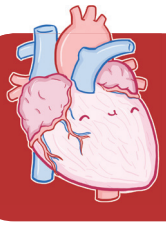

NOTES
CARDIAC CYCLE

MEASURING CARDIAC OUTPUT - FICK PRINCIPLE

osms.it/Fick-principle

- Model used to measure cardiac output (CO)
  - Output of left, right ventricles equal during normal cardiac function
- **Steady state**: rate of O_2 consumption = amount of O_2 leaving lungs via pulmonary vein - amount of O_2 returning via pulmonary arteries x CO
- Pulmonary blood flow of right heart = CO of left heart: used to calculate CO

$$\text{Cardiac Output} = \frac{O_2 \text{ consumption}}{[O_2] \text{ pulmonary vein} - [O_2] \text{ pulmonary artery}}$$

- 250mL/minute = total O_2 consumption (70kg, biologically-male individual); pulmonary venous O_2 content = 0.20/mL; pulmonary arterial O_2 content = 0.15/mL

$$\text{Cardiac Output} = \frac{250\text{mL/min}}{0.20\text{mL} - 0.15\text{mL}} = 5000\text{mL/min}$$

- Also measures blood flow to individual organs
  - Renal blood flow = renal O_2 consumption / renal arterial O_2 - renal venous O_2

CARDIAC & VASCULAR FUNCTION CURVES

osms.it/cardiac-and-vascular-function-curves

- Curves depicting functional connections between vascular system, right atrial pressure, and CO

CARDIAC FUNCTION CURVE (CO CURVE)

- Plot of relationship between left ventricle (LV) CO, right atrial (RA) pressure
- Based on Frank–Starling relationship describing CO dependence on preload
  - Preload (determined by RA pressure), independent variable; CO, dependent variable
  - ↑ venous return → ↑ RA pressure → ↑ LV end-diastolic volume (EDV)/preload, myocardial fiber stretch → ↑ CO
  - LV CO (L/min) = LV venous return/ preload (RA pressure in mmHg)
  - Relationship remains intact with steady state of venous return
  - RA pressure 4mmHg → curve levels off at maximum 9L/min

VASCULAR FUNCTION CURVE

- Plot of relationship between venous return, RA pressure
- Independent of Frank–Starling relationship
  - Venous return independent variable; RA pressure dependent variable
  - Venous return, RA pressure: inverse relationship
- ↑ RA pressure → ↓ pressure gradient between systemic arteries, RA → ↓ venous return to RA; CO

Mean systemic pressure (MSP)

- Pressure equal throughout vasculature
- Influenced by blood volume, distribution

Total peripheral resistance (TPR)

- Primarily determined by pressure in arterioles; determines slope of curve
- ↓ TPR (↓ arteriolar resistance) → ↑ flow from arterial to venous circulation → ↑ venous return → clockwise rotation of curve
- ↑ TPR (↑ arteriolar resistance) → ↓ flow from arterial to venous circulation → ↓ venous return → counterclockwise rotation of curve

ALTERING CARDIAC & VASCULAR FUNCTION CURVES

osms.it/altering-cardiac-vascular-function-curves

- Curves combined → changes in CO visualized, cardiovascular parameters altered
- Curves can be displaced by changes in blood volume, inotropy, TPR

INOTROPIC AGENTS

- Alters cardiac curve
- Positive inotropic agents (e.g. digoxin) at any level of RA pressure
  - ↑ contractility, stroke volume (SV), CO → (1) cardiac curve shifts upward, (2) vascular function curve not affected, (3) x-intercept (steady state) shifts upward, to left
- Negative inotropic agents (e.g. beta-blockers)
  - Opposite effect

BLOOD VOLUME

- Alters vascular curve
- ↑ circulating volume (e.g. blood transfusion)
  - ↑ MSP → (1) curves intersect at ↑ CO, RA pressure, (2) parallel shift of x-intercept (steady state), vascular curve to right, (3) no change in TPR
- ↓ circulating volume (e.g. hemorrhage)
  - Opposite effect
- Changes in venous compliance are similar to blood volume changes
  - ↓ venous compliance → changes similar to ↑ circulating volume
  - ↑ venous compliance → changes similar to ↓ circulating volume

