ACIMED Imagerie Cardiovasculaire

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Plan

1. Introduction aux maladies Cardiovasculaires.
2. Modalités d'imagerie, Modes d'imagerie.
3. Applications Cliniques.

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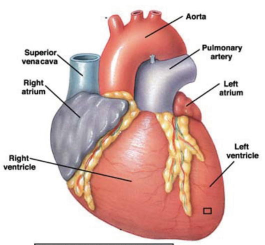
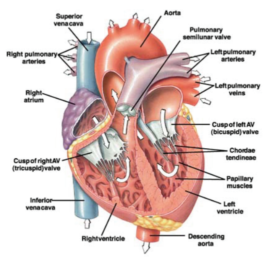
Introduction

Système Physiologique Cardiovasculaire

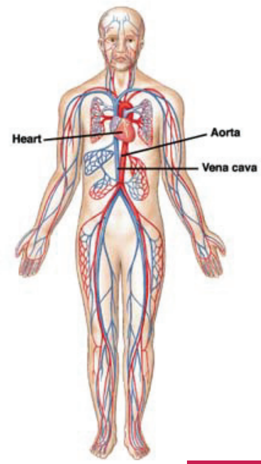
- Cardiaque
  - Ventricules, valves, myocarde
- Vasculaire
  - Artères et veines



The ventricles occupy the bulk of the heart. The arteries and veins all attach to the base of the heart.

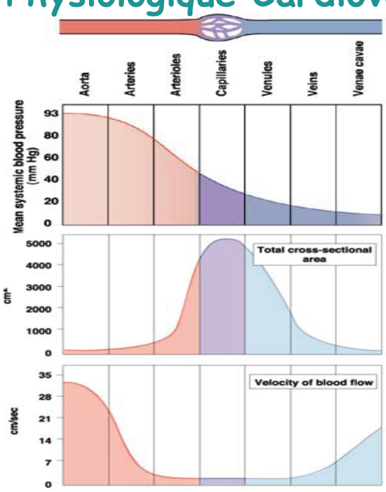


One-way flow through the heart is ensured by two sets of valves.



Introduction

Système Physiologique Cardiovasculaire



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Introduction

Incidence et Santé Publique

- Cardiovasculaire: 1/3 des examens d'imagerie médicale dans le monde.
- Coût:
  - US (U),
  - CT-SPECT (3U),
  - IRM (5U),
  - PET(14U),
  - Cathérisation (20U)

2005

[Eugenio Picano, « Economic and biological costs of cardiac imaging »,*cardiovascular Ultrasound*, 3:13, 2005]

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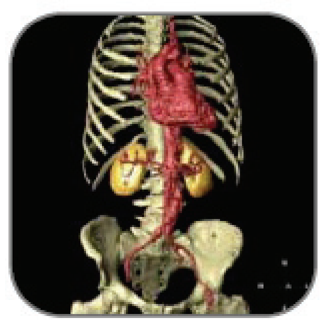
Introduction

Imagerie Cardiovasculaire

- Modalités d'Imagerie:
  - X-Ray, CT, IRM, US,
  - PET-SPECT.
- Protocoles d'imagerie:
  - Repos
  - Dynamique
  - Effort (stress)
  - Perfusion
  - Agent de contraste



Philips Medical Systems

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Introduction

Pathologies

- Liste des Pathologies
  - Abnormal Heart Rhythms
  - Aneurysms and Aortic Dissection
  - Atherosclerosis
  - Cardiomyopathy
  - Coronary Artery Disease
  - Heart Failure
  - Heart Valve Disorders
  - High or Low Blood Pressure
  - Infective Endocarditis
  - Pericardial Disease
  - Peripheral Arterial Disease
  - Venous Disorders

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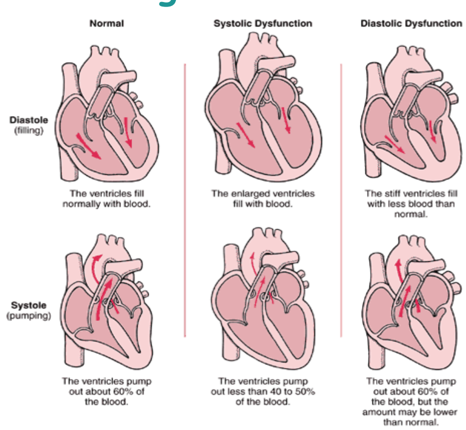
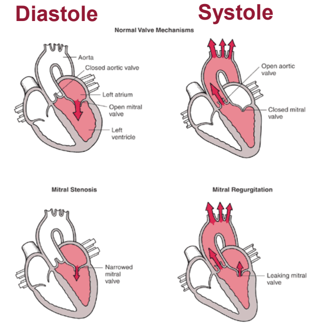
Introduction

Pathologies



Myopathies Cardiaques



Myopathies des Valves

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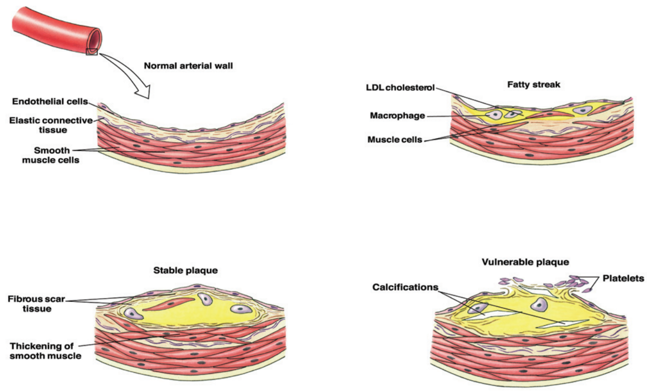
Introduction

Pathologies: Plaques sur parois des artères



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Introduction

- Propriétés mécaniques des artères:
  - Composition de la paroi des vaisseaux et des plaques.
  - Vulnérabilité des plaques.
  - Effets d'une intervention chirurgicale.
  - Effets de traitements médicamenteux.
  - Age d'une thrombose.

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Plan

2.1 Modalités d'Imagerie

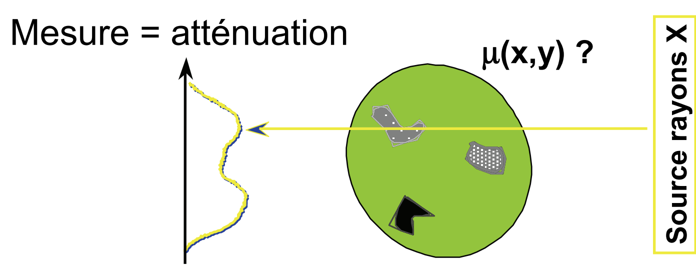
- CT
- Ultrasons
- IRM
- PET/SPECT

2.2 Modes d'Imagerie

- Statique
- Dynamique
- Effort (stress exams): perfusion/oxygène
- Agents de contraste

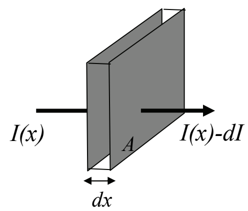
Modalités d' Imagerie

- CT : Rayons-X par tomographie



Modalités d' Imagerie

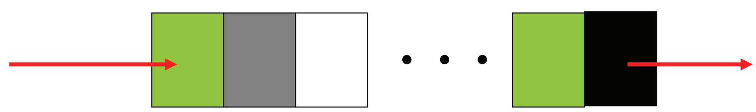
- CT



$$I(x) = I_0 e^{-\mu x}$$

$$\mu_m = \mu / \rho$$

Atténuation dans milieu hétérogène:



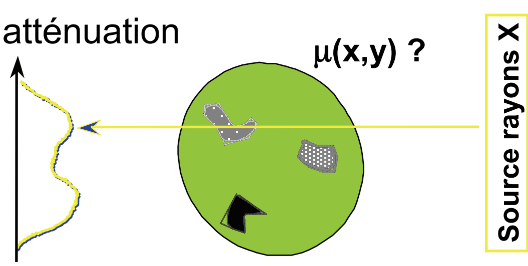
$$I(x) = I_o\, e^{-\mu_1 \Delta x} \times e^{-\mu_2 \Delta x} \times e^{-\mu_3 \Delta x} \times \ldots \times e^{-\mu_{N-1} \Delta x} \times e^{-\mu_N \Delta x}$$

$$I(x) = I_o \exp\left(\sum_{n=1}^{N} \mu_n \Delta x\right) = I_o \exp\left(\int_0^x \mu_n dx\right)$$

Modalités d' Imagerie

- CT

Mesure = atténuation

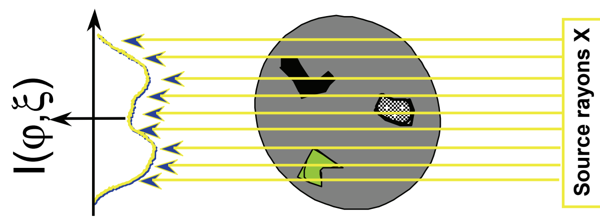


$$I = I_0 \exp\left(-\int_L \mu(x,y) dl\right)$$

$$\Rightarrow \mu_{total} = \int_L \mu(x,y) dl = -\ln\left(\frac{I}{I_0}\right)$$

