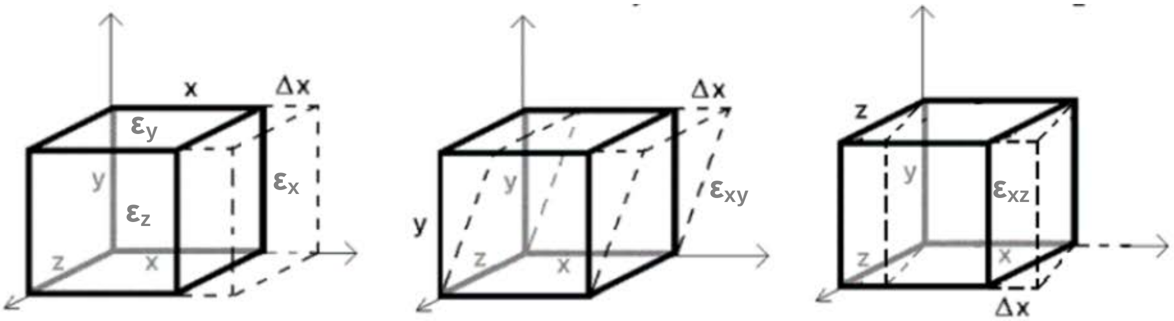
Appendix 1: Calculation of Myocardial Principal Strain

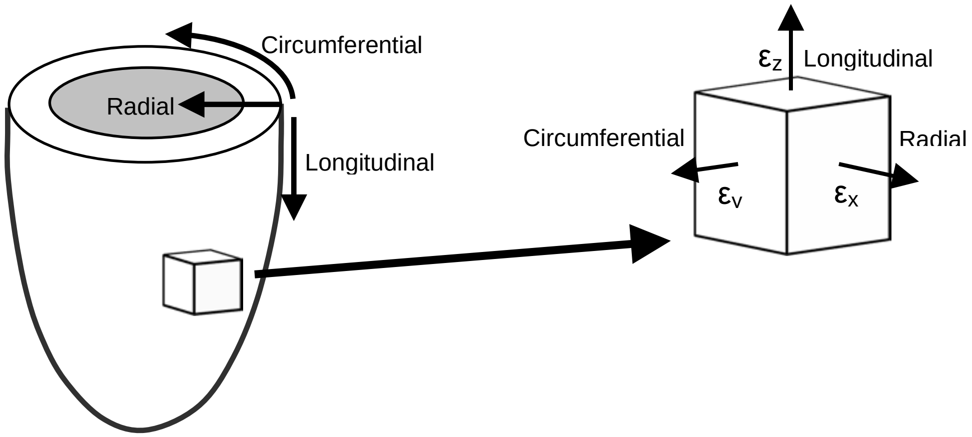
Strain is the measure of deformation in a material or object. Myocardial deformation occurs in 3-dimensions (x,y,z) resulting in a 3D strain matrix containing normal strains and shear strains. Normal strains (**ε_x, ε_y, ε_z**) measure change in length along one direction while shear strains (**ε_{xy}, ε_{yz}, ε_{xz}**) measure change in angles with respect to two directions.

Three Dimensional Strain Matrix. Normal strains (ε_x, ε_y, ε_z) are represented along the diagonal while the off-diagonal elements (ε_{xy}, ε_{yz}, ε_{xz}, ε_{yx}, ε_{zy}, ε_{zx}) represent the shear strains. For a biological system the strain matrix is symmetric meaning the upper and lower off-diagonals are equal



Graphic Depiction of 3D Strain. Normal strains (ε_x, ε_y, ε_z) act in one direction perpendicular to the surface resulting in a change in length in that direction. Shear strains (ε_{xy}, ε_{yz}, ε_{xz}) act parallel to the surface resulting in a change in angle but no change in length

For **cardiac wall based strains** the strain matrix is oriented with respect to the left ventricular geometry. The coordinate system is rotated so that the x, y, and z direction align with the radial, circumferential, and longitudinal direction of the LV respectively. Components of the normal and shear strains are expressed as magnitudes values in the given wall based direction. Changes in cardiac strain, as during remodeling, are reported as normal and shear values with constant orientation. Normal strains are easily interpreted while shear strains are more difficult to comprehend because of their definition and complex orientation.