TOTAL PERIPHERAL RESISTANCE

- Alters both curves due to changes in afterload (cardiac curve), venous return (vascular curve)
- ↑ TPR → ↑ arterial pressure → ↑ afterload → ↓ CO → (1) downward shift of cardiac curve, (2) counterclockwise rotation of vascular curve, (3) ↓ venous return, (4) RA pressure unchanged, ↓/↑ (depending on cardiac, venous curve alteration), (5) curves intersect at altered steady state
- ↓ TPR (arteriolar dilation)
  - Opposite effect

PRESSURE-VOLUME LOOPS

osms.it/pressure-volume_loops

- Graphs represent pressure, volume changes in LV during one heartbeat (one cardiac cycle/"stroke work")
- Pressure in left ventricle on y axis, volume of left ventricle on x axis

FOUR PHASES

Ventricular filling during diastole

- At end of this phase:
  - Mitral valve closed
  - Left ventricle filled (EDV); relaxed, distended
  - EDV = 140mL

Isovolumic contraction

- Systole begins (ventricular contraction)
- No changes to ventricular volume (mitral, aortic valve closed)
- Pressure builds

Ventricular ejection

- Pressure in left ventricle > aortic pressure → aortic valve opens → blood ejected

Isovolumic relaxation

- Ventricle starts relaxing → aortic pressure > LV pressure → aortic valve closes
- End of systole
- ESV = 70mL

STROKE VOLUME (SV)

- STROKE VOLUME (SV)
- Amount of blood pumped by ventricles in one contraction
- SV = EDV - ESV

STROKE WORK (SW)

- Work of ventricles to eject a volume of blood (i.e. to eject SV)
- Represented by area inside of loop

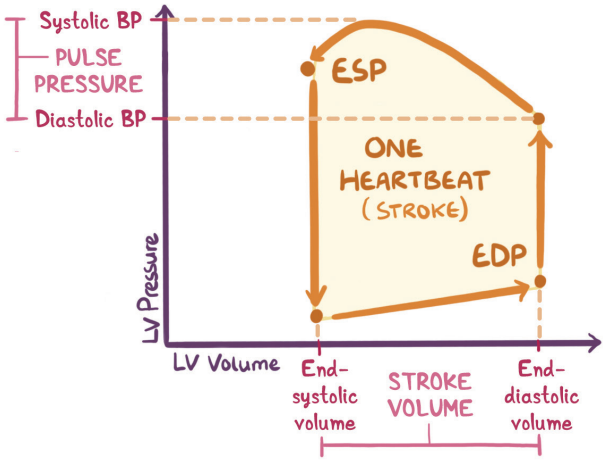

Figure 16.1 Measurements that can be obtained from the pressure-volume loop graph. Pulse pressure is measured in mmHg and reflects the throbbing pulsation felt in an artery during systole. Pulse pressure = systolic blood pressure - diastolic blood pressure. Stroke volume is measured in mL and is blood volume ejected by left ventricle during every heartbeat. Stroke volume = end-diastolic volume - end systolic volume.

