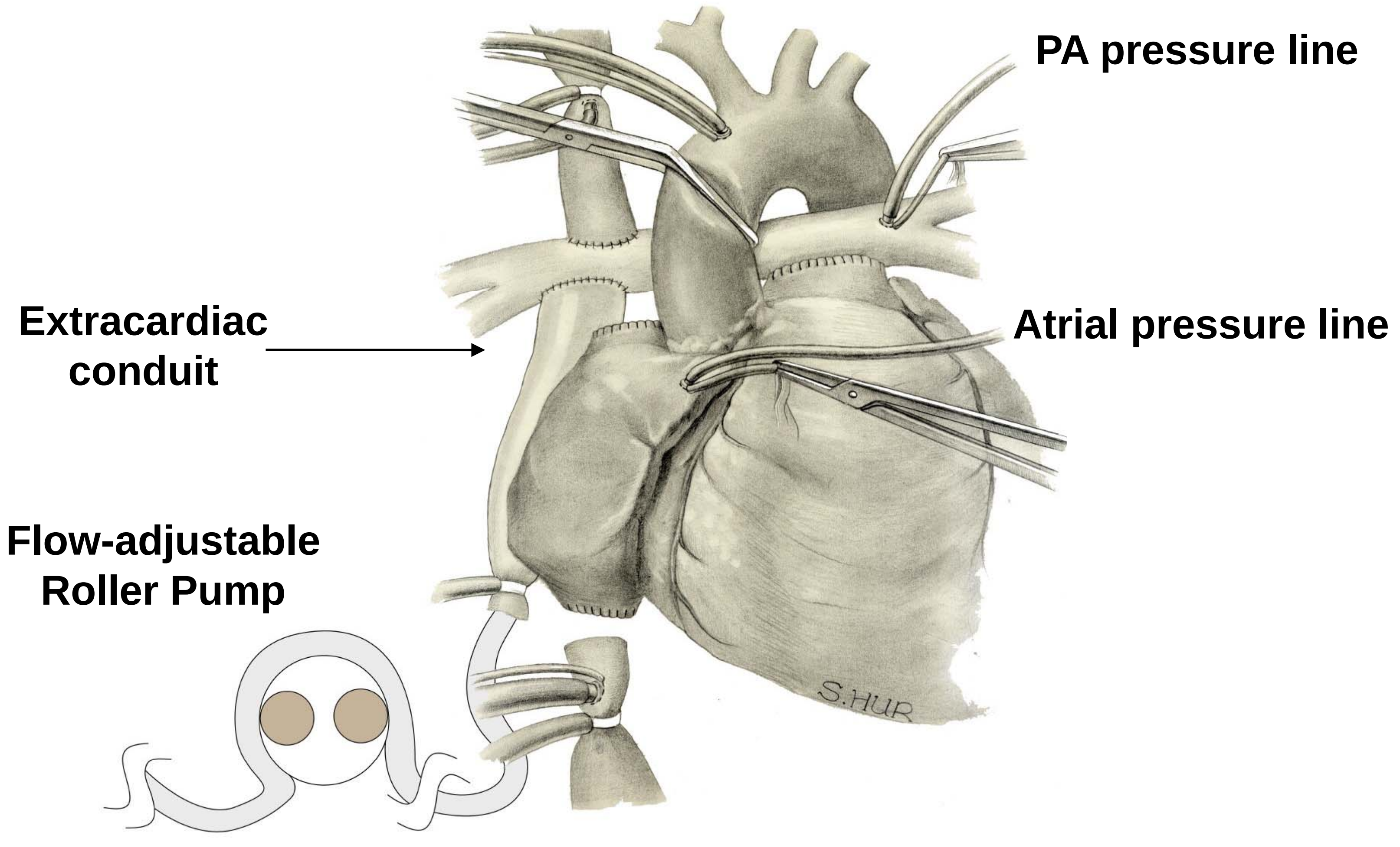


Flow study in PA,VSD,MAPCA

(Reddy et al, 1997)