Modalités d' Imagerie

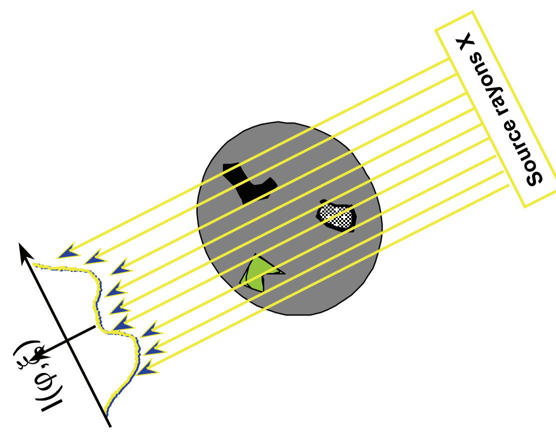
- CT



Acquisition de multiples projections en translation et rotation

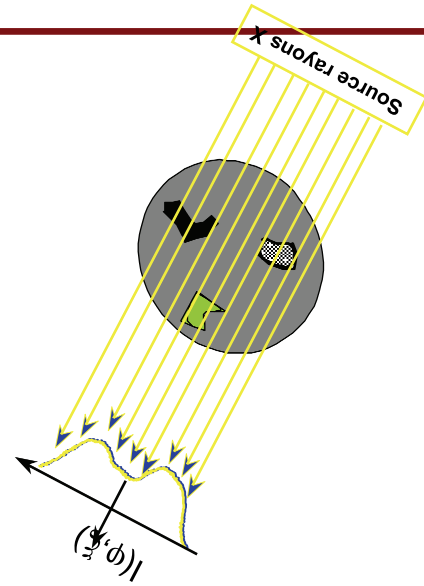
Modalités d' Imagerie

- CT



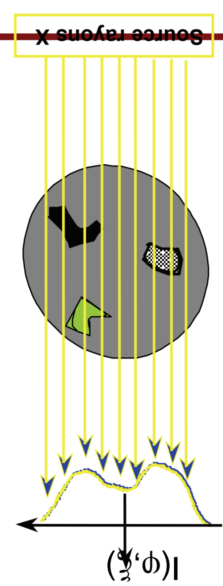
Modalités d' Imagerie

• CT



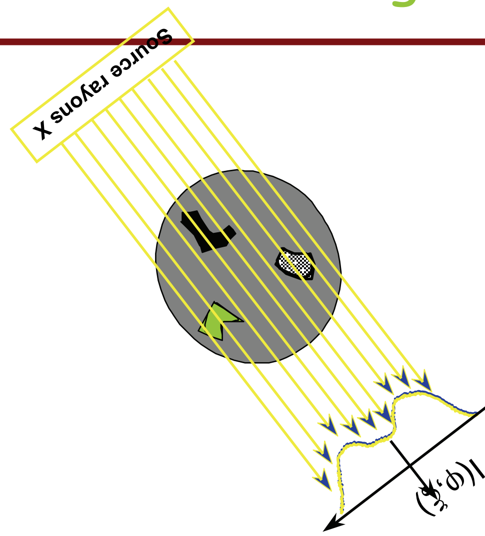
Modalités d' Imagerie

• CT



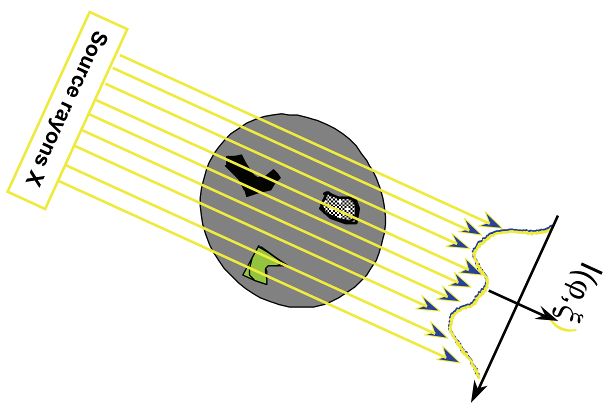
Modalités d' Imagerie

- CT



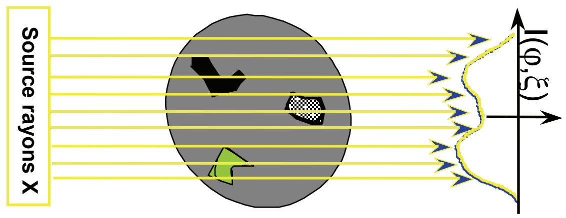
Modalités d' Imagerie

- CT



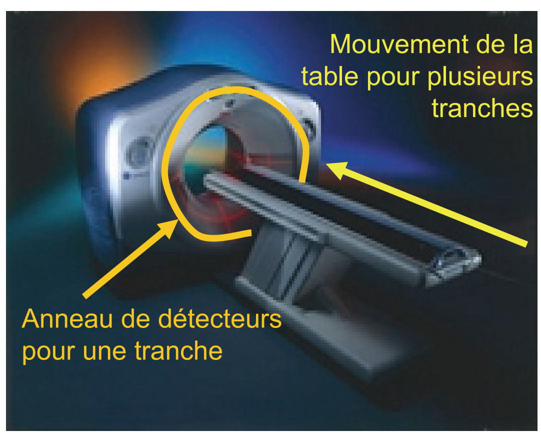
Modalités d' Imagerie

- CT



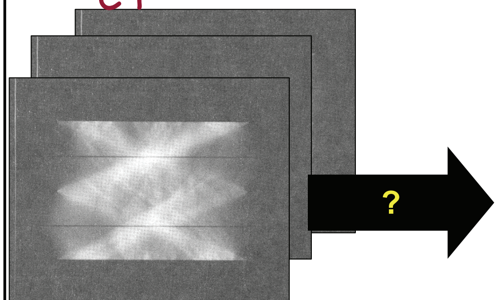
Modalités d' Imagerie

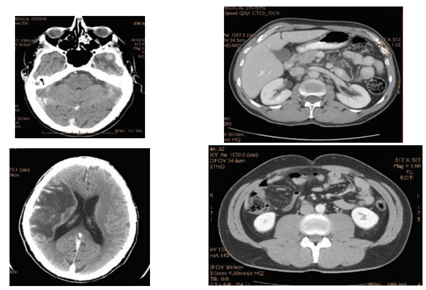
- CT



Modalités d' Imagerie

- CT





Comment obtenir des images de coupe à partir des valeurs d'atténuation de projection?

Modalités d' Imagerie

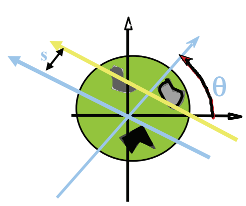
- CT

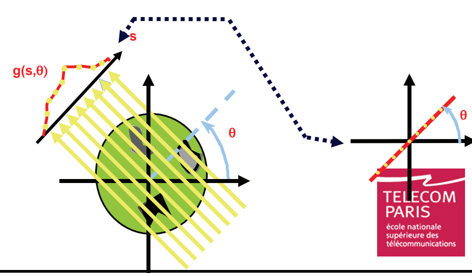
Reconstruction tomographique (cf, cours précédent)

- Transformée de Radon

$$g(s,\theta) = \int_L \mu(x,y)\,dl$$
$$= \int \mu(s\cos\theta - y'\sin\theta - s\sin\theta + y'\sin\theta)\,dy'$$

Théorème de projection: Si $g(s,\theta)$ = TR(f(x,y)), alors: $G(\omega_s,\theta)$=TF($g(s,\theta)$) est égale à la tranche centrale, suivant l'angle θ, de la TF 2D $F(\omega_x,\omega_y)$ de la fonction f(x,y).





Modalités d' Imagerie

- CT

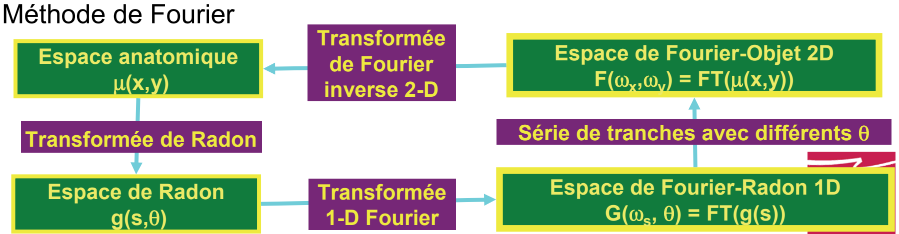
Reconstruction tomographique

• Rétroprojection filtrée (filtered backprojection)

$$f(x,y)=\int_0^{\pi}\hat{g}(s=x\cos\theta+y\sin\theta,\theta)d\theta$$

$$with\ \ \hat{g}(s,\theta)=\int_{-\infty}^{\infty}|\omega_S|G(\omega_S,\theta)\exp(i\omega_S s)d\omega_S$$

• Méthode de Fourier

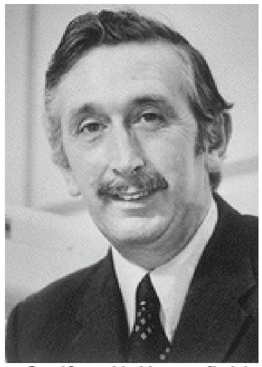


Modalités d' Imagerie

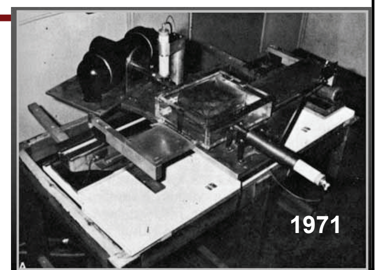
- CT
  - 1917: Radon montre la possibilité mathématique de reconstruire des formes bi ou tridimensionnelles à partir de projections multiples.
  - 1961 à 1968: Plusieurs études théoriques sur des appareils d'imagerie de reconstruction d'images sont faites sans résultat pratique (Cormack, Tufts Univ).
  - 1972: La firme de production de musique *EMI* après les succès des Beatles, investit dans la recherche qui aboutissent au premier appareil *EMISCANNER* par Hounsfield, ingénieur électronicien et informaticien.
  - 1972 - 1982: Nombreuses tentatives industrielles dans le domaine de l'imagerie tomographique avant d'abandonner (en particulier *EMI*); la technique est reprise par les grands fabricants de radiologie.
  - 1979 : Hounsfield et Cormack reçoivent le prix Nobel de Médecine pour leur invention.
  - 1988 : les premiers scanographes à rotation continue sont utilisés.