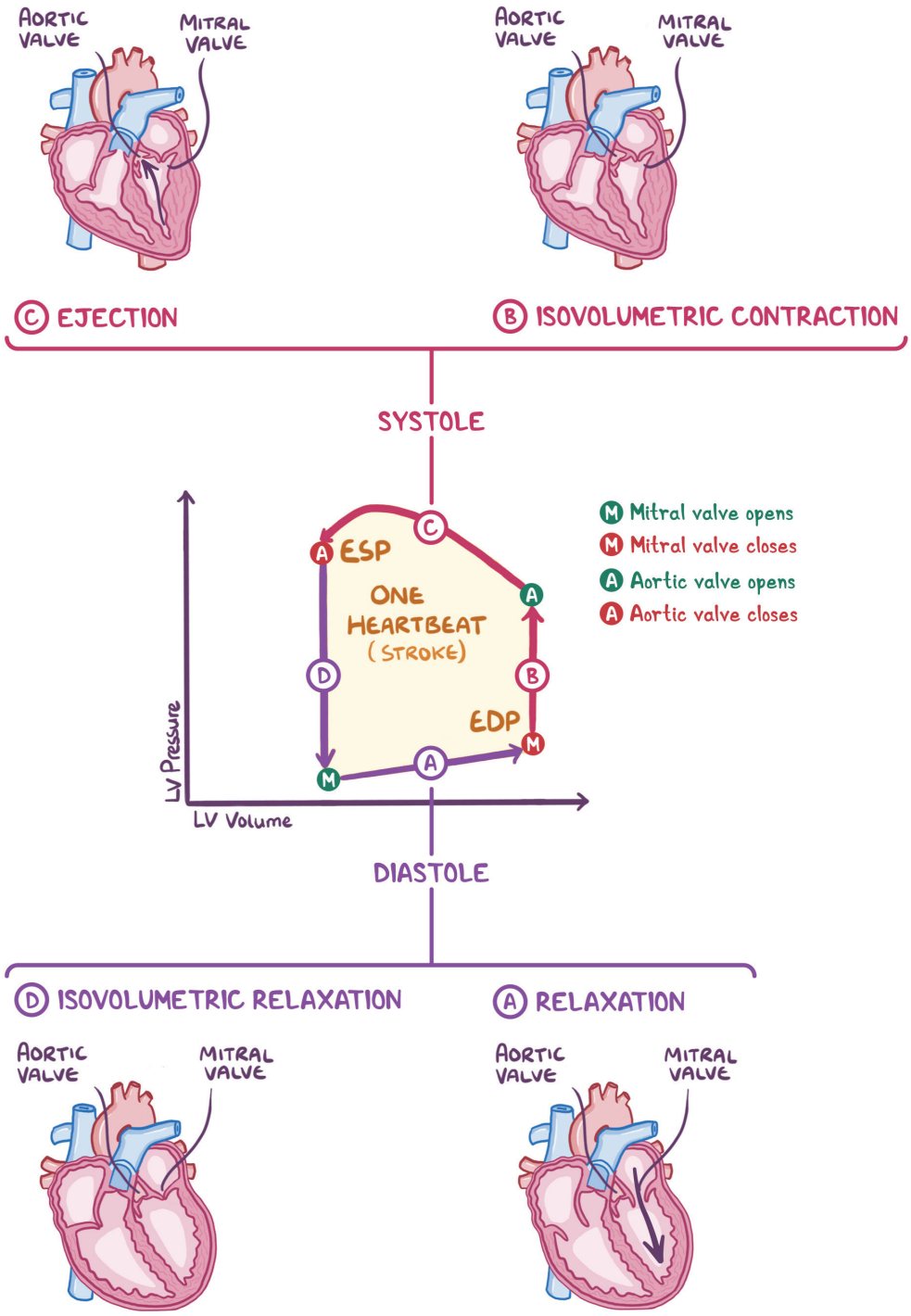

Figure 16.2 The four phases of the pressure-volume loop and the condition of the heart during each phase.

CHANGES IN PRESSURE-VOLUME LOOPS

osms.it/changes_in_pressure-volume_loops

- Cardiac parameters change → volume-pressure loops change
- ↑ preload (↑ EDV) → ↑ strength of contraction → ↑ stroke volume → larger loop
- ↑ afterload → ↑ ventricular pressure during isovolumetric contraction → ↑ less blood leaves ventricle → ↑ end-systolic volume (ESV) → ↓ SV → loop narrower, taller (smaller SV, higher pressure; stroke work remains relatively stable)
- ↑ contractility → blood under ↑ pressure → longer ejection phase → left ventricular pressure = aortic pressure → ↑ SV, stroke work, ↓ ejection fraction (EF), EDV → loop widens