Intra-operative Flow Study

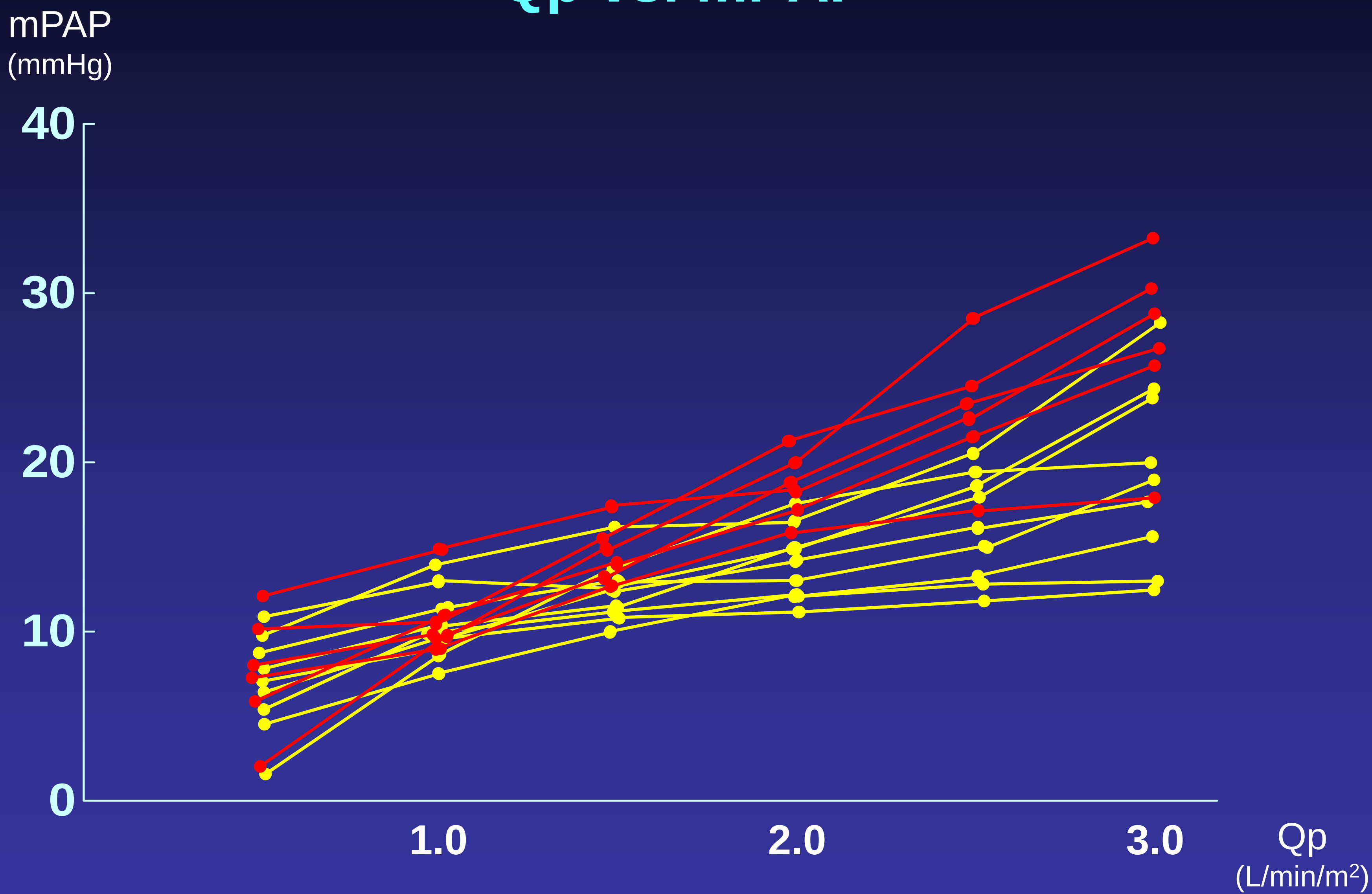


PVC from Intra-op flow study

- Single institution (AMC)
- Duration: Jul 2005 – Mar 2008
- 18 selected patients with ECC Fontan
- Age: 24 m – 26 y (median: 41 m)
- Fenestration : 7/18
- Postoperative functional MR study: 12 / 18
- $$\text{PVC} = \frac{Q_3 - Q_1}{P_3 - P_1} = \frac{2}{P_3 - P_1} \quad (\text{ml/mmHg}\cdot\text{min}\cdot\text{m}^2)$$

