
# PET/MRI Nükleer Tıp Bakişaçısı

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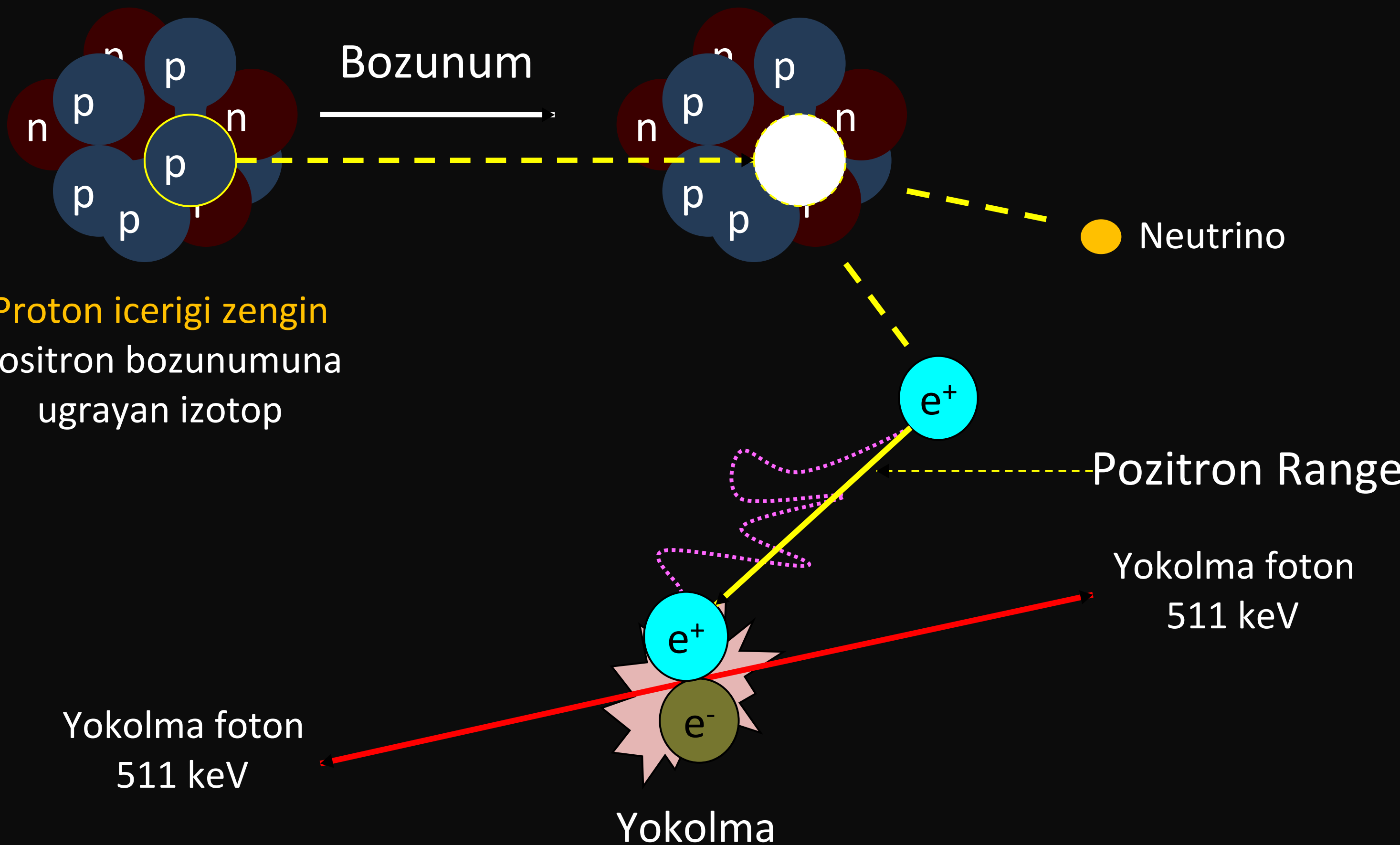
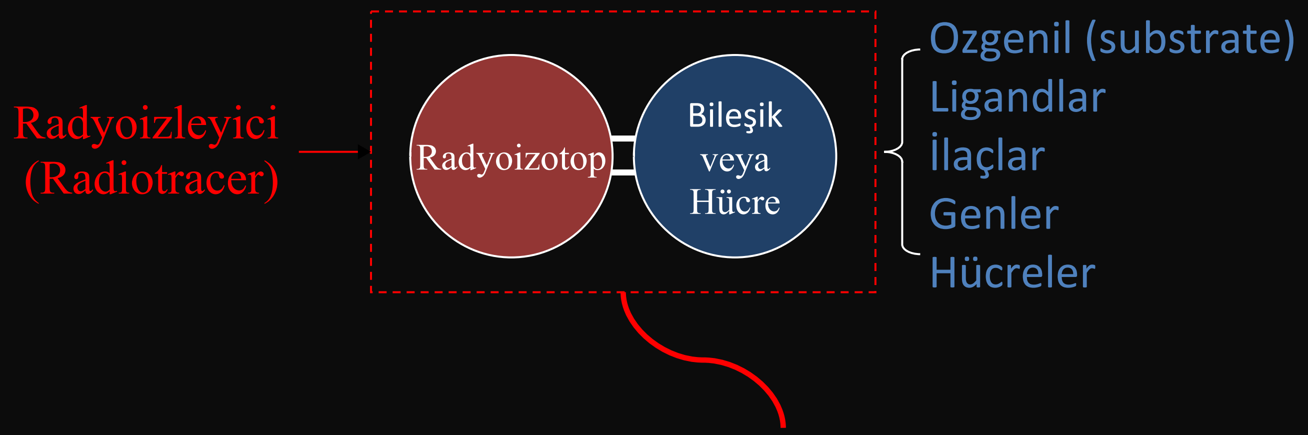
# Içerik