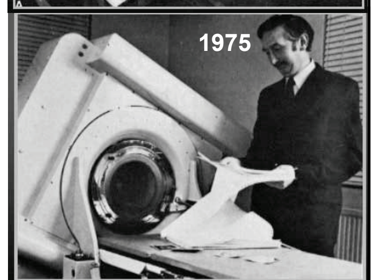
Modalités d' Imagerie

- CT



Godfrey N. Hounsfield





http://www.medinfo.ufl.edu/other/histmed/klioze/

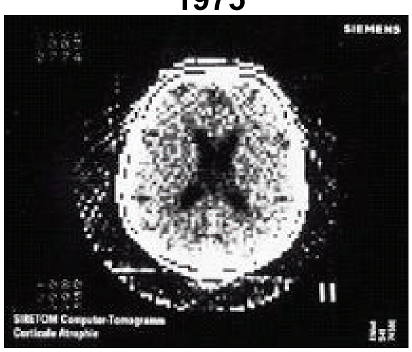
http://www.nobel.se/medicine/laureates/1979/hounsfield-autobio.html

http://www.teaching-biomed.man.ac.uk/student_projects/2000/mmmr7gjw/technique.htm

Modalités d' Imagerie

- CT

1975



128x128 pixels, 1-4 heures d'acquisition, 1-5 jours de calcul.

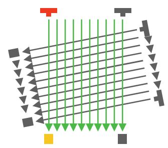
2000

512x512pixels, 0.35 sec d'acquisition, <1sec de calcul.

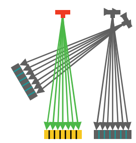
Modalités d' Imagerie

- CT

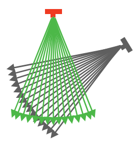
1ère génération: translation et rotation



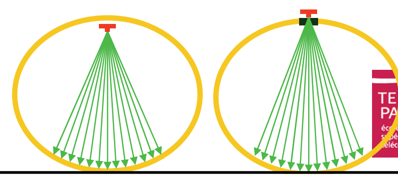
2eme génération: translation et rotation (émetteur en éventail)



3eme génération: rotation-rotation



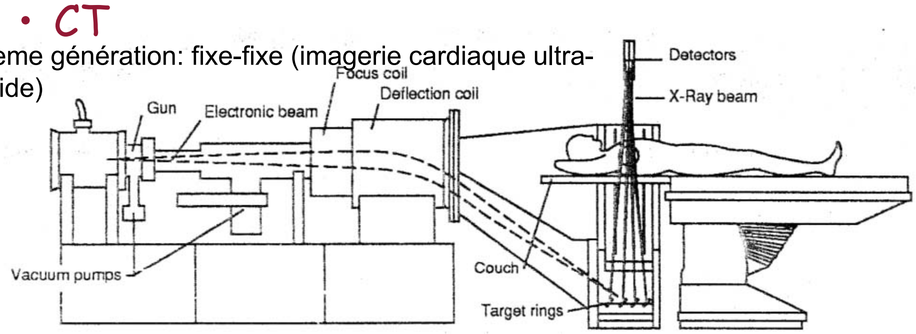
4eme génération: rotation-fixe



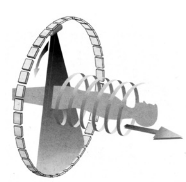
Modalités d' Imagerie

- CT

• 5eme génération: fixe-fixe (imagerie cardiaque ultra-rapide)



• Scanner hélicoïdal (Spiral CT): mouvement continu de la table d'examen.



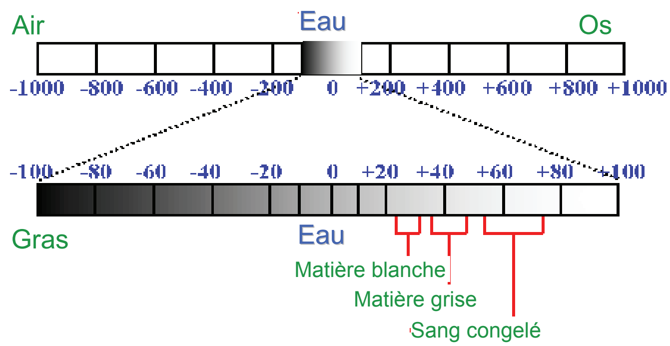
Modalités d’ Imagerie

- CT

$$HU = 1000 \bullet \frac{\mu - \mu_W}{\mu_W}$$

Unité de Hounsfield: Rapport entre le coefficient d’atténuation linéaire mesuré et le coefficient pour l’eau à 50keV.

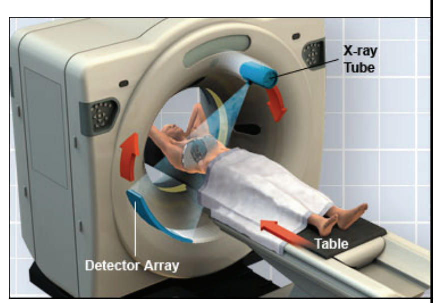
Valeurs des organes du corps humain.



Modalites d’ Imagerie

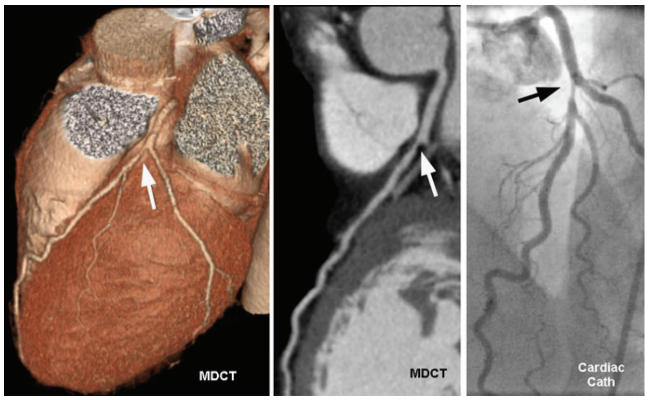
- CT Angiography
  - **Spatial resolution** 0.4 mm (conventional coronary angiography 0.15-0.25 mm)
  - **Temporal resolution** (shutter speed) improved to 166 msec with faster gantry rotation (330 msec) (conventional angiography 6 msec)
  - Up to **64 slices** in one rotation (overlapping slices).
  - Entire heart imaged in 5-15 seconds

$\Rightarrow$ less radiation and contrast required.



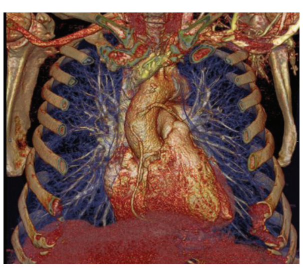
Modalités d' Imagerie

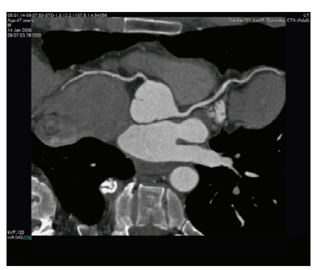
- CT Angiography



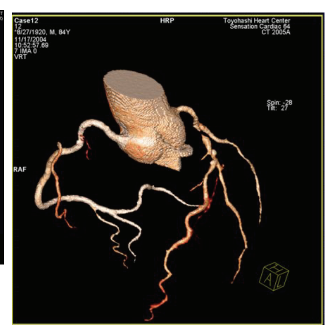
Modalités d' Imagerie

- CT: Visualisation 3D





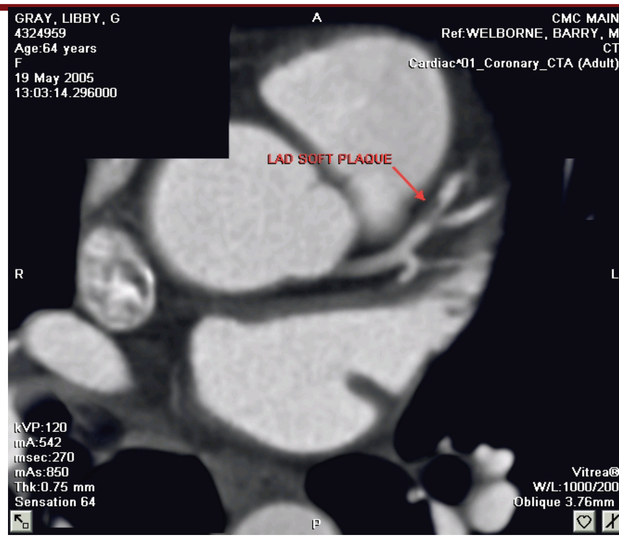
« Plan » 3D



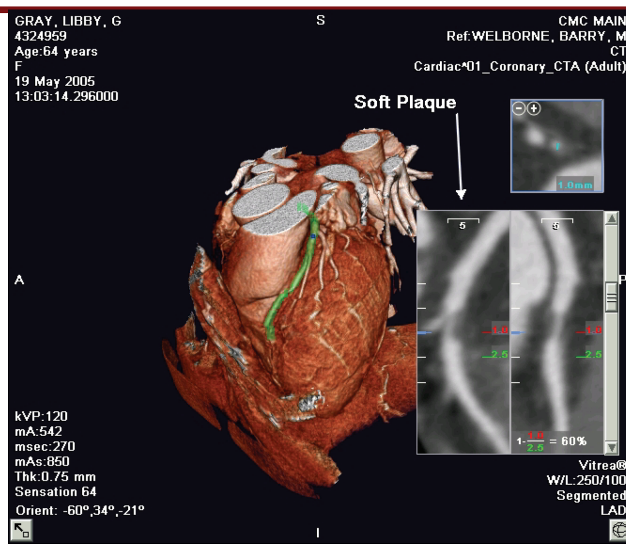
Coronaires

Modalités d' Imagerie

• CT



Modalités d' Imagerie



Modalités d' Imagerie

- CT: Conclusions Actuelles
  - ***ne remplacera pas*** les examens d'angiographie classiques.
  - Post-traitement des images très difficile.
  - Très bonne prédiction négative.
  - IRM à préférer à cause des radiations

Modalités d' Imagerie

- CT: Inconvénients:
  - Rythmes cardiaques rapides (>80 bpm) et irréguliers.
  - Stents.
  - Besoin d'agents de contraste (Cr > 2.0 mg/dl).
  - Limitation de résolution spatiale (<1.5 mm).
  - Patients obèses.
  - EXPOSITION AUX RADIATIONS.