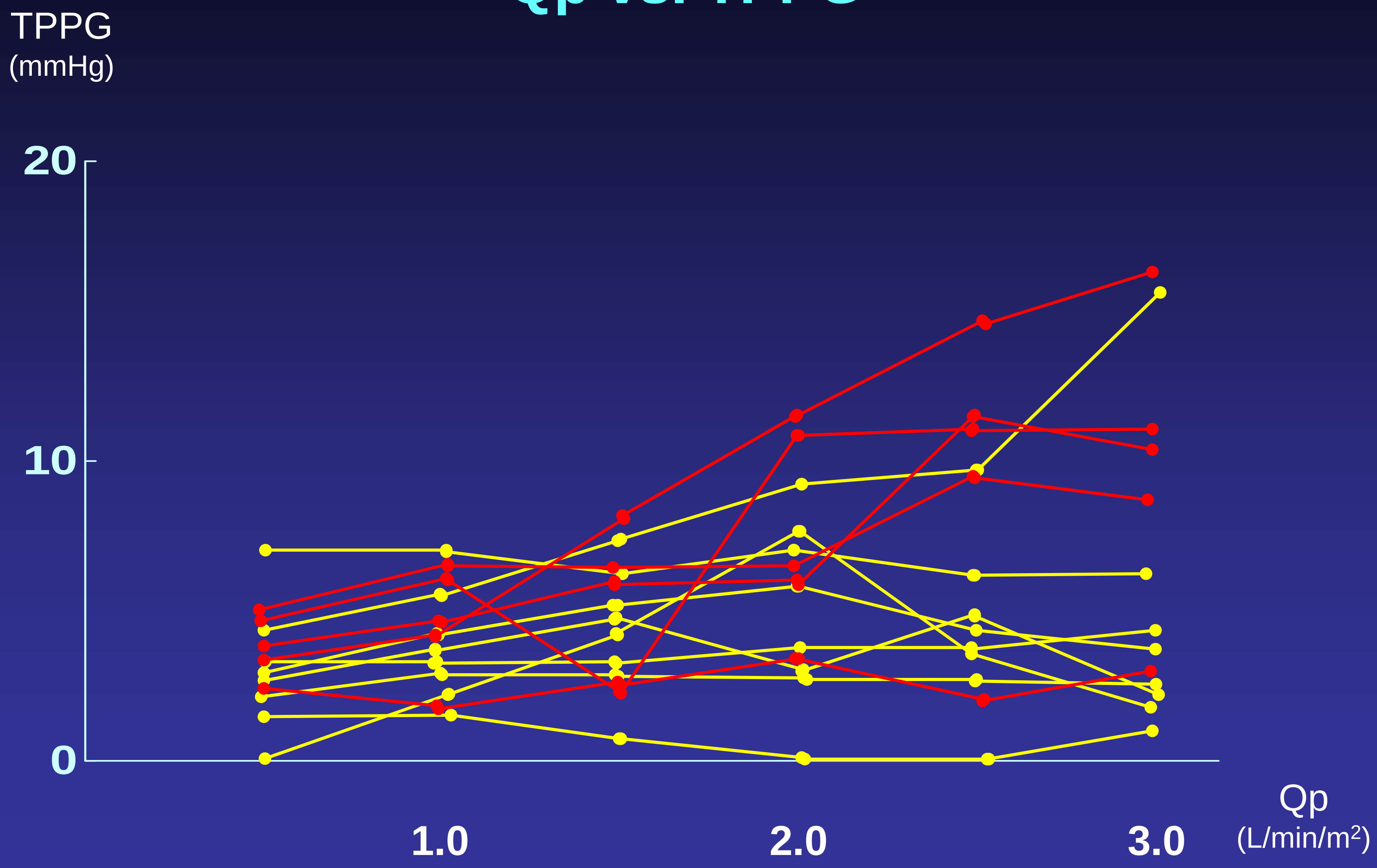
Intra-operative flow study

- Qp vs. mPAP -



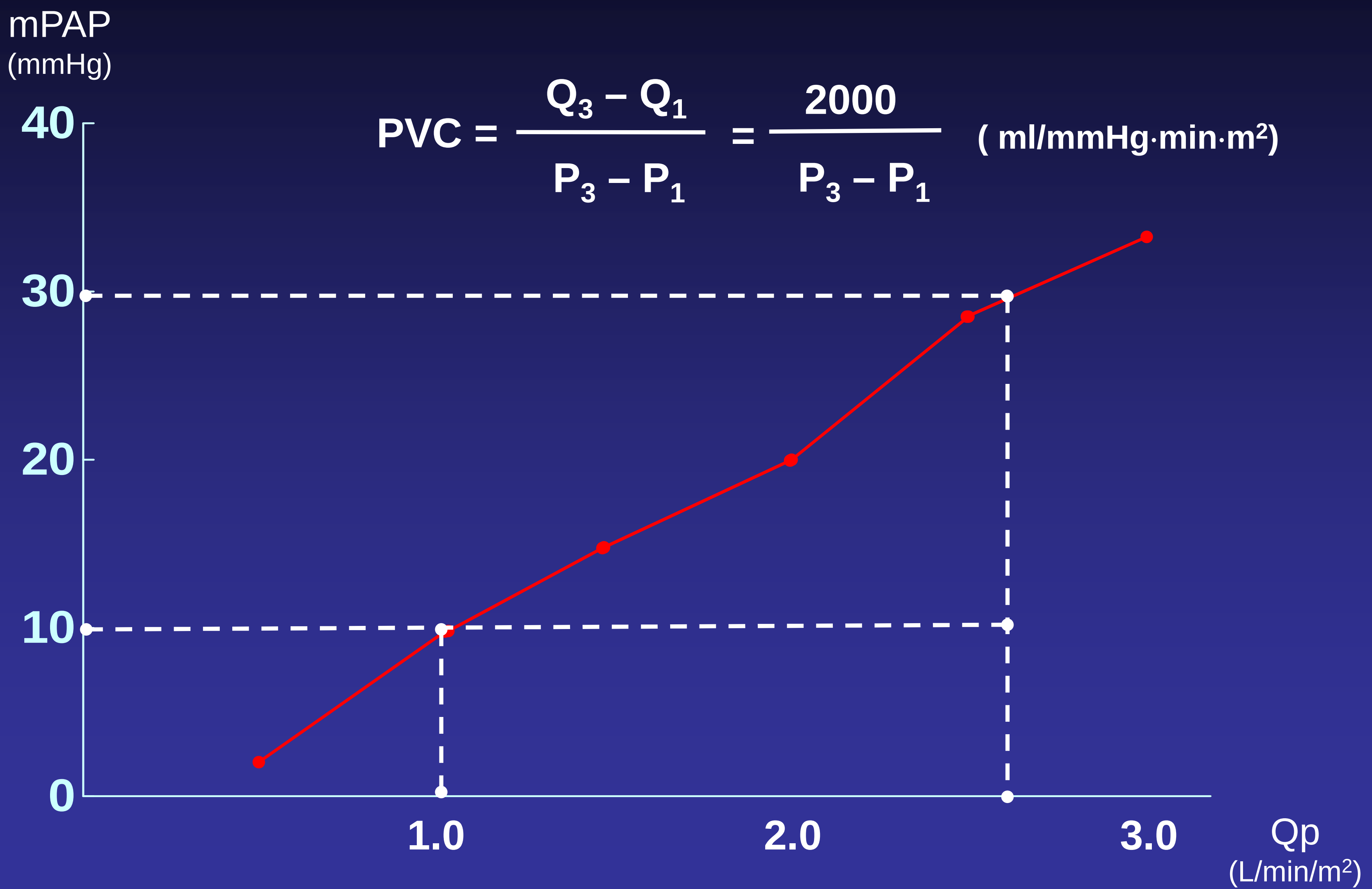
Intra-operative flow study

- Qp vs. TPPG -

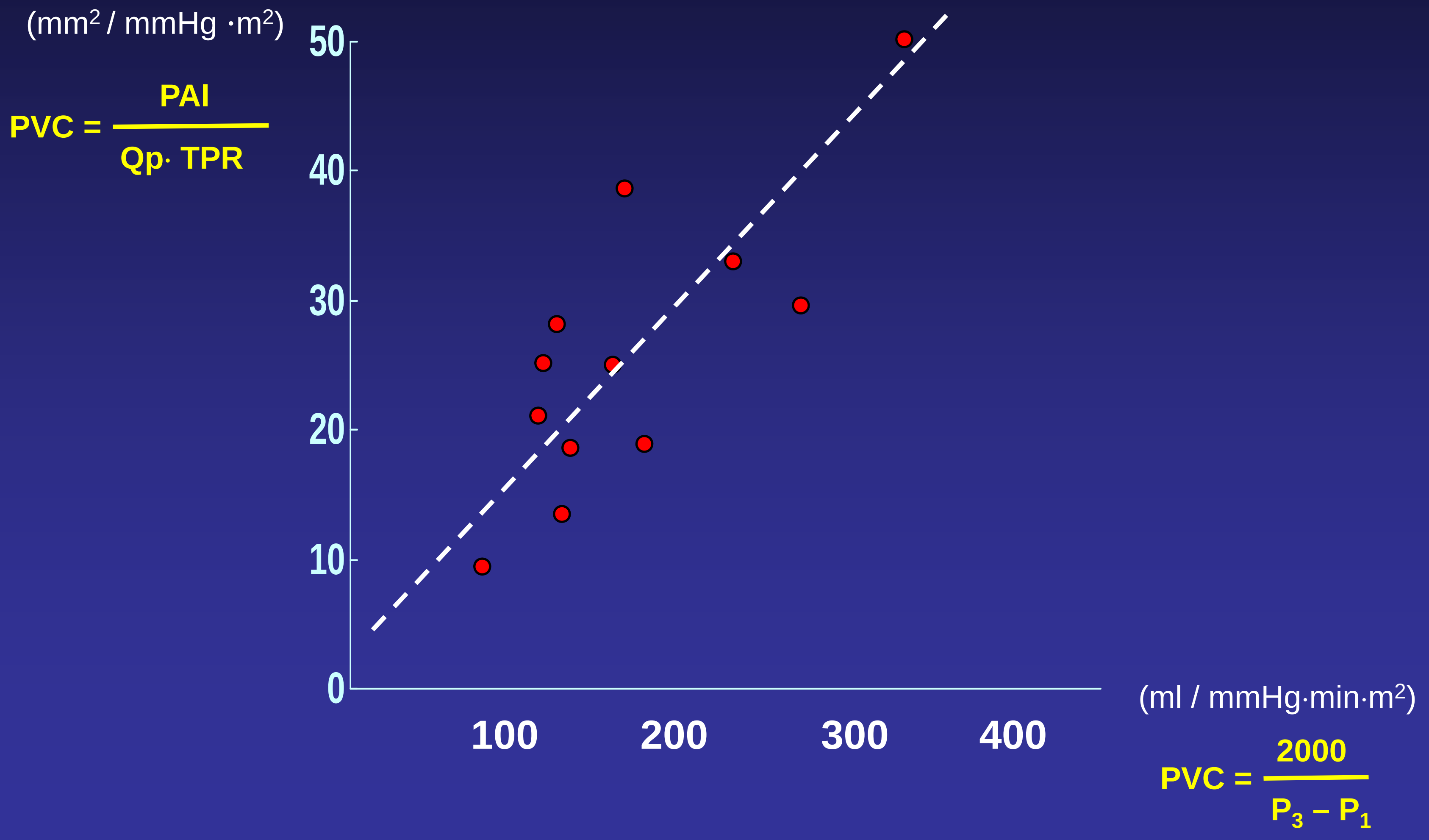