- Giriş
- PET/MRI
- İnstrumentasyon
- Ham Görüntulere uygulanan düzeltmeler
    - Foton azalmasinin düzeltilmesi
    - Bundan dogan görüntü hataları
- Tartışma ve Sonuçlar

# Pozitron bozunumu ve yokolma (Annihilation)




**Yok olma** olayından sonra elektron ve pozitron, sahip oldukları kütlelerin enerji eşdeğeri olan 511 KeV enerjili iki fotona dönüşürler.




Radyoizleyiciler dokudaki moleküler, biyokimyasal veya fizyolojik olayları (doku kan dolaşımı gibi) denetlemek için kullanılır.

| İzotop | Yari Ömür (dk) | Maximum Enerji (MeV) | Positron Menzili (Su) (Max, Ortalama) mm |
|---|---|---|---|
| F-18 | 109.7 | 0.635 | (2.4, 0.6) |
| C-11 | 20.4 | 0.96 | (4.1, 1.1) |
| N-13 | 9.96 | 1.19 | (5.1, 1.5) |
| Ga-68 | 68.3 | 1.89 | (8.2, 2.9) |
| Rb-82 | 1.25 | 3.4 | (14.1, 5.9) |

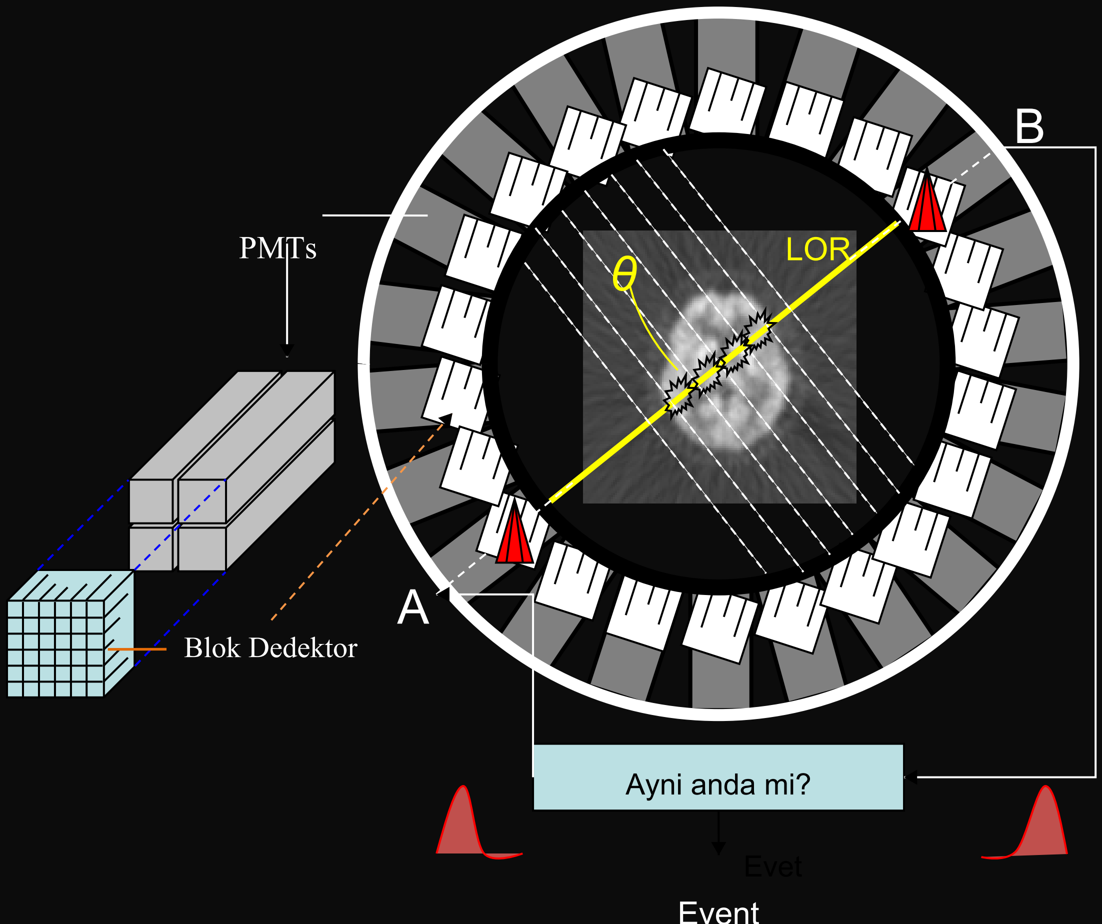
Generatorle üretilirler.