Modalités d' Imagerie

- CT: Irradiations
  - PA/Lateral CXR 0.04-0.06 mSv
  - Head CT 1-2 mSv
  - Chest CT 5-7 mSv
  - Abd/Pelvis CT 8-11 mSv
  - Diagnostic Cor Angiogram 3-5 mSv
  - MSCT angiography 9.3-11.3 mSv

**Average annual background radiation in U.S ~ 3.6 mSv*

Morin et al. Circulation 2003;107:917-22.

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Modalités d' Imagerie

- CT: Irradiations
  - Quantification des effets nocifs des radiations difficile à évaluer.
  - Enfant de moins de 15 ans: risque de cancer par 1 examen CT = 1 sur 500.
  - Adulte de 45 ans: risque de cancer par 1 examen CT = 1 sur 1250.

Brenner et al. Radiology, 231(2):440-445.

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Modalités d' Imagerie

- CT: Prescription
  - **Score de calcium**: stratification de risques sur des patients à risques intermédiaires.
  - Angiographie des coronaires non-invasive: patients symptomatiques à bas risques ou patients asymptomatiques à risques intermédiaires.

*Un test *négatif (normal CTA) a 98% de chance d'avoir un résultat d'angiographie coronaire normal*

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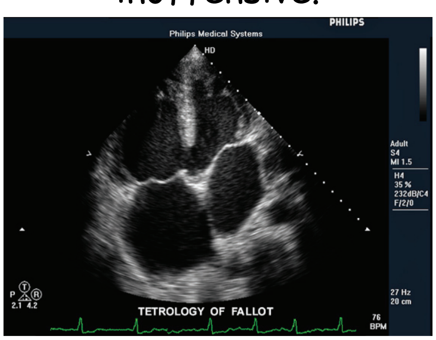
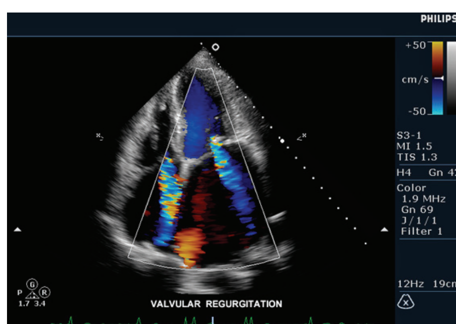
Modalites d' Imagerie

- Ultrasons
  - Modalité temps-réel, économique, portable, inoffensive.





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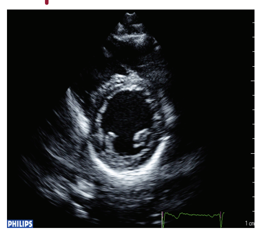
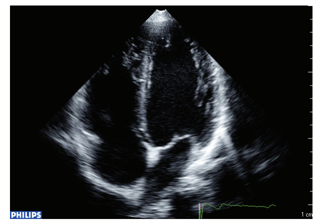
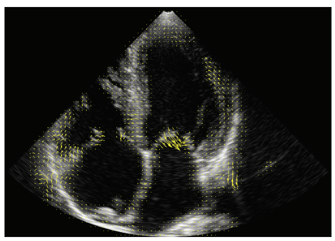
Modalites d' Imagerie

- Ultrasons Temps-réel

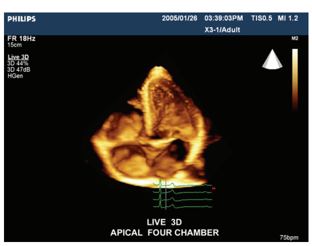


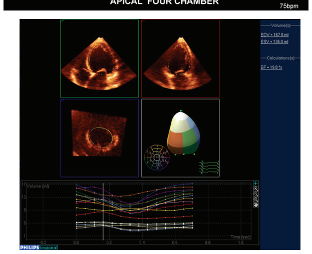


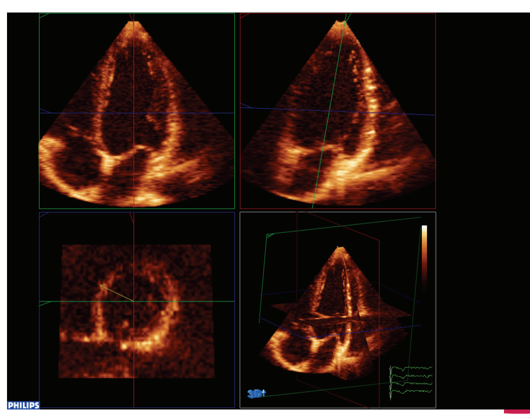


Modalites d' Imagerie

- Ultrasons 3D





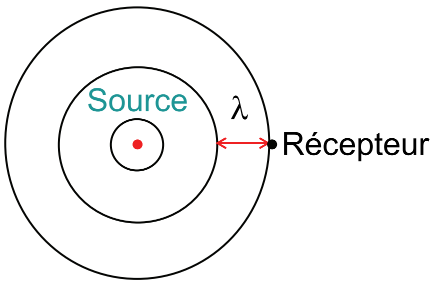


Modalités d' Imagerie

- Ultrasons: Doppler

Effet Doppler

Changement de la fréquence observée d'une onde sonore quand la source ou le récepteur est en mouvement par rapport à l'autre.



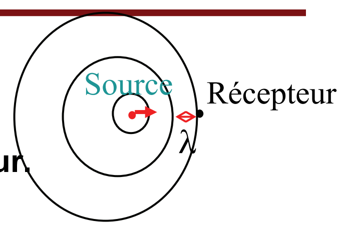
$f_s = f_r$ et $\lambda_s = \lambda_r$

(f_s,λ_s) = fréquence et longueur d'onde de la source.
(f_r,λ_r) = fréquence et longueur d'onde reçues.

Modalités d' Imagerie

- Ultrasons: Doppler

Configuration de Mouvement:
- **Récepteur stationnaire.**
- **Source en mouvement vers le récepteur.**



La longueur d'onde λ_r du bruit entendu est raccourcie:

$$\lambda_r = \lambda_s - \Delta\lambda$$

avec λ_s la longueur d'onde de la source, et $\Delta\lambda$ la distance parcourue par la source en une période .
Soit pour une vitesse de la source V_s :

$$\Delta\lambda = V_s/f_s$$

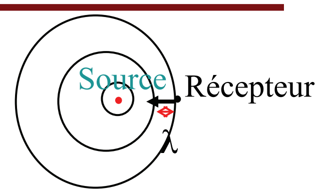
Modalités d' Imagerie

- Ultrasons: Doppler

Configuration de Mouvement:

- Source stationnaire.

- Récepteur en mouvement vers la source.



La longueur d'onde λ_r du bruit entendu est raccourcie:

$$\lambda_r = \lambda_s - \Delta\lambda$$

avec λ_s la longueur d'onde de la source, et $\Delta\lambda$ la distance parcourue par le récepteur en une période .

Soit pour une vitesse du récepteur V_r :

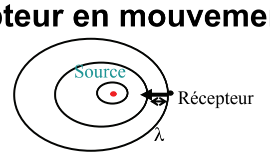
$$\Delta\lambda = V_r/f_r$$

Modalités d' Imagerie

- Ultrasons: Doppler

- Source stationnaire.

- Récepteur en mouvement.

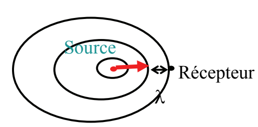


Approche $f_r = f_0\left(\frac{(c+V_r)}{c}\right)$

Éloignement $f_r = f_0\left(\frac{(c-V_r)}{c}\right)$

- Récepteur stationnaire.

- Source en mouvement.



Approche $f_r = f_0\left(\frac{c}{(c-V_s)}\right)$

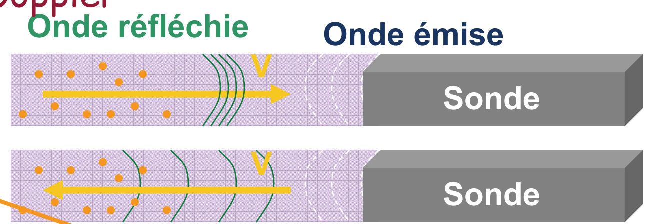
Éloignement $f_r = f_0\left(\frac{c}{(c+V_s)}\right)$

Modalités d' Imagerie

- Ultrasons: Doppler

Approche

Eloignement



Visualisation de globules rouges dans les vaisseaux (artères ou veines) combine les 2 effets: récepteur puis source mobile en approche ou éloignement:

$$f_r = f_0\left(\frac{(c+V)}{(c-V)}\right)$$

$$\Delta f = f_r - f_0 = \left(\frac{2V}{(c-V)}\right) f_0$$

$c >> V$

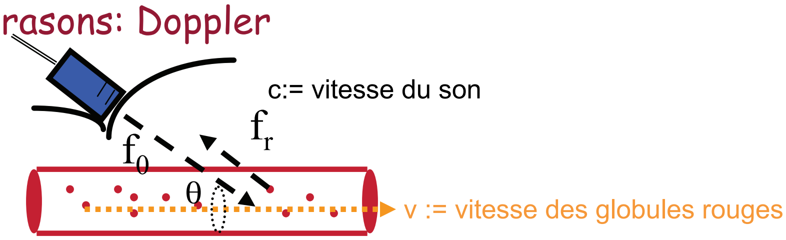
$$|\Delta f| = \frac{2V}{c} f_0$$

$$f_r = f_0\left(\frac{(c-V)}{(c+V)}\right)$$

$$\Delta f = f_r - f_0 = \left(\frac{-2V}{(c+V)}\right) f_0$$

Modalités d' Imagerie

- Ultrasons: Doppler



- Possibilité de mesurer indirectement la vitesse V du sang dans le vaisseau.
- Ajustement de la mesure de la vitesse suivant l'orientation du vaisseau:

$$|\Delta f| = \frac{2V\cos(\theta)}{c} f_0 \quad \Rightarrow V = \frac{c|\Delta f|}{2 f_0 \cos(\theta)}$$