PVC from Intra-operative flow study

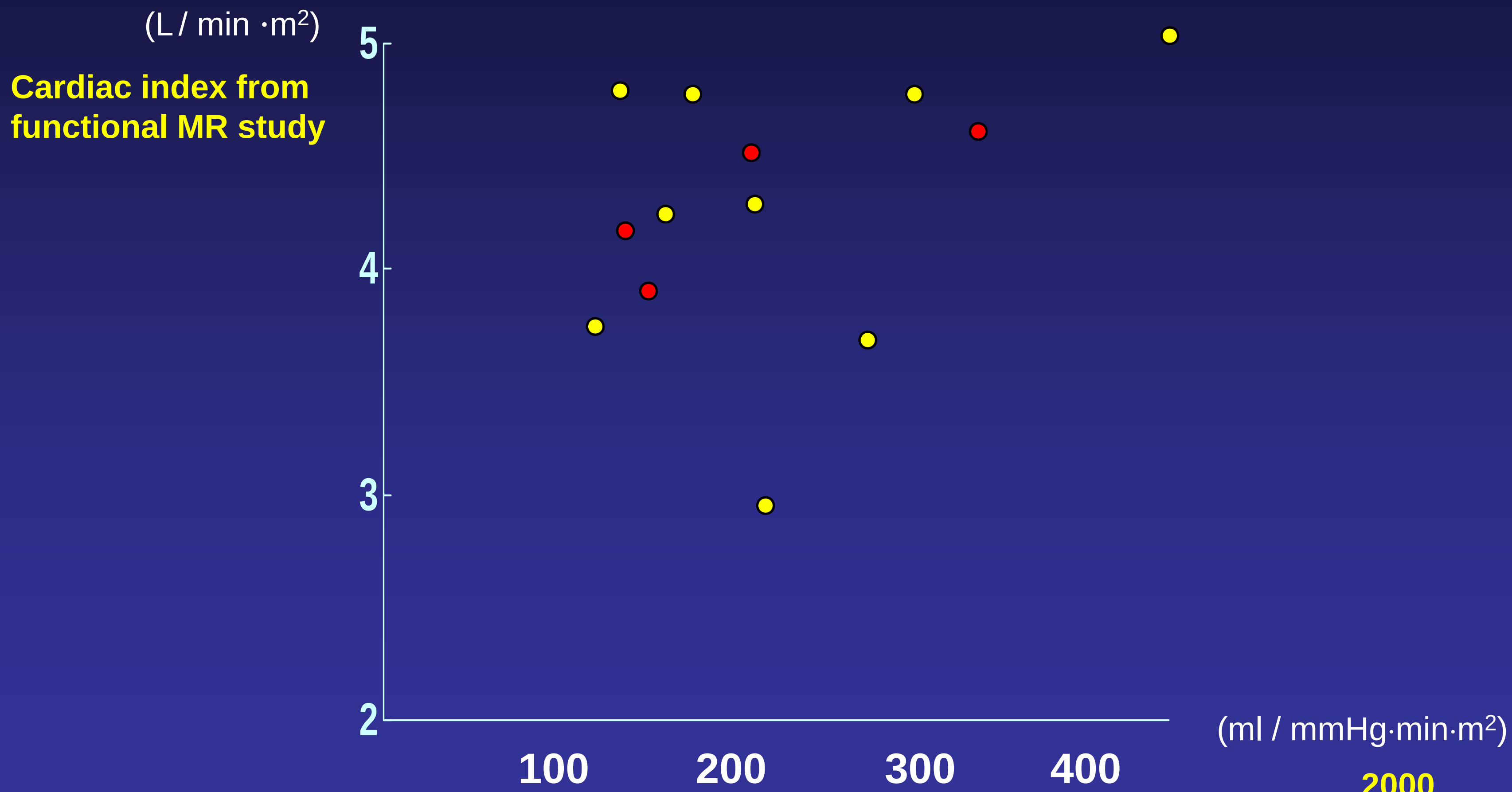
$$PVC = \frac{Q_3 - Q_1}{P_3 - P_1} = \frac{2000}{P_3 - P_1} \quad (\text{ml/mmHg·min·m}^2)$$