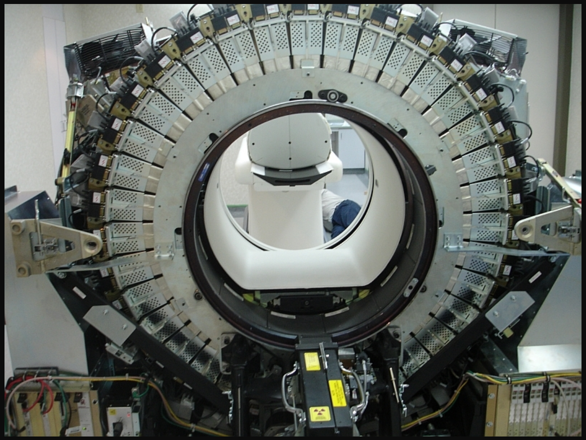
Dale L. Bailey, et al. (Eds), Positron Emission Tomography, Springer, 2005

# Yaygin Kullanilan Radyoizleyiciler

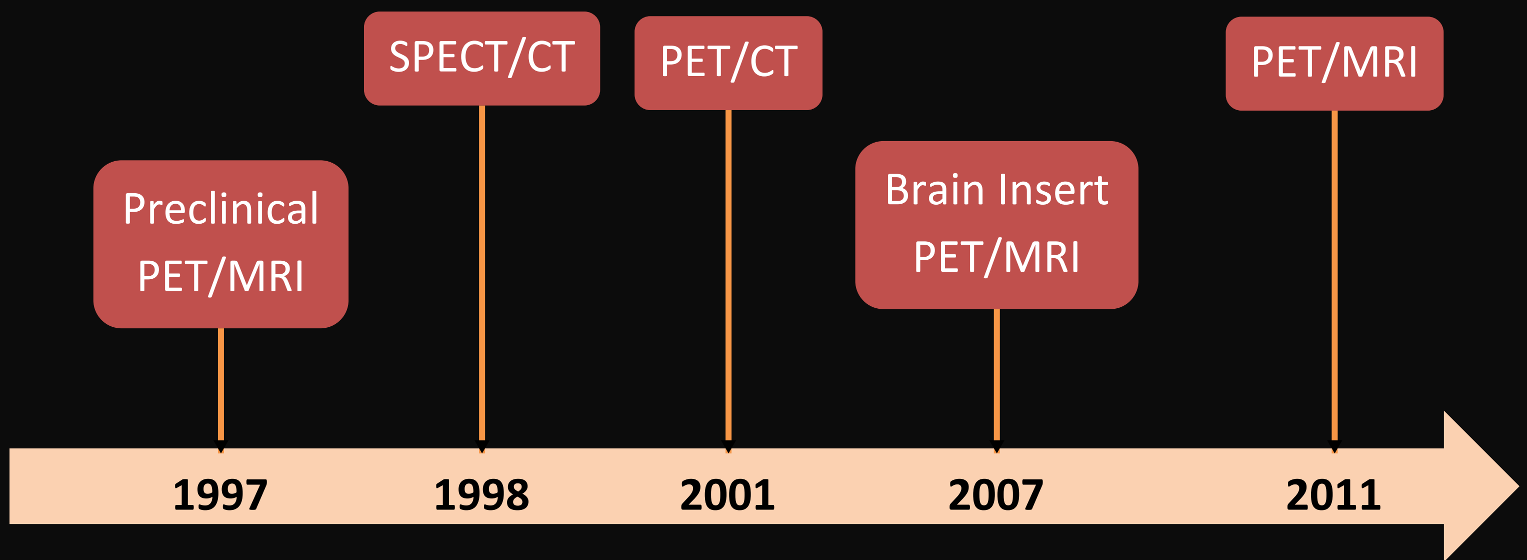
| Radyoizleyici | Hedef Biokimyasal Proses | Klinik Uygulama |
|---|---|---|
| $^{18}$F-FDG | Glucose metabolizm | Onkoloji ve Noroloji |
| $^{68}$ Ga-Dotatate | Somatostatin receptors | Nueroendorin Tumorleri |
| $^{18}$F-FLT | Hücre bölünmesi | Radyoterapi |
| $^{18}$F-FMISO | Hypoxia | Radyoterapi |
| $^{18}$F-Fluorocholine | Hücre zari | Prostate |
| $^{18}$F-Fluoride | Kemik oluşumu | Kemikteki metastaz |
| $^{82}$RbCl and $^{13}$N-NH3 | Perfusion | Kalp |
| $^{18}$F-Florbetapir | Beta-Amyloid | Alzheimer |