Angles utilisés en pratique: problèmes de réfraction $30^o < \theta < 60^o$ $|\Delta f|$ trop petit

Modalités d' Imagerie

- Ultrasons: Doppler

Exemples d'effet Doppler en médical

- Doppler continu
- Doppler par pulsation: Doppler Spectral

⇨ **Mesures d'indices spectraux**

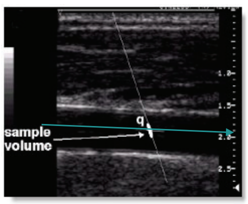


Figure 1

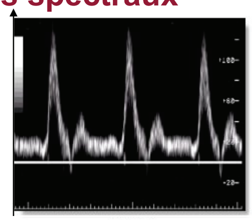


Figure 2

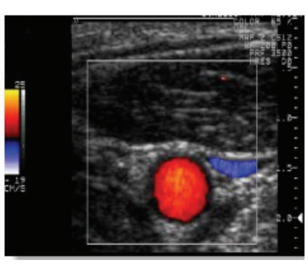
Spectre de Fourier

Modalités d' Imagerie

- Ultrasons: Doppler

Exemples d'effet Doppler en médical

- Doppler couleur

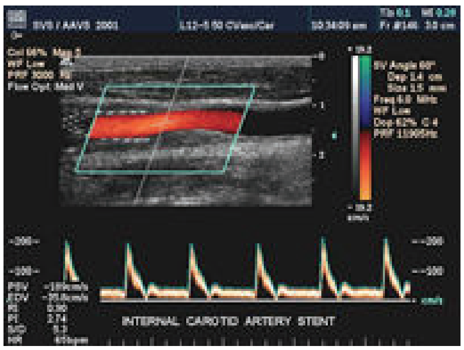


Artère et veine ombilicales

Source: www.gehealthcare.com

Modalités d’ Imagerie

- Ultrasons: Doppler
- **Exemples de Doppler en Medical**



Modalités d’Imagerie

- Ultrasons: Elastographie
  - Elastographie: mesure de contraintes (strain) des tissus par une déformation controllée.
  - La réponse des tissus est fonction de leurs propriétés mécaniques.
  - Imagerie de Strain: Mesures de contraintes (strain) des tissus sous l’effet de déformations physiologiques (pression sanguine, contractions des muscles).
  - Différentes méthodes de mesures de contraintes:

1. rf ou enveloppe des échos.
2. Tissue Doppler Imaging: contrainte/déformations.
3. Sonoelasticité.

Modalités d'Imagerie

- Ultrasons: Elastographie

$$\sigma(t) = E \times \varepsilon(t)$$

Elasticité

Force totale (wall stress)

Déformation

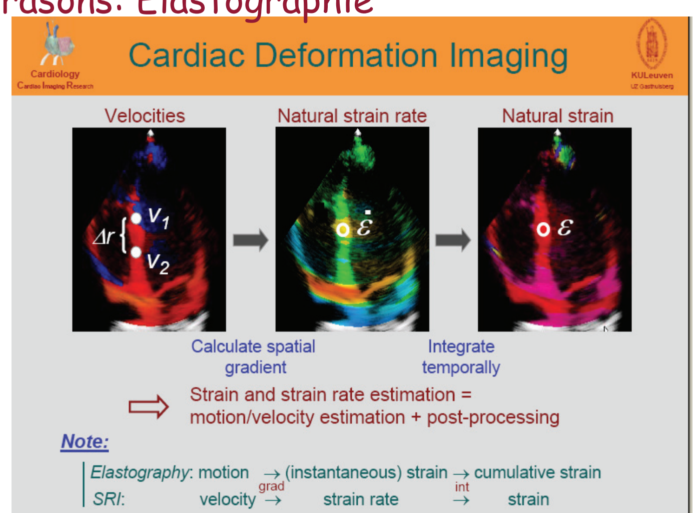
Strain: Déformation d'un objet par rapport à sa forme de référence.

Mesures par elastographie

$$\frac{V_2 - V_1}{\Delta x} = \dot{\varepsilon}(t)$$

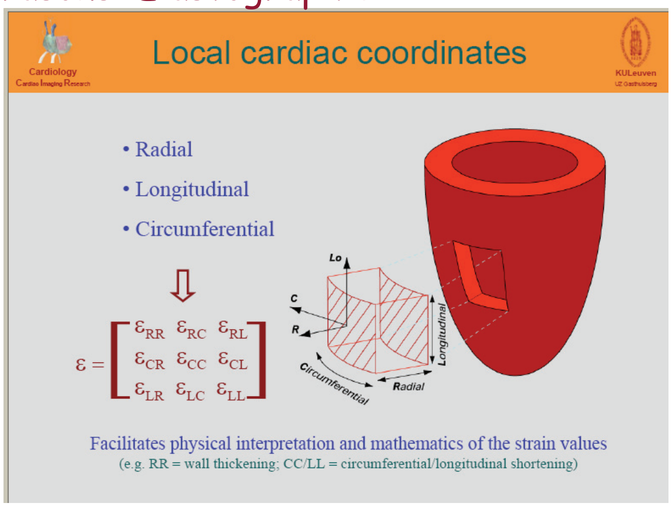
Modalités d'Imagerie

- Ultrasons: Elastographie



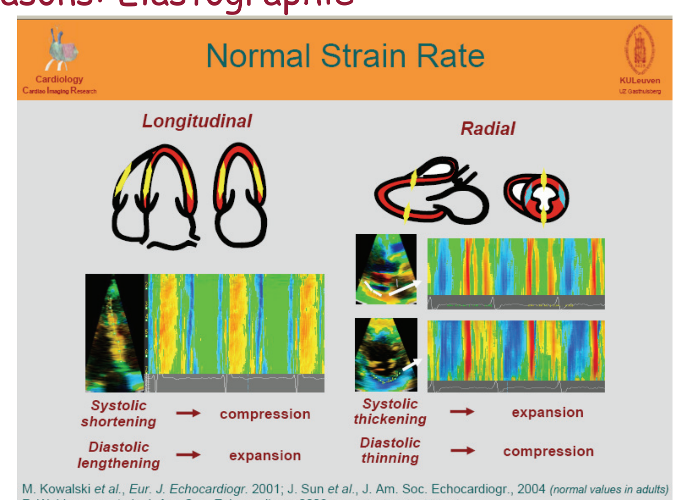
Modalités d'Imagerie

- Ultrasons: Elastographie



Modalités d'Imagerie

- Ultrasons: Elastographie



Modalités d'Imagerie

- IRM
  - Nombreux protocoles d'acquisition (CINE).
  - Antenne de surface.
  - Apnée.
  - Sang noir ou blanc.
  - Résolution ~1.5mm^2*8mm.
  - Synchronisation par ECG.
  - ~16 images par cycle.
  - Agent de contraste (gadolinium) + rehaussement tardif.

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Modalités d'Imagerie

- IRM

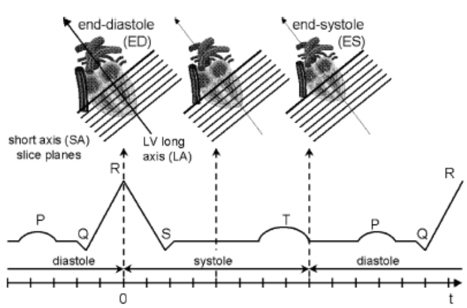

Fig. 1. Illustration of a classical acquisition of SA images with a ECG-gated cine MR sequence. The same slice is acquired at successive time points of the cardiac cycle. However, due to the motion of the heart, we do not observe the same anatomical region within the same slice. Moreover, several cardiac cycles are required to reconstruct slices. When possible, patients are asked to retain their breath (15–20 s) during acquisition.

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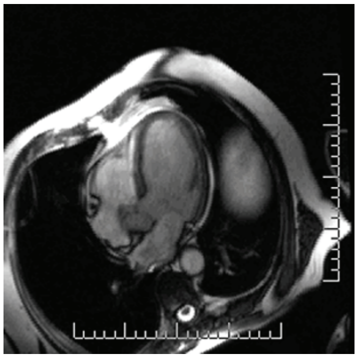
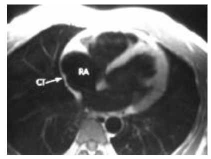
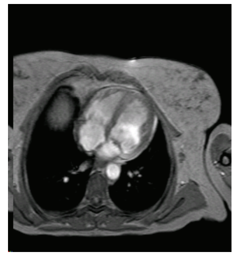
Modalités d'Imagerie

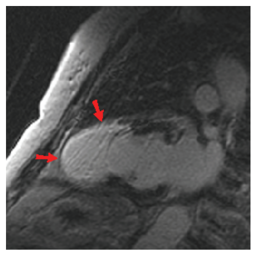
- IRM



Courtesy of Robert R. Edelman







Modalités d'Imagerie

- IRM: Rehaussement tardif
  - Viabilité du myocarde supposant que les zones infarctées sont réhaussées 10-15 minutes après l'injection d'un agent de contraste paramagnétique.
  - Réhaussement par accumulation de gadolinium dans l'espace extracellulaire à cause de la perméabilité de la membrane.
  - Quantification de la taille, localisation et étendue transmurale de l'infarctus.
  - Si < 50% de l'épaisseur du muscle: contractilité améliorée sur le segment après revascularisation.