Comparison of PVC from Senzaki's method and PVC from flow study



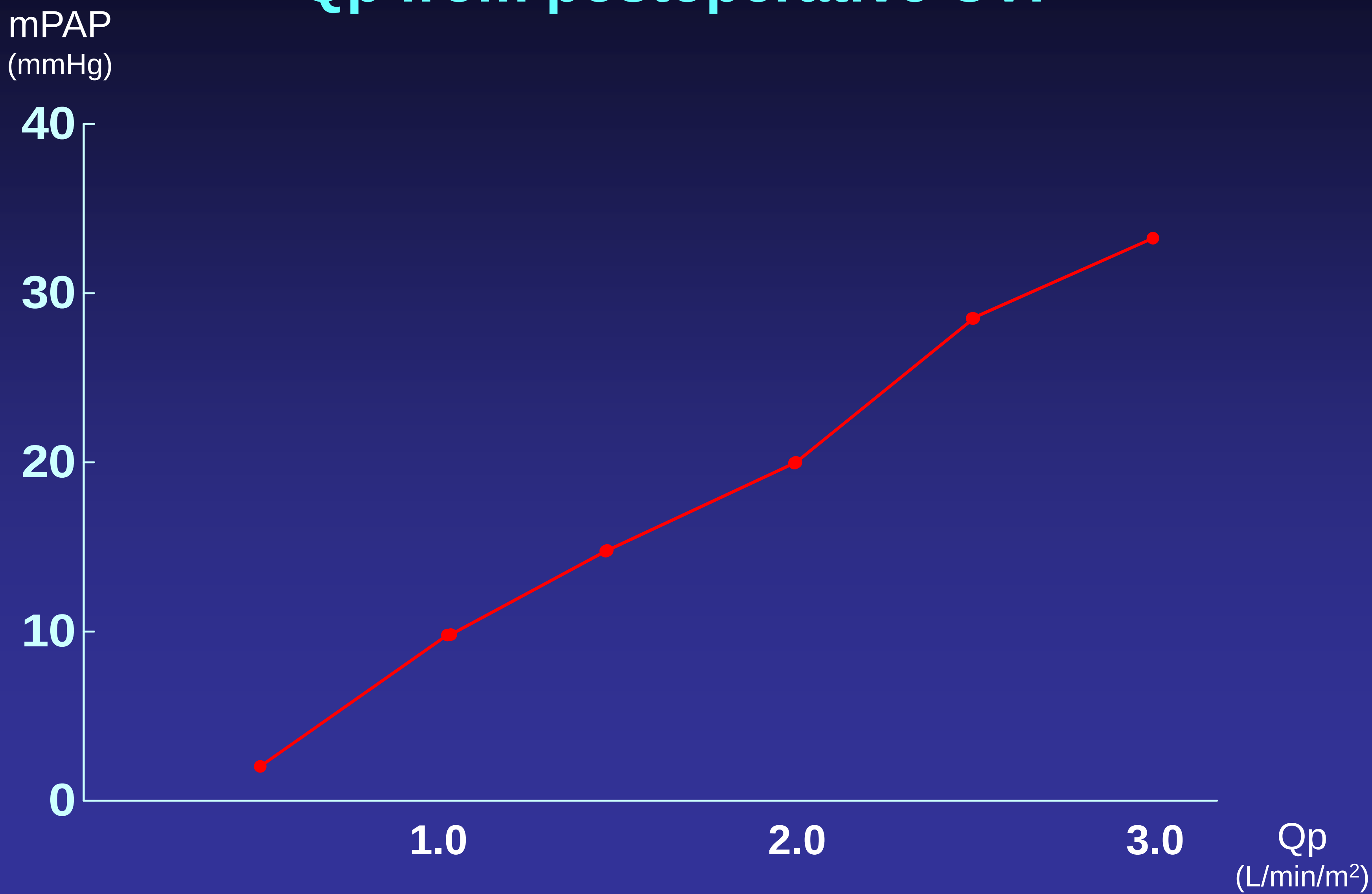
PVC from flow study vs. postoperative cardiac index from functional MR