# PET Kameralar Nasil Calişır?

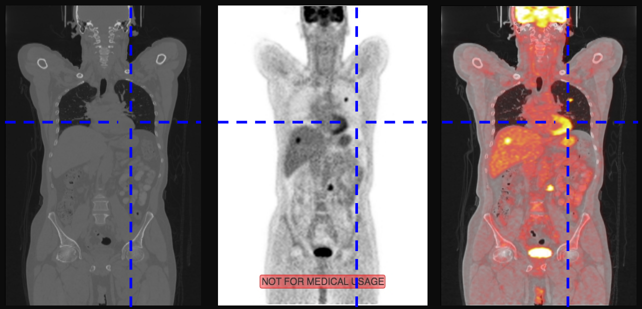


# Hybrid Imaging Modalities



# PET/CT

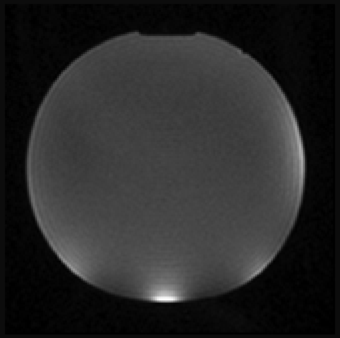


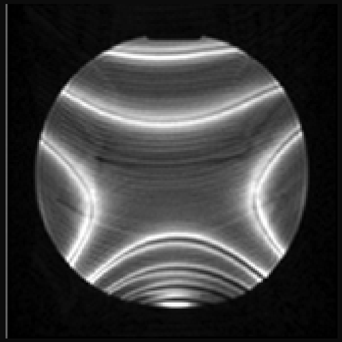
# Karşılaştırma

PET/CT

PET/MR

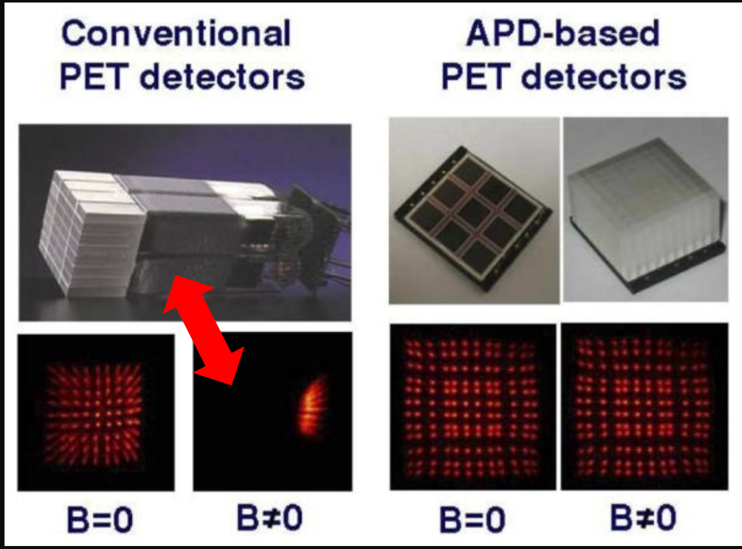
# PET/MRI Entegrasyonun Zorluklari





X-ray detector

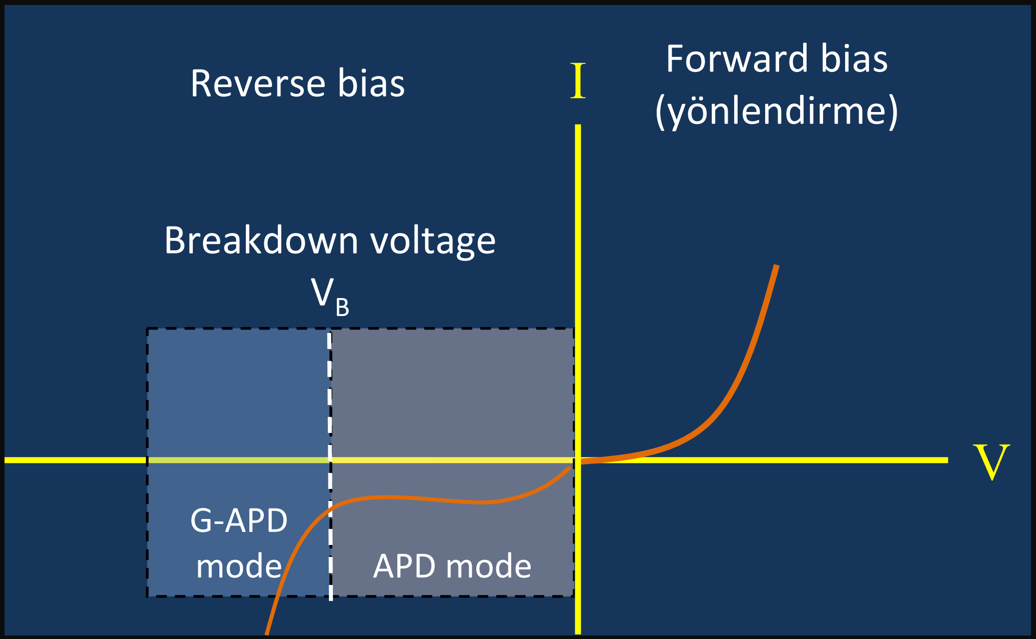
Fahrig, R. et al, *Proceedings of the IEEE* , vol.96, No.3, 2008