Modalités d'Imagerie

- IRM: tagging
  - Production de bandes de saturation (tag) par pulsations de radiofrequences.
  - Imagerie multiphasée pour détecter des diminutions de saturation
  - Mouvement des lignes de taggues pendant le cycle cardiaque.
  - Calcul de strain.
  - Problème: Détection de lignes de taggues et des intersections.

Modalités d'Imagerie

- IRM: tagging

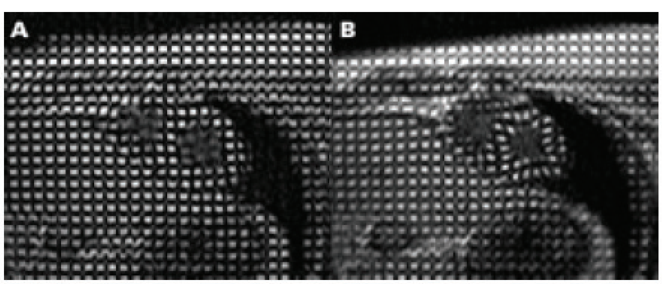


Figure 17 Tagged short axis images at the mid ventricular level in 16 year old patient with normal heart. (A) Diastolic image. (B) Systolic image. Note the distortion of the tagging lines on the systolic frame.

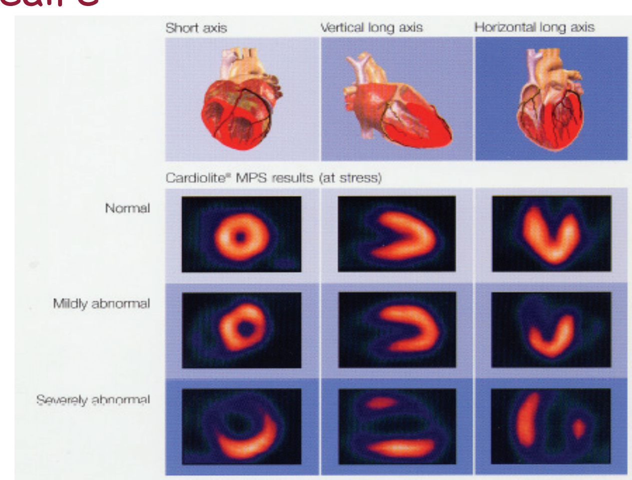
Modalités d'Imagerie

- Nucléaire
  - Imagerie de perfusion myocardique.
  - Utilisation d'agents radioactifs (sur globules rouges)
    - Thallium – 201
    - Technetium-99 m Sestamibi
    - Technetium-99 m Tetrofosmin

Modalités d'Imagerie

- Nucléaire

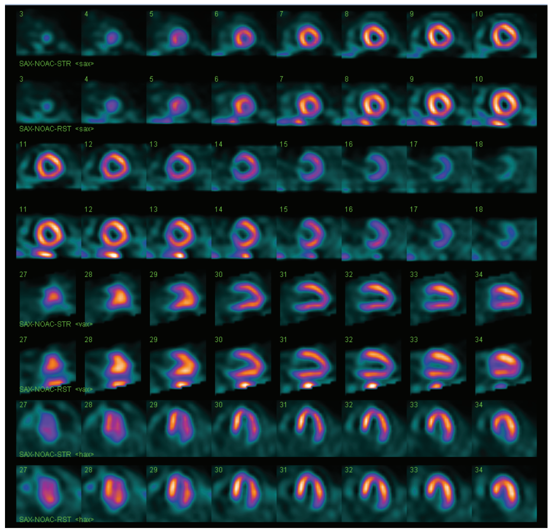
Imagerie de perfusion dynamique et statique



Modalités d'Imagerie

Imagerie de perfusion statique

Stress
Rest



SA

SA

VLA

HLA

Stress
Rest

Stress
Rest

Stress
Rest

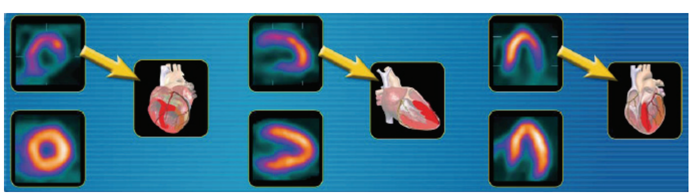
Modalités d'Imagerie

- Imagerie nucléaire: statique (perfusion)

Examens d'efforts (stress exams)

Flux sanguin anormal

Flux sanguin normal



Stress

Rest

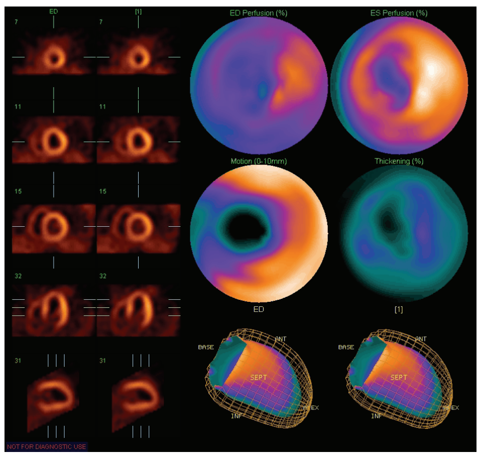
Modalités d'Imagerie

- Imagerie nucléaire: dynamique (perfusion)

SA

HLA

VLA



- Synchronisée par ECG.
- Estimation de la fonction cardiaque:
  - Mouvement: contraction uniforme du myocarde?
  - Fraction d'ejection.

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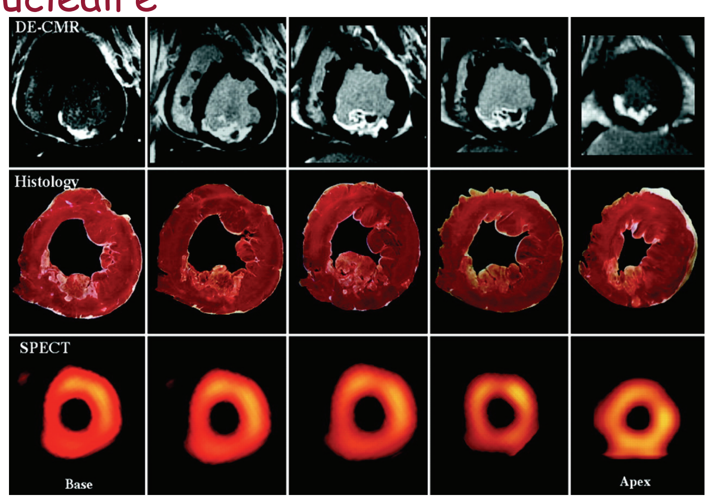
Modalités d'Imagerie

- Nucléaire



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Plan

3.1 Applications Cliniques

3.2 Applications Recherche

Applications Cliniques

Mesures du volume cardiaque

- Modalités:
  1. Imagerie nucléaire synchronisée
  2. Angiographie
  3. IRM
  4. Echocardiographie

Applications Cliniques

Mesures du volume cardiaque

1. Imagerie nucléaire synchronisée

1. Radionuclide: Technetium-99 (½ vie ~6 heures)
   Injection dans le sang
2. Détection des γ-émissions atour du ventricle cardiaque.
- Synchronisation des périodes de countage par l'ECG
- Comparaison des comptages à fin-diastole & fin-systole.
3. Ratio ~ EDV/ESV = Fraction d'Ejection

⇒ Pas quantitatif

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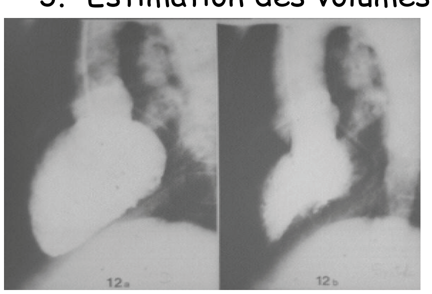
Applications Cliniques

Mesures du volume cardiaque

2. Angiographie

1. Agent de contraste radio-opaque.
   Injection sanguine.
2. Acquisition de série d'images rayons-X.
3. Estimation des volumes sur images 2D.



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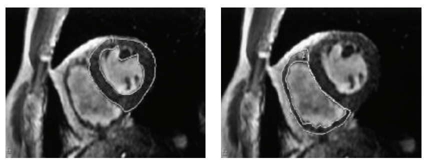
Applications Cliniques

Mesures du volume cardiaque

3. IRM

1. Densité de protons.
2. Acquisition lente (synchronisée) et résolution spatiale limitée.
3. Estimation des volumes sur des coupes épaisses.



www.emedecine.com

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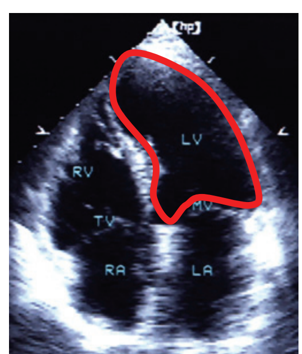
Applications Cliniques

Mesures du volume cardiaque

4. Echocardiographie

1. Acquisitions 2D (parasternale, épicardiales ou trans-oesophageale)
2. Estimation de volumes



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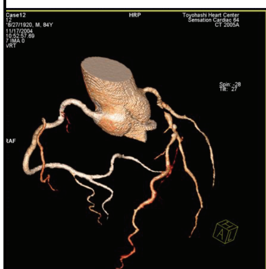
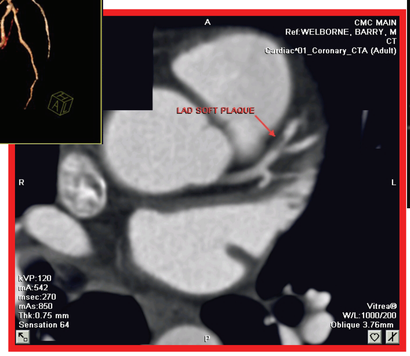
Applications Cliniques