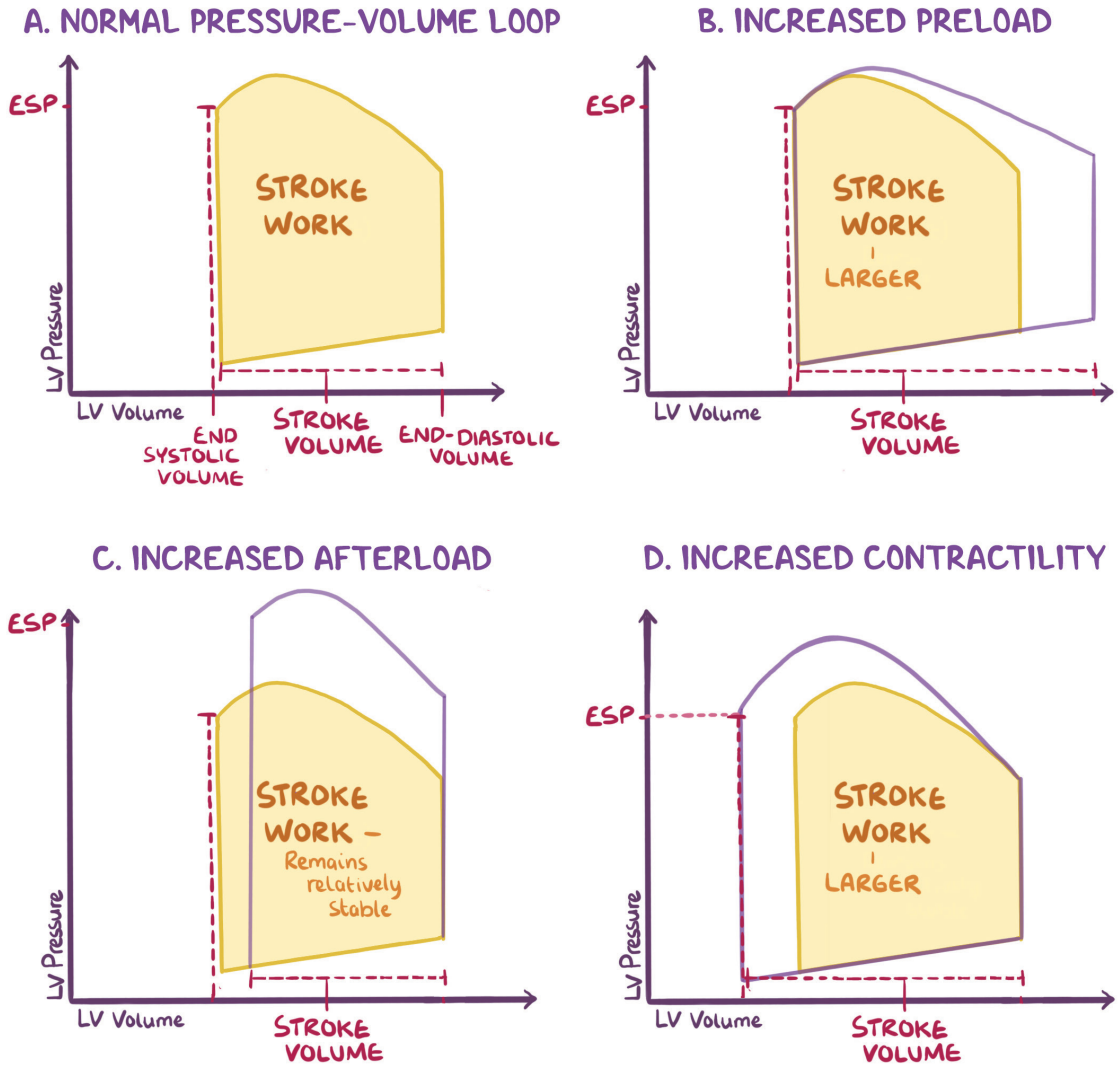

Figure 16.3 Changes in stroke work as a result of increased preload (B), afterload (C), and contractility (D) represented on pressure-volume loop graphs.

CARDIAC WORK

osms.it/cardiac-work

- Work heart performs as blood moves from venous to arterial circulation during cardiac cycle

PHASES OF CARDIAC WORK

Atrial systole

- Begins when atria, ventricles in diastole
- Atrioventricular (AV) valves open → passive ventricular filling
- Atrial depolarization → atria contract (atrial kick during systole) → completes ventricular filling (EDV)
- *Venous pulse*: "a" wave (↑ atrial pressure)
- ECG
  - P wave, PR interval

Isovolumetric ventricular contraction

- Ventricular contraction begins (ventricular systole) → ventricular pressure > atrial pressure → AV valves close (S1); semilunar valves closed
- ECG
  - QRS complex

Rapid ventricular ejection

- Ventricular systole continues → left ventricular pressure > aortic pressure → aortic valve forced open → blood ejected (SV) (blood also ejected into pulmonary vasculature via pulmonic valve)
- ↑ aortic pressure
- Atrial filling begins
- ECG
  - ST segment