Semin Nucl Med. 2008 May; 38(3): 199–208

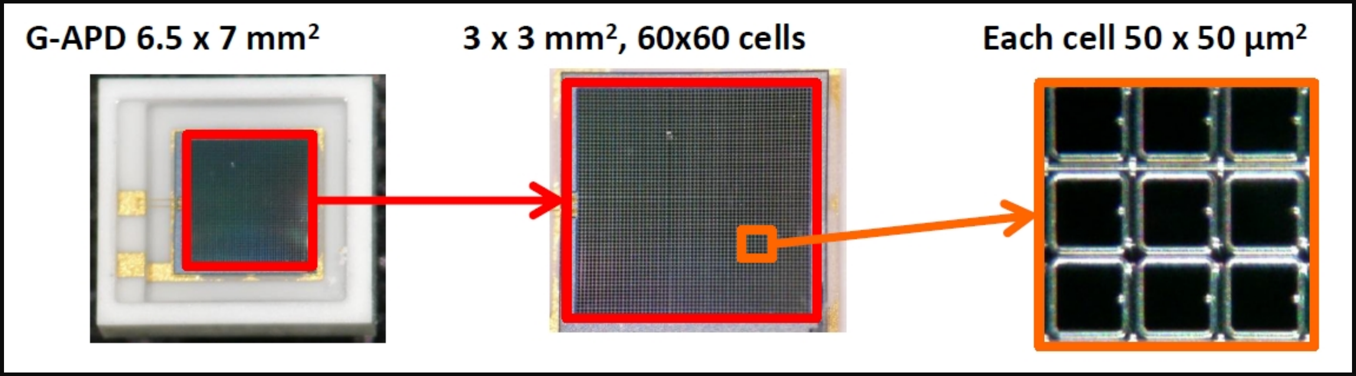
# MR Uyumlu Fotodetektörler: APDs ve G-APDs

APD ve Geiger Mode (SiPM)