- CT: Calcium Scoring





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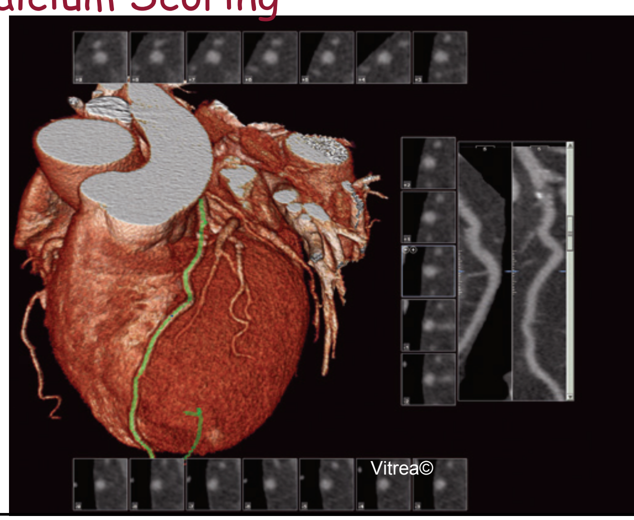
Applications Cliniques

- CT: Calcium Scoring



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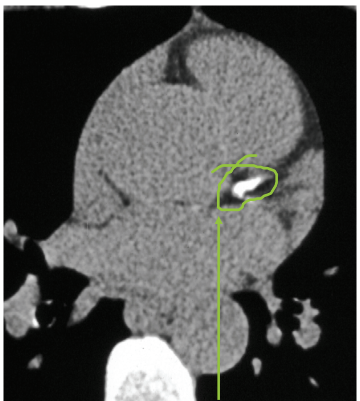
Applications Cliniques

- CT: Calcium Scoring



Area = 15 mm²
Peak CT = 450
Score = 15 x 4 = 60

Total Score = S

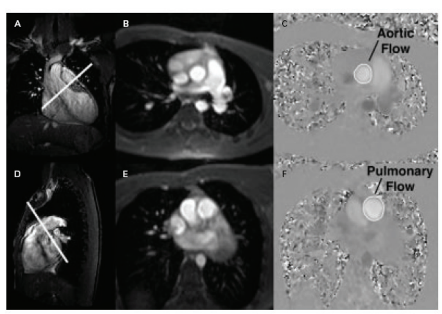
Hn x-factor
(Agatston Scoring)

130-199	1
200-299	2
300-399	3
>400	4

Area = 8 mm²
Peak CT = 290
Score = 8 x 2 = 16

Applications Cliniques

- IRM: Mesure de flux



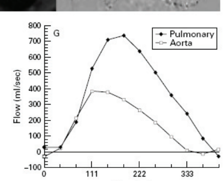
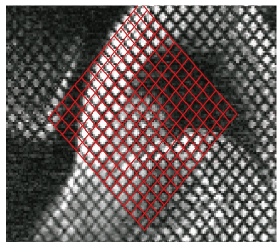
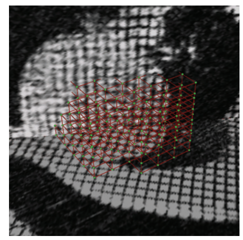


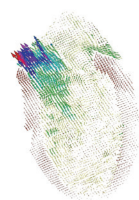
Figure 16 Pulmonary and systemic arterial flow determination by phase contrast magnetic resonance imaging in a 17 year old patient with partial anomalous pulmonary venous connection. (A) Coronal positioning scan for aortic acquisition, showing position of aortic phase contrast section. (B) Magnitude image from aortic phase contrast section. (C) Corresponding phase image from aortic section. (D) Sagittal positioning scan for pulmonary acquisition, showing position of pulmonary phase contrast section. (E) Magnitude image from pulmonary phase contrast section. (F) Corresponding phase image from pulmonary section. (G) Calculated systemic and pulmonary flow rates. Calculated Qp:Qs ratio was 2.17:1.

Applications Cliniques

- IRM: tagging



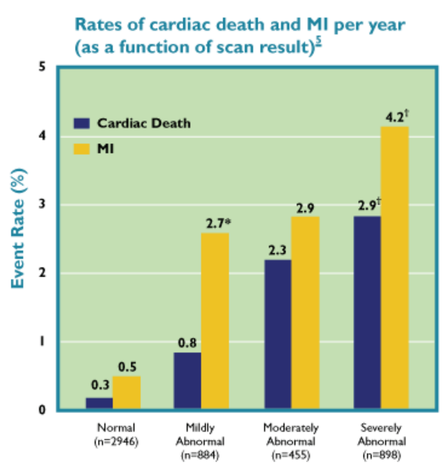




Applications Cliniques

- Nucléaire

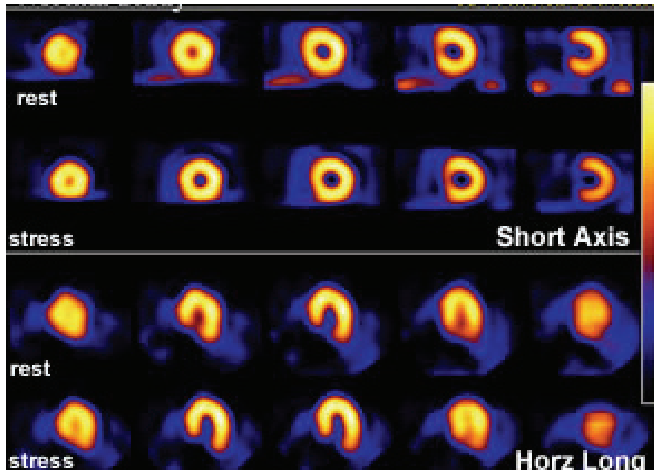
Eviter la cathétarisation



Applications Cliniques

- Nucléaire

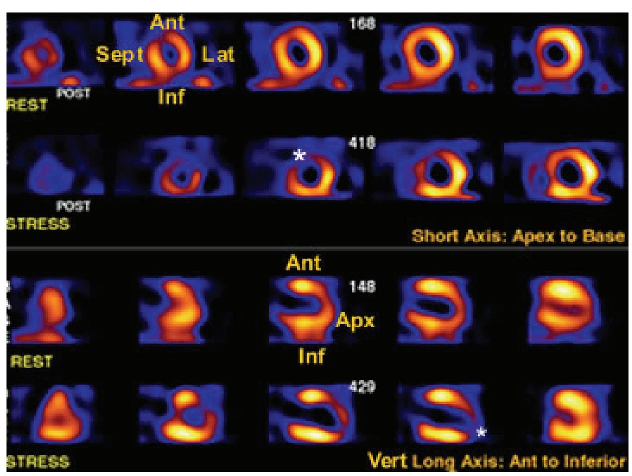
Normal



Applications Cliniques

- Nucléaire

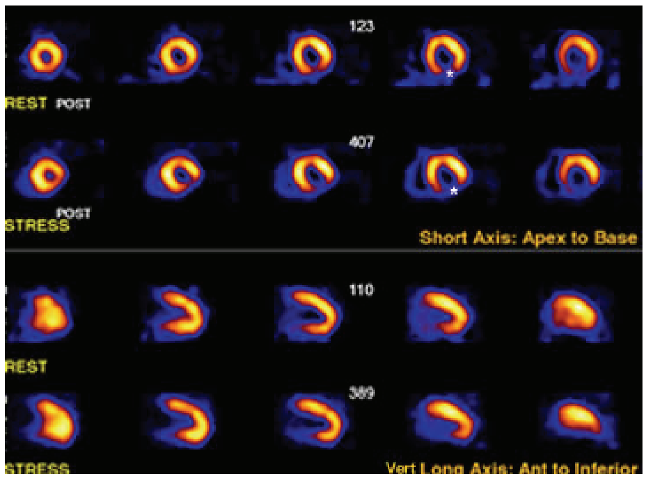
Ischémie



Applications Cliniques

- Nucléaire

Infarctus



Applications Recherche

- Modélisation cardiaque

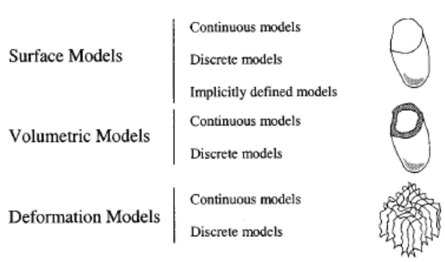
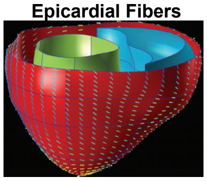


Fig. 2. Proposed classification of cardiac modeling approaches.