Reduced ventricular ejection

- ↓ ventricular ejection velocity
- ↑ atrial pressure
- Ventricular repolarization begins
- ECG
  - T wave

Isovolumetric ventricular relaxation

- Ventricles relaxed (ventricular diastole); ventricular pressure < aortic pressure → aortic valve closes (S2); causes dicrotic notch on aortic pressure curve
- All valves closed
- Ventricular volume
  - Constant
- Complete ventricular repolarization
- ECG
  - T wave ends

Rapid ventricular filling

- Ventricular diastole continues → ventricular pressure < atrial pressure → AV valves open
- Passive ventricular filling (ventricles relaxed, compliant)
- S3 (normal in children) produced by rapid filling

Reduced ventricular filling (diastasis)

- Ventricular diastole continues; ventricles relaxed
- Mitral valve open
- Changes in heart rate (HR) alter length of diastasis

TYPES OF CARDIAC WORK

Internal work

- *Pressure work*: within the ventricle to prepare for ejection
- Quantified by multiplying isovolumic contraction time by ventricular wall stress
- Accounts for 90% of cardiac work

External work

- *Volume work*: ejecting blood against arterial resistance; product of pressure developed during ejection, SV
- Represented by area contained in pressure-volume loop
- Accounts for 10% of cardiac work

Myocardial oxygen consumption

- Pressure work > volume work

- Aortic stenosis → ↑↑ pressure work → ↑↑ oxygen consumption, ↓ CO
- Strenuous exercise → ↑ volume work → ↑ oxygen consumption, ↑ CO

LV and right ventricle (RV)

- *Volume work*: CO LV = RV CO
- *Pressure work*: LV (aortic pressure 100mmHg) > RV (pulmonary pressure 15mmHg)
  - ↑ systemic pressure (e.g. hypertension) → ↑ LV pressure work → ventricular wall hypertrophy
  - *Law of Laplace for sphere (e.g. heart): thickness of heart wall increases → greater pressure produced*

CARDIAC PRELOAD

osms.it/cardiac-preload

- *EDV*: volume load created by blood entering ventricles at end of diastole before contraction
- Establishes sarcomere length, ventricular stretch as ventricles fill (length-tension relationship)

FACTORS AFFECTING PRELOAD

Venous pressure

- Includes blood volume, rate of venous return to RA
- ↑ blood volume, venous return → ↑ preload

Ventricular compliance

- *Flexibility*: ability to yield when pressure applied
- Compliant, "stretchy" ventricles → ↑ preload
- Noncompliant, stiff ventricles → ↓ preload

Atrial contraction

- Early ventricular diastole → ventricles relaxed, passively fill with blood from atria via open AV valves → late ventricular diastole atrial systole (atrial kick) → additional blood into ventricles
- Accounts for 20% of ventricular preload

Resistance from valves

- Stenotic mitral, tricuspid valves create inflow resistance → ↓ filling → ↓ preload
- Stenotic pulmonic, aortic valves create outflow resistance → ↓ emptying → ↑ preload

HR

- Normal heart rate allows adequate time for ventricles to fill
- Tachyarrhythmias → ↓ filling time → ↓ preload

CARDIAC AFTERLOAD

osms.it/cardiac-afterload

- Amount of resistance ventricles must overcome during systole
- Establishes degree, speed of sarcomere shortening, ventricular wall stress (force-velocity relationship)
- ↑ afterload → ↓ velocity of sarcomere shortening
- ↓ afterload → ↑ velocity of sarcomere shortening

FACTORS AFFECTING AFTERLOAD

LV

- Systemic vascular resistance (SVR)
- Aortic pressure

RV

- Pulmonary pressure

Resistance from valves

- Stenotic pulmonic, aortic valves create outflow resistance → ↑ afterload

LAW OF LAPLACE

osms.it/law-of-Laplace

- Describes pressure-volume relationships of spheres
- Blood vessels
  - > radius of artery = > pressure on arterial wall
- Heart
  - Wall tension produced by myocardial fibers when ejecting blood depends on thickness of sphere (heart wall)
- *Laplace's formula*: tension on myocardial fibers in heart wall = pressure within ventricle x volume in ventricle (radius) / wall thickness
- $T = \frac{P \times r}{h}$
  - T = wall tension
  - P = pressure
  - r = radius of ventricle
  - h = ventricular wall thickness
- Dilation of heart muscle increases tension that must be developed within heart wall to eject same amount of blood per beat
- Myocytes of dilated left ventricle have greater load (tension)
  - Must produce greater tension to overcome aortic pressure, eject blood → ↓ CO