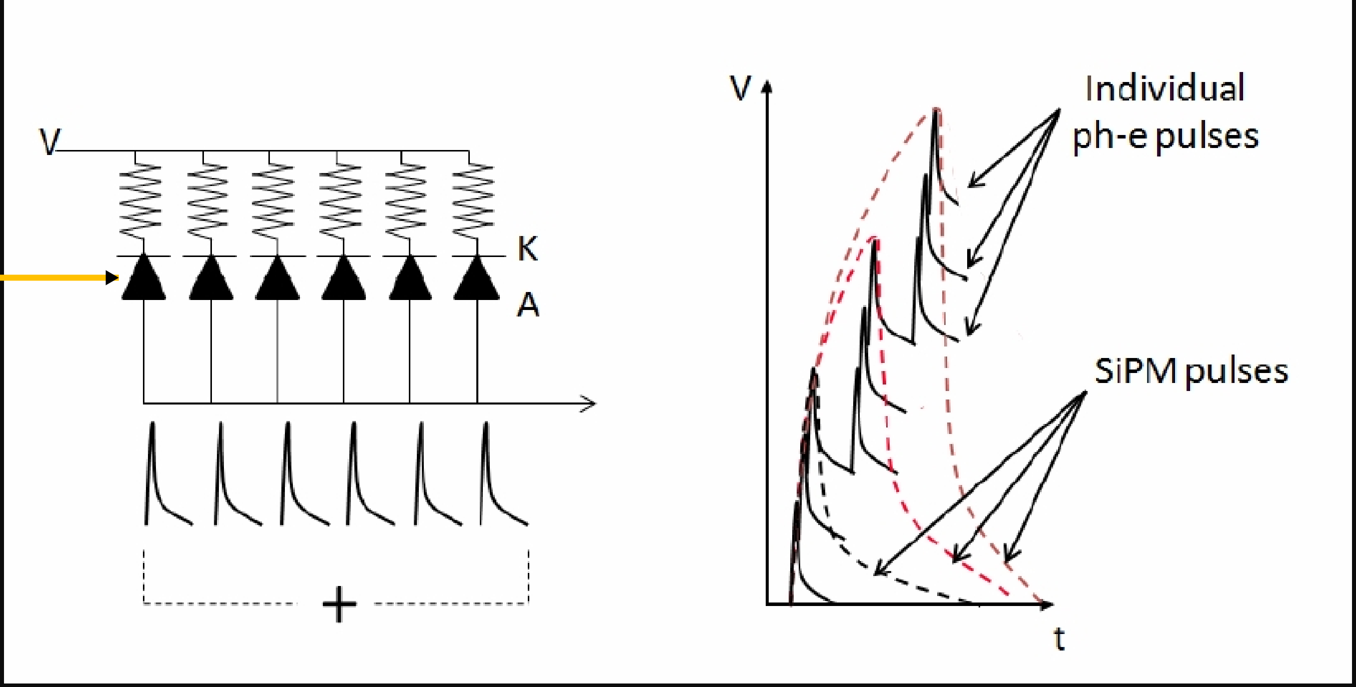


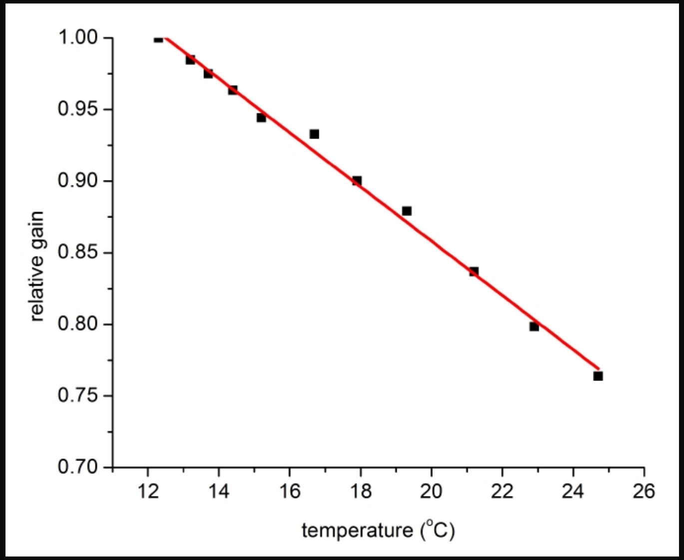

Impact Ionization

# SiPM (G-APD, SPAD)

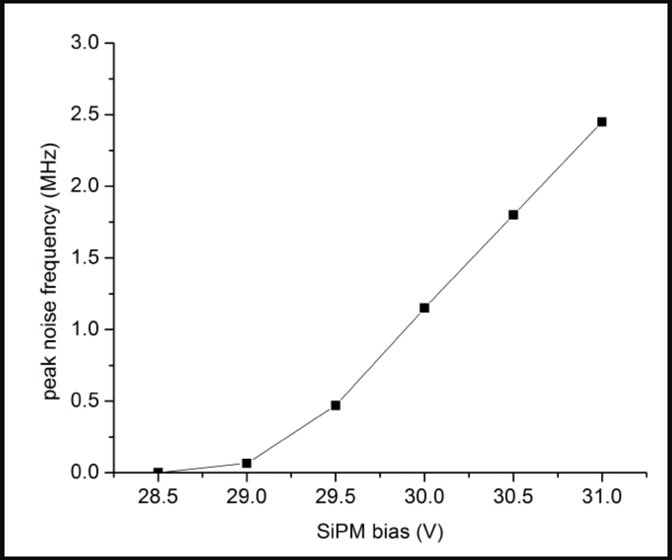



APDs

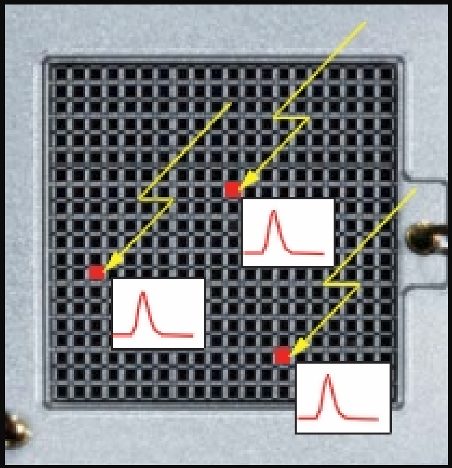





Gain ısıdan etkilenmekte

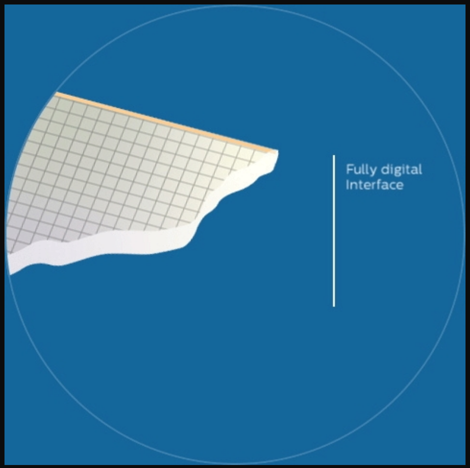



Noise de bias voltajindan etkilenir.



SiPM

Analog signal generated
by each cell is added




dSiPM

Digitized and time stamped
At the cell level

# PET/MR’da Kullanilan Fotodetektörler

| Photodetector | PMT | APD | SiPM |
|---|---|---|---|
| Detection Efficiency | 25% | 75% | 25% |
| Yönlendirme Voltajı | 1-3 kV | 100-500 V | 20-80 V |
| Kazanç | ~$10^6$ | 50-1000 | $10^6$ |
| Spectral Response | 300-550 nm | 320-1000nm | 320-900 nm |
| Manyetik alandan etkilenme | Evet | Hayır | Hayır |
| Time-of-Flight | Evet | Hayır | Evet |
| Isıdan etkilenme (%/C⍰) | 1 | 3 | 1-8 |
| Fiyat/channel ($) | > 200 | ~100 | ~50 |

Sensors, 2010, pp. 10484-10505

# $B_0$'nun Pozitron Range Üzerinde Etkisi

- Arti yüklü positron parcaciklari $B_0$ ye dik olan duzlem uzerinde daha kısa mesafe yol alırlar.
- In-plane cözünürlülüğü olumlu yönde etkiler
- F18 görüntülerde faydasi yok
- 3T da Ga68 görüntülerde faydası olabilir [1]