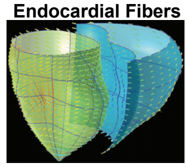
Applications Recherche

Modèle Cardiaque: FEM

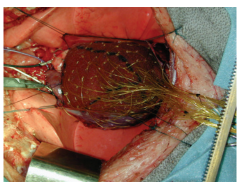
Epicardial Fibers

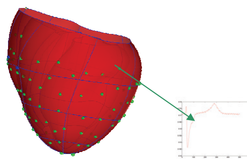


Endocardial Fibers

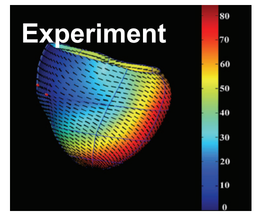


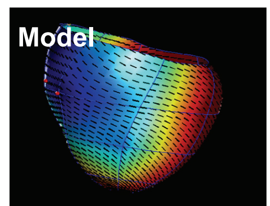
Physiologie musculaire





Physiologie électrique





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Applications Recherche

Modèle Cardiaque

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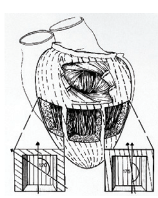
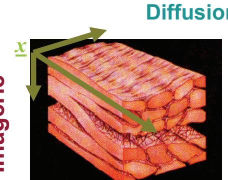
1. Physiologie



Fox and Hutchins (1972). Johns Hopkins Med. J. 130(5): 289-299

2. Imagerie

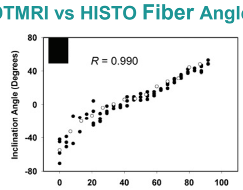
Diffusion Tensor MR Imaging (DTMRI)



- **DTMRI ⇒ 3x3 diffusion tensor $M_i(\underline{x})$**
- **Hypothesis – The principle eigenvector of $M_i(\underline{x})$ is aligned with fiber direction at point $\underline{x}$**

DTMRI vs HISTO Fiber Angles

3. Mesures

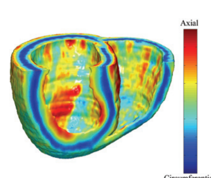


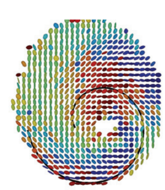
Scollan et al (1998). *Am. J. Physiol.* 275: H2308

Holmes, A. et al (2000). *Magn. Res. Med.*, 44:157

DTMRI Reconstruction of Canine Ventricles

4. Intégration dans le modèle





Scollan et al (2000). *Ann. BME*. 28(8): 934

Applications Recherche

- Modélisation cardiaque

Automatic Construction of Multiple-Object Three-Dimensional Statistical Shape Models: Application to Cardiac Modeling

Alejandro F. Frangi*, Daniel Rueckert, Julia A. Schnabel, and Wiro J. Niessen

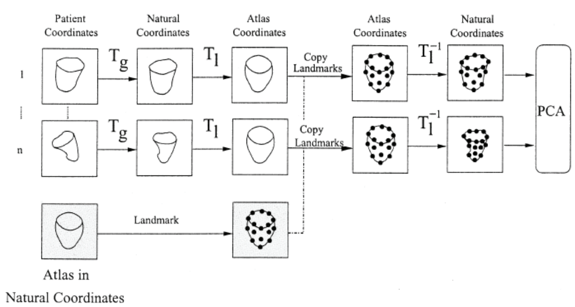


Fig. 1. Overview of the automatic landmarking framework. All individual data sets are matched to an atlas via a quasi-affine transformation ($\mathbf{T}_g$) and a nonrigid transformation ($\mathbf{T}_l$). The landmarks in the atlas can then be copied to the individual patients. The nonrigid deformation is subsequently reversed. Thus, PCA is carried out in a space where all shapes are aligned with the atlas (the *natural coordinate system,* explained in Section IV-C3). The principal modes of variation will therefore account for nonrigid deformations and not for pose or size differences.

Applications Recherche

- Modélisation cardiaque

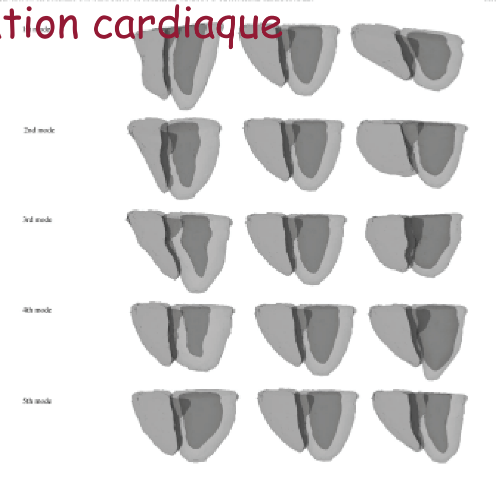


Fig. 10. Shape instances generated using the 3-D two-chamber model and the κ statistic registration measure from 14 cardiac data sets. The instances are generated by varying a single shape parameter, fixing all others at zero standard deviations from the mean shape. This two-chamber model consists of 679 LV endocardial nodes, 1352 LV epicardial nodes, and 1841 RV endocardial nodes.

Applications Recherche

- IRM

Kinematics of the Heart: Strain-Rate Imaging From Time-Resolved Three-Dimensional Phase Contrast MRI

Pernilla Selskog*, Einar Heiberg, Tino Ebbers, Lars Wigström, and Matts Karlsson

A. Theory

To calculate strain-rate from a velocity field, the 3×3 velocity gradient tensor (Jacobian) L_{ij} is calculated according to

$$L_{ij} = \frac{\partial u_i}{\partial x_j} \quad (1)$$

where u_i, $i = 1,2,3$ are the three velocity components in the x_j direction, $j = 1,2,3$ [7].

Strain-rate is represented by the strain-rate tensor D_{ij}, which is the symmetric part of L_{ij} [7]

$$D_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right). \quad (2)$$

An invariant I_t representing the total amount of strain-rate in each voxel was calculated according to

$$I_t = \lambda_1^2 + \lambda_2^2 + \lambda_3^2. \quad (3)$$

The eigenvalues and eigenvectors of the strain-rate tensor are the principal values and the principal directions of strain-rate in the myocardium. The sign of the eigenvalue distinguishes between positive and negative material stretching in the direction of the corresponding eigenvector.

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- IRM

D. In Vivo Data

Calculations were performed using velocity data for a healthy 24-year-old volunteer with a heart rate of 66 bpm. The velocity measurements were performed using a 1.5 T Signa Horizon Echospeed scanner (General Electric Medical Systems, Milwaukee, WI) with a 3-D cine phase contrast pulse sequence, allowing offline retrospective gating based on the signal from a pulse oximeter [9], [12].

Velocity encoded data were acquired in all three directions at 12 times for each phase-encoding step. A complete set of 3-D k-space data was interpolated in the time domain to 32 time-frames using an interpolation method based on a normalized convolution algorithm with a Gaussian interpolation function [9]. Using peripheral gating, i.e., gating based on the signal from a pulse oximeter on the finger, the first time frame corresponds to approximately 200 ms after onset of electrical systole. Only a cylindrical region of k-space was collected in order to reduce the acquisition time by not acquiring the corners of the $k_y - k_z$ plane [13].

All three velocity components were measured in a $30.0 \times 30.0 \times 11.2$ cm axial volume, suitable for myocardial motion studies, with a spatial resolution of $1.2 \times 4.0 \times 4.0$ mm and a temporal resolution of 108 ms (TR = 27 ms, TE = 7.2 ms, VENC = 0.18 m/s, flip angle = 20°, one NEX, acquisition time 39:14 min). The technique includes automated unwrapping of aliased velocities [9]. The MRI data were resampled using zero-filling in the Fourier domain to a voxel size of $1.5 \times 1.5 \times 1.5$ mm. Saturation bands superior and inferior to the imaging volume were used to reduce the signal from the blood [14]. After the 3-D inverse Fourier transform, the phase contribution from concomitant field (Maxwell) effects was calculated and subtracted from the velocity data [15].

A linear 3-D least square fit to the data from regions containing stationary tissue was subtracted for correction of eddy current effects [16]. Conventional 2-D time-resolved gradient-echo images were acquired in short- and long-axis cardiac views for better depiction of anatomical landmarks.

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Applications Recherche

- IRM

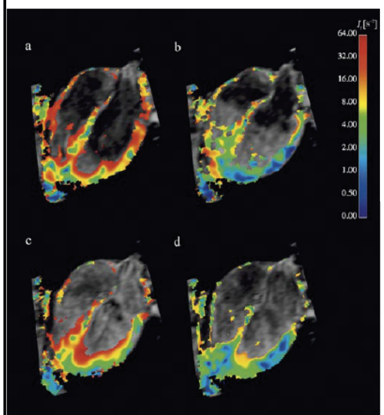

Fig. 4. A color map of the invariant (I_t) for a long-axis slice through the myocardium in (a) early diastole, (b) end diastole, (c) systole, and (d) end systole. A time plot of I_t at a point in the lateral left ventricular wall is shown in Fig. 5.

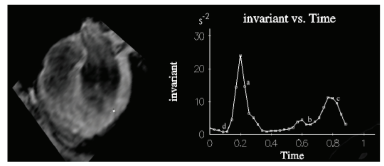

Fig. 5. Strain-rate invariant $I_t = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$ at a point in the lateral left ventricular wall (highlighted in the left figure) throughout the cardiac cycle (right). Peaks are found in early diastole and in systole. (a)–(d) refer to the time frames displayed in Fig. 4.

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Applications Recherche

- Ultrasons

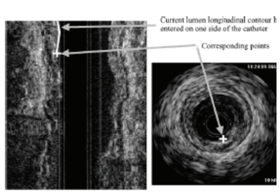

Fig. 2. (a) Longitudinal IVUS image of the 3-D data set in which a conto
being entered and (b) current longitudinal contour point displayed on the
responding 2-D IVUS image. At the end of the initialization procedure, 4
were traced in 3 longitudinal images (that converts into 6 points on the lu
border and 6 points inside the media in each axial frame).

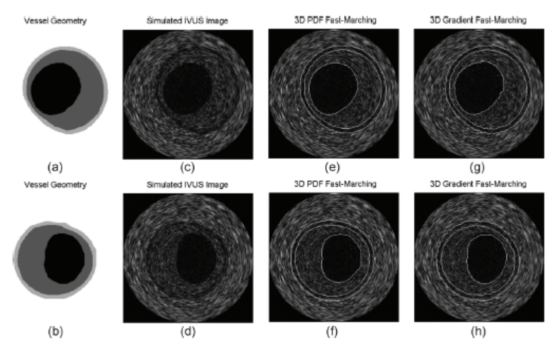

Fig. 5. Segmentation examples on simulated data. (a) and (b) Vessel geometries and (c) and (d) simulated IVUS cross-sectional images. Lumen, thickened intima, and media detected boundaries with (e) and (f) PDFs and (g) and (h) gradient 3-D fast-marching methods.

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Applications Recherche

- Ultrasons