$$PVC = \frac{2000}{P_3 - P_1}$$

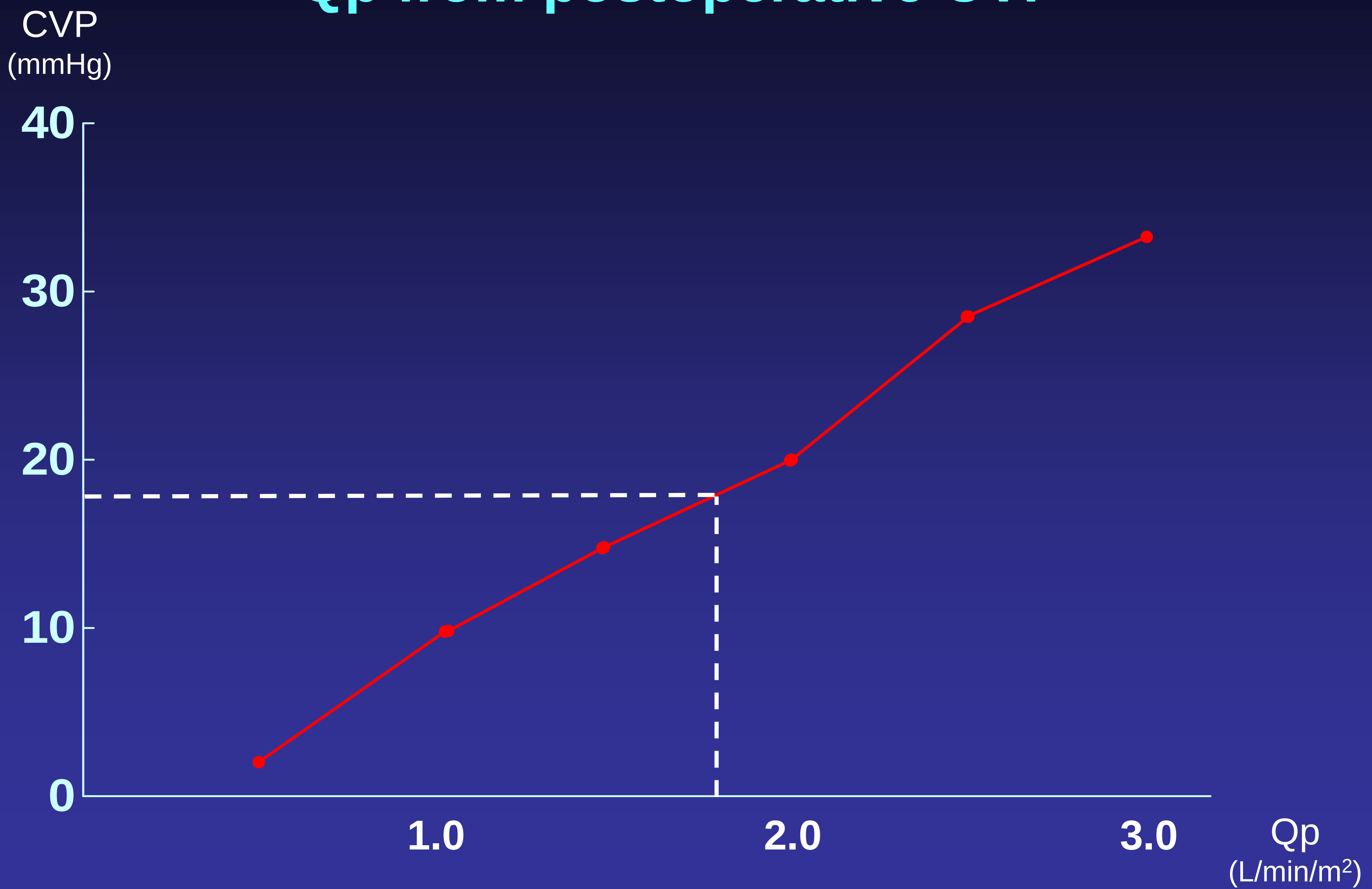
Intra-operative flow study

- Qp from postoperative CVP -

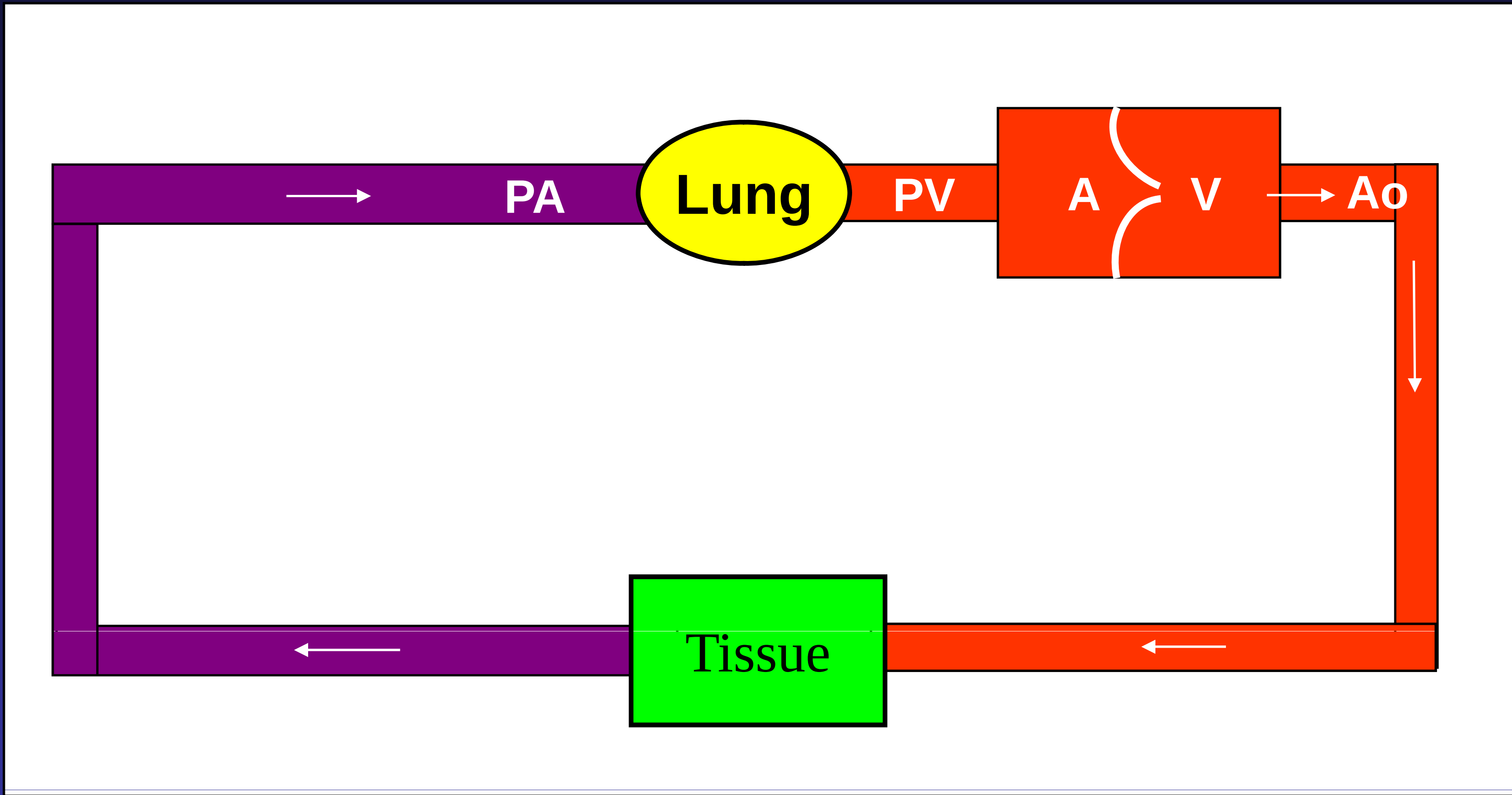


Intra-operative flow study

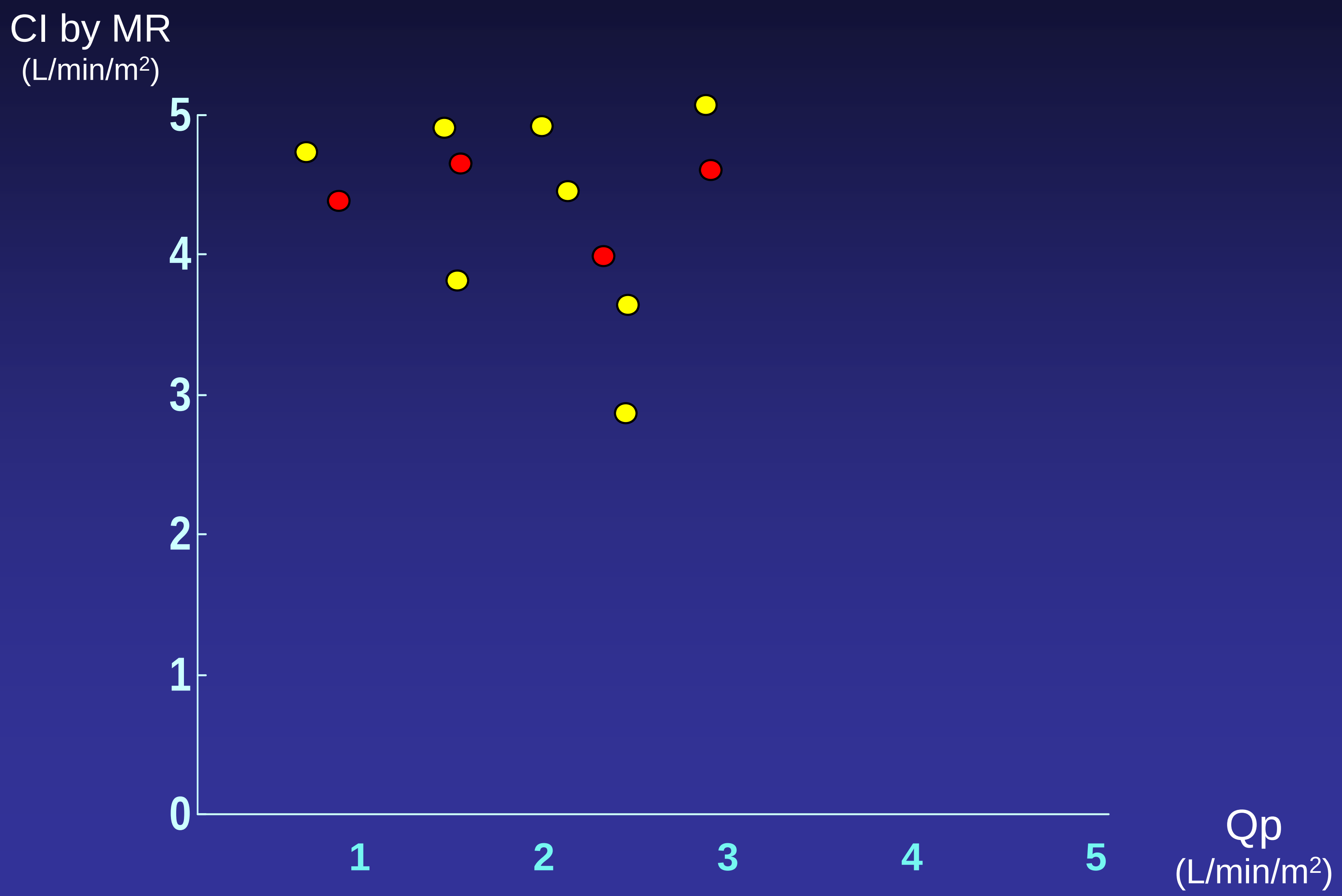
- Qp from postoperative CVP -