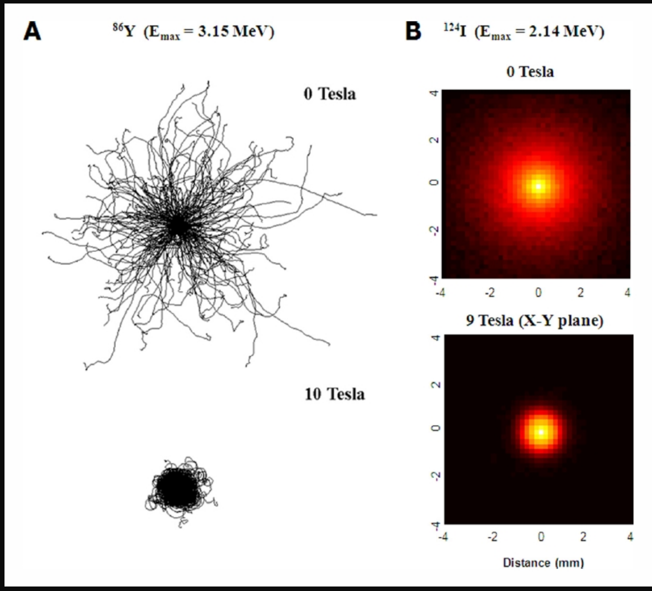



FIG. 2. (a). Influence of the magnetic field on positron range, for $^{86}$Y ($E_{max}$ = 3.15 MeV) in water, illustrated by Monte Carlo simulations obtained at 0 T (top) and 10 T (bottom) field. The 3D tracks are projected onto a plane perpendicular to the direction of the magnetic field. The average distance between the emission and annihilation point is reduced considerably in the presence of the magnetic field. (b). Simulated positron range reduction for I-124 ($E_{max}$ = 2.14 MeV) in a 0 T (top) and 9 T (bottom) magnetic field. Adapted with permission from Blanco *et al.*, Nucl. Phys. B, Proc. Suppl., **158**, 157–160, 2006 and Burdette *et al.*, *IEEE Nuclear Science Symposium Conference Record*, 2376–2380, 2005. Refs. 20, 22.

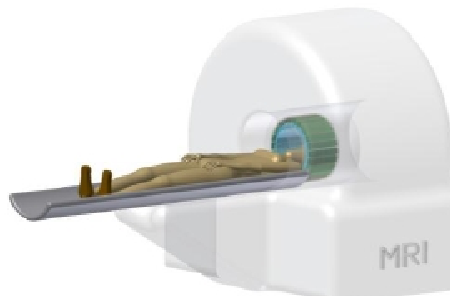
[1] PLOS ONE | www.plosone.org , 10 April 2014, Volume 9, Issue 4, pp. 3-10

# Değişik Dizayn Modelleri

**side-by-side**

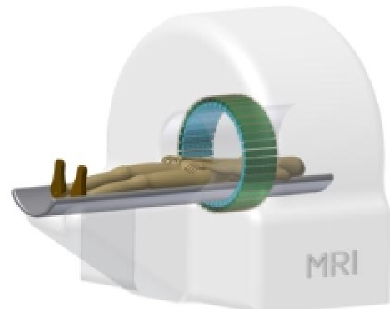

- Use current PMT technology
- Move PET readout away from MR field

**PET-insert**




- Requires use of MR compatible light detector
- Only modify PET to be transparent to MRI

**Integrated PET/MRI**




- Merge PET and MRI technology
- Fully integrate PET into the MRI hardware

Slide Courtesy of Martin S. Judenhofer

# Ilk Klinik PET Detektor

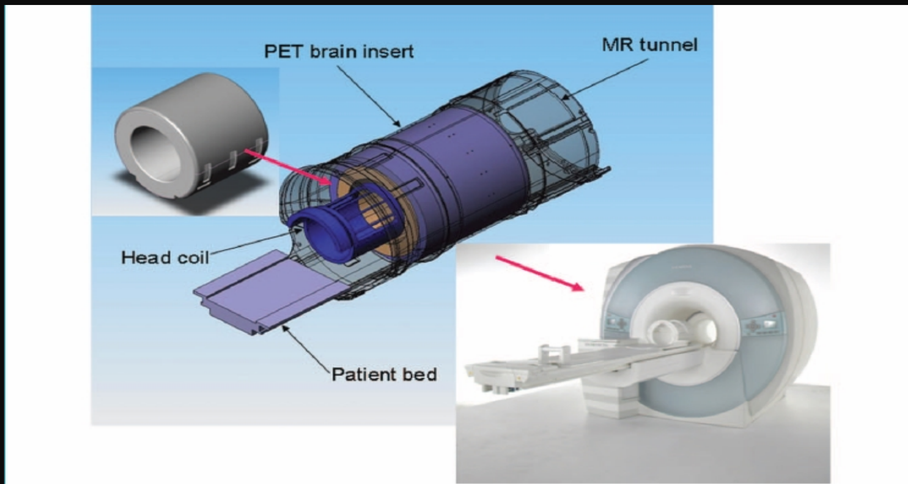
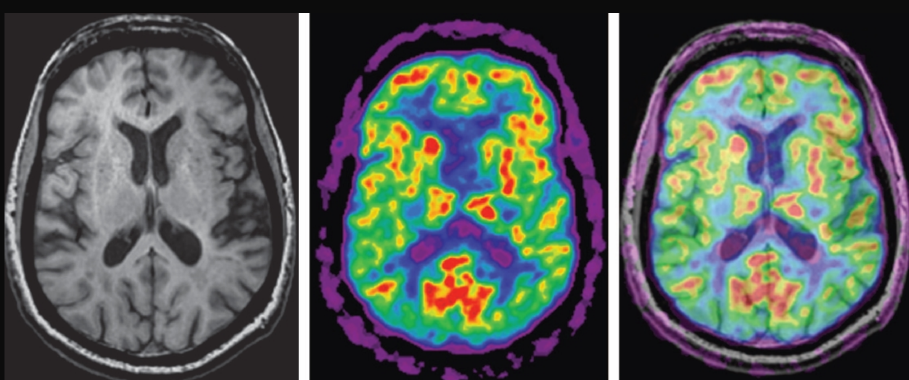



**Figure 1:** Drawing and photograph of integrated MR/PET design shows isocentric layering of MR head coil, PET detector ring, and tunnel of MR magnet.