FRANK–STARLING RELATIONSHIP

osms.it/Frank-Starling_relationship

- Loading ventricle with blood during diastole, stretching cardiac muscle → force of contraction during systole
- Length-tension relationship
  - Amount of tension (force of muscle contraction during systole) → depends on resting length of sarcomere → depends on amount of blood that fills ventricles during diastole (EDV)
  - Length of sarcomere determines amount of overlap between actin, myosin filaments, amount of myosin heads that bind to actin at cross-bridge formation
  - Low EDV → ↓ sarcomere stretching → ↓ myosin heads bind to actin → weak contraction during systole → ↓ SV
  - Too much sarcomere stretching prevents optimal overlap between actin, myosin → ↓ force of contraction → ↓ SV
- Allows intrinsic control of heart = venous return with SV
- Extrinsic control through sympathetic stimulation, hormones (e.g. epinephrine), medications (e.g. digoxin) → ↑ contractility (positive inotropy), SV
- Negative inotropic agents (e.g beta-blockers) → ↓ contractility → ↓ SV

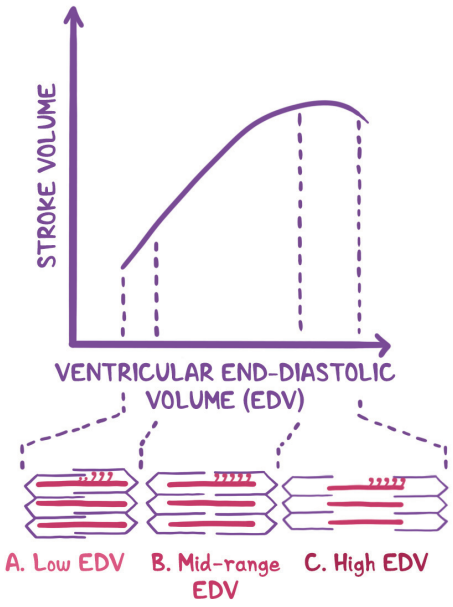

Figure 16.4 Graphical representation of the Frank–Starling relationship and sarcomere length at low, mid-range, and high EDVs. A mid-range EDV (B), where the volume of blood returning to the ventricles is increasing but is not too large (C), allows for best myosin-actin binding → ↑ strength of contractions → ↑ stroke volume.

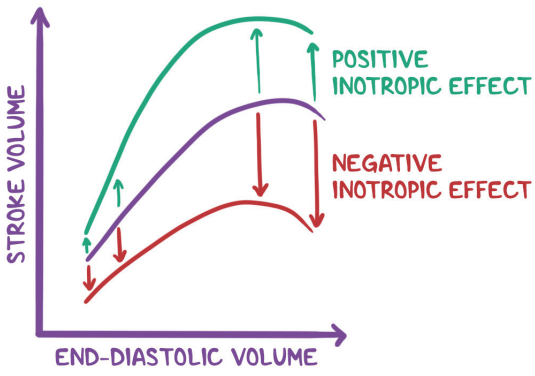

Figure 16.5 Graphical representation of positive and negative inotropic effects on the Frank–Starling relationship.

STROKE VOLUME, EJECTION FRACTION, & CARDIAC OUTPUT

osms.it/stroke-volume-ejection-fraction-cardiac-output

SV

- Volume of blood (mL) ejected from ventricle with each contraction
- Calculated as difference between volume of blood before ejection/EDV, after ejection (ESV)
- EDV (120mL) - ESV (50mL) = 70mL
- SV affected by preload, afterload, inotropy

EF

- Fraction of EDV ejected with each contraction
- SV (70)/EDV (120) = 58 (EF)
- Average = 50–65%

CO

- Volume of blood ejected by ventricles per minute
- SV (120) x HR (70) = 4900mL/min