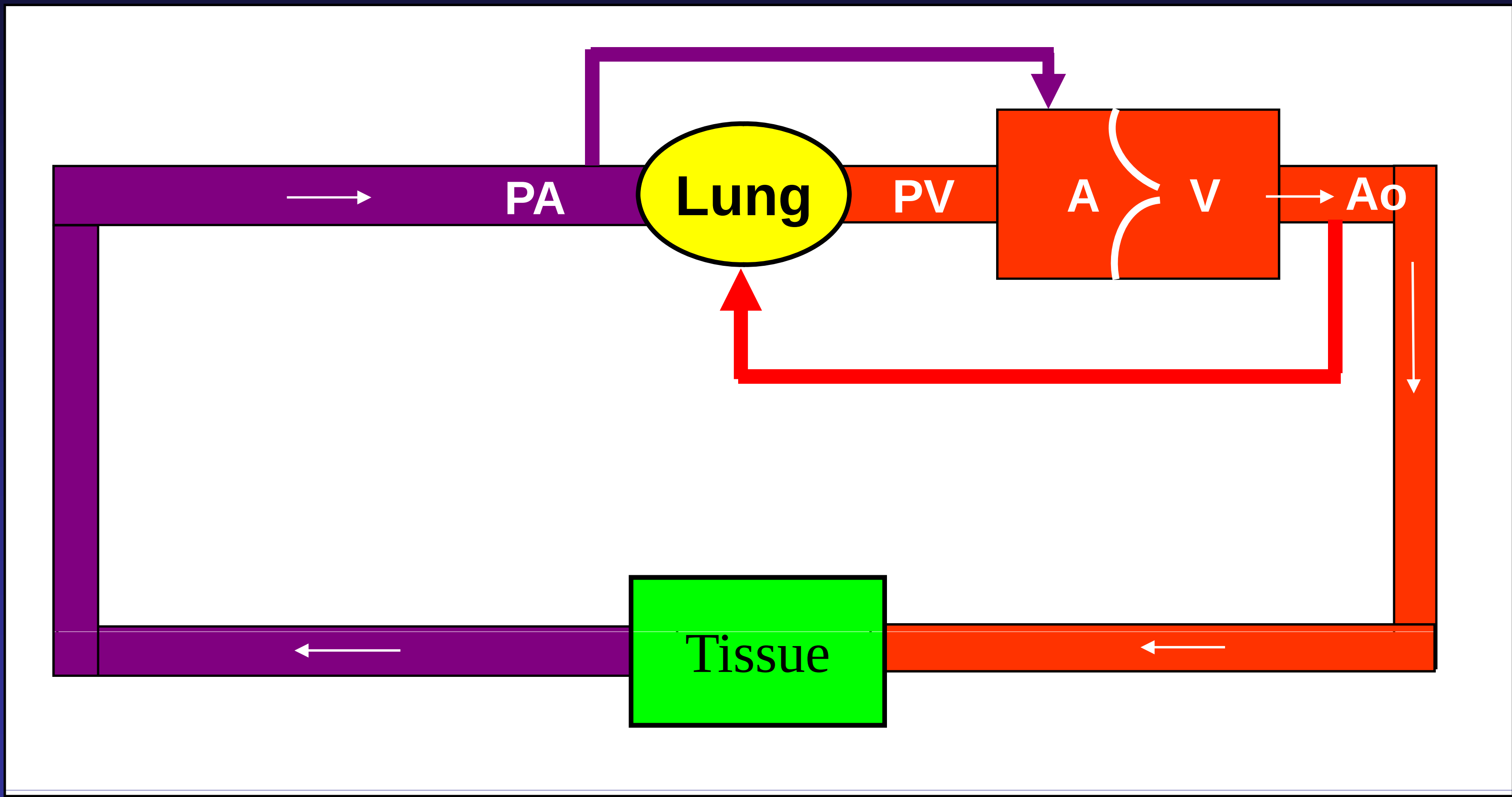
Qp = Cardiac output



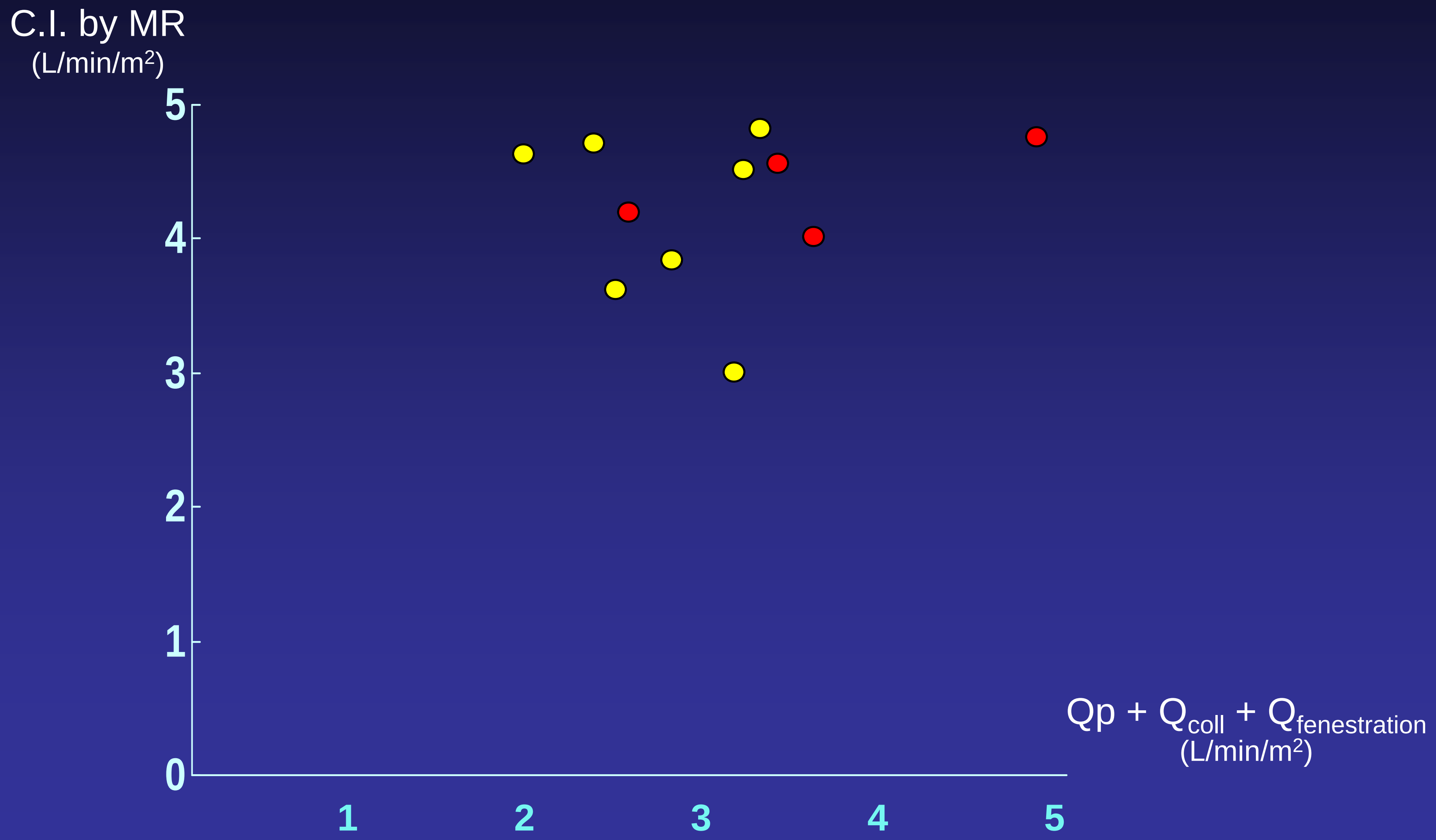
Comparison of C.I. from postop MR and postop Qp from CVP and flow study



$C.O. = Q_{ep} + Q_{collateral} + Q_{fenestration}$



Comparison of C.I. from postop MR and Q_{ep} + $Q_{collateral}$ + $Q_{fenestraion}$



Conclusion

- Preoperative risk analysis for Fontan candidates is still less than optimal.
- PVC can be easily calculated from basic catheterization data based on electrical circuit analogue, or from intraoperative flow study.
- PVC may improve post-Fontan outcome predictability.