3T MRI: Trio

Radiology: Volume 248: Number 3—September 2008



a. b. c.

**Figure 3:** Simultaneously acquired **(a)** MR, **(b)** PET, and **(c)** superimposed combined MR/PET images of 66-year-old man after intravenous injection of 370 MBq of FDG. Tracer distribution was recorded for 20 minutes at steady state after 120 minutes.

PET:
Crystal: 12x12 blocks (2.5x2.5x20 mm)
3x3 APD arrays (5x5 mm active surface area)
Axial FOV: 19.2 cm
Ring Diameter: 35.5 cm
Timing Res: 5.6 msec
Energy Res: 20%
Resolution (FWHM): 2.5 mm in the center and 4.5 mm @10 cm

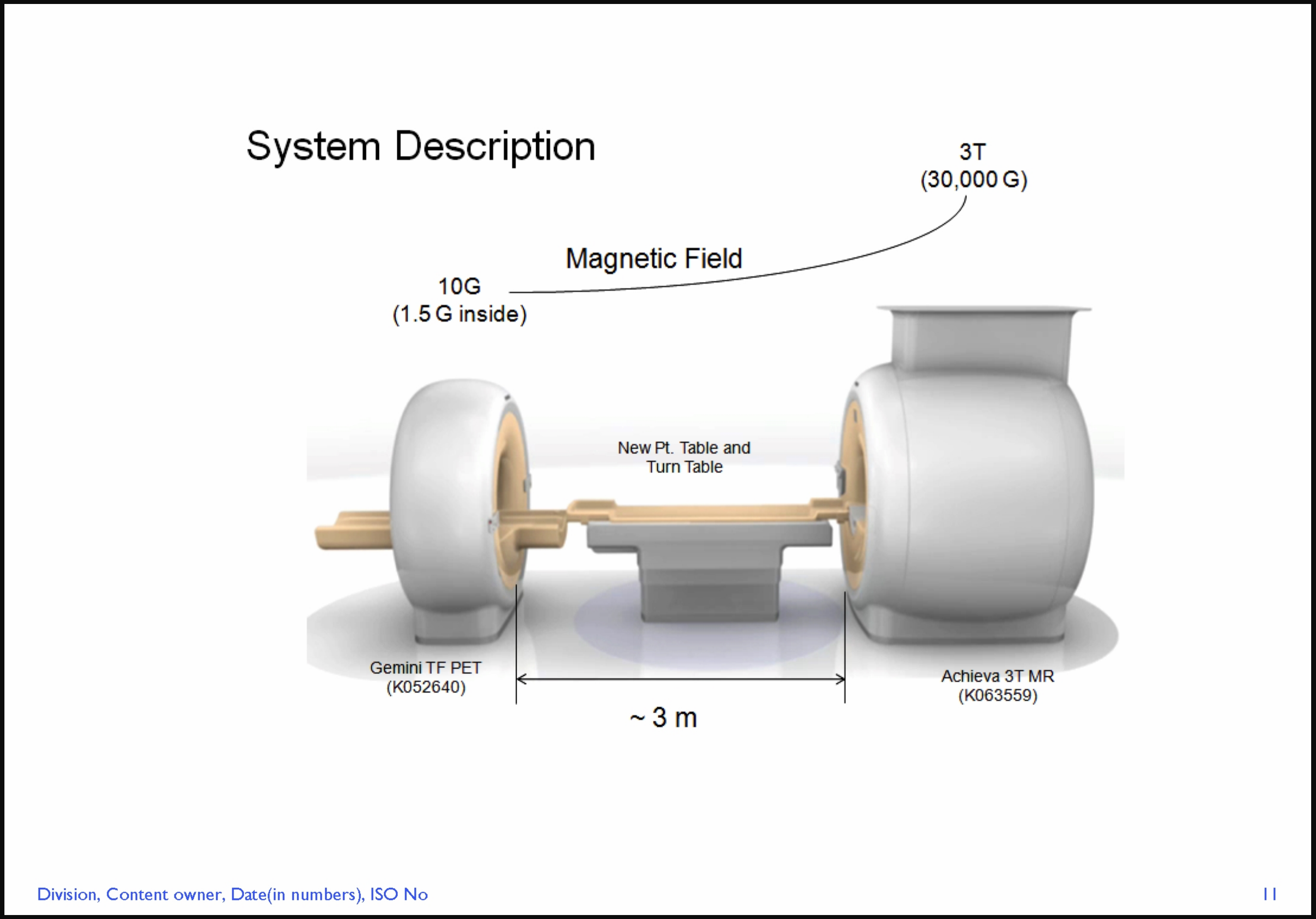
Two patients: 370 MBq of FDG, 120 min.
Scan time of 40 min.
All corrections were done. MR-based AC correction: Air and Tissue. Images were registered using VINCI

No significant degradation in MRI or PET in terms of uniformity or homogeneity