Graphic Description of Cardiac Wall Based Strains. The strain matrix is oriented to the left ventricular geometry with normal and shear strains referenced to the radial, circumferential and longitudinal directions.

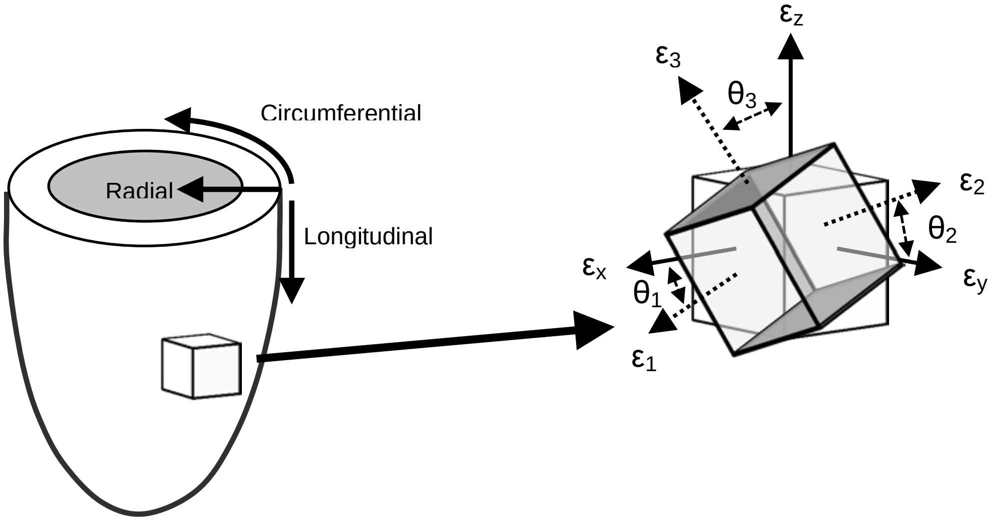
Principal strains convert the 3D strain matrix with 6 independent elements, 3 normal and 3 shear, to a matrix with three non-zero elements along the diagonal. This is performed mathematically be solving the eigenvalue equation $Av=\lambda v$, where A is the strain matrix, λ is the eigenvalue, and v is the eigenvector corresponding to each eigenvalue. This operation creates a diagonal matrix where the shear strains are combined with the normal strains eliminating the shear component. The eigenvalue represents the magnitude of the principal strain and eigenvector the orientation. For a 3D strain matrix there exists three principal strains: maximum (ε_1), minimum (ε_3), and intermediate (ε_2) where ε_1 is the maximum stretch, ε_3 the maximum shortening, and ε_2 the mutually orthogonal component of stretch or shortening.

$$\xrightarrow{Av=\lambda v}$$

3D Strain Matrix Principal Strain Matrix

Principal Strain Matrix. Converting the 3D strain matrix to the principal strain matrix creates a diagonal matrix eliminating the shear elements. Each principal strain eigenvalue has a corresponding eigenvector which determines the direction of the strain

Graphically, the conversion of the 3D strain matrix to the principal strain matrix is accomplished by altering the coordinate orientation to eliminate the shear components. This results in the strain being represented as normal to the surface without shear. Using principal strain, maximum stretch and maximum shortening magnitudes and the associated angles can be determined making strain tracking during remodeling sensitive to not only magnitude but also direction.



Graphic Description of Principal Strain. Converting the 3D strain matrix to the principal strain matrix involves rotating the coordinate system to eliminate the shear component and making maximum stretch and shortening normal to the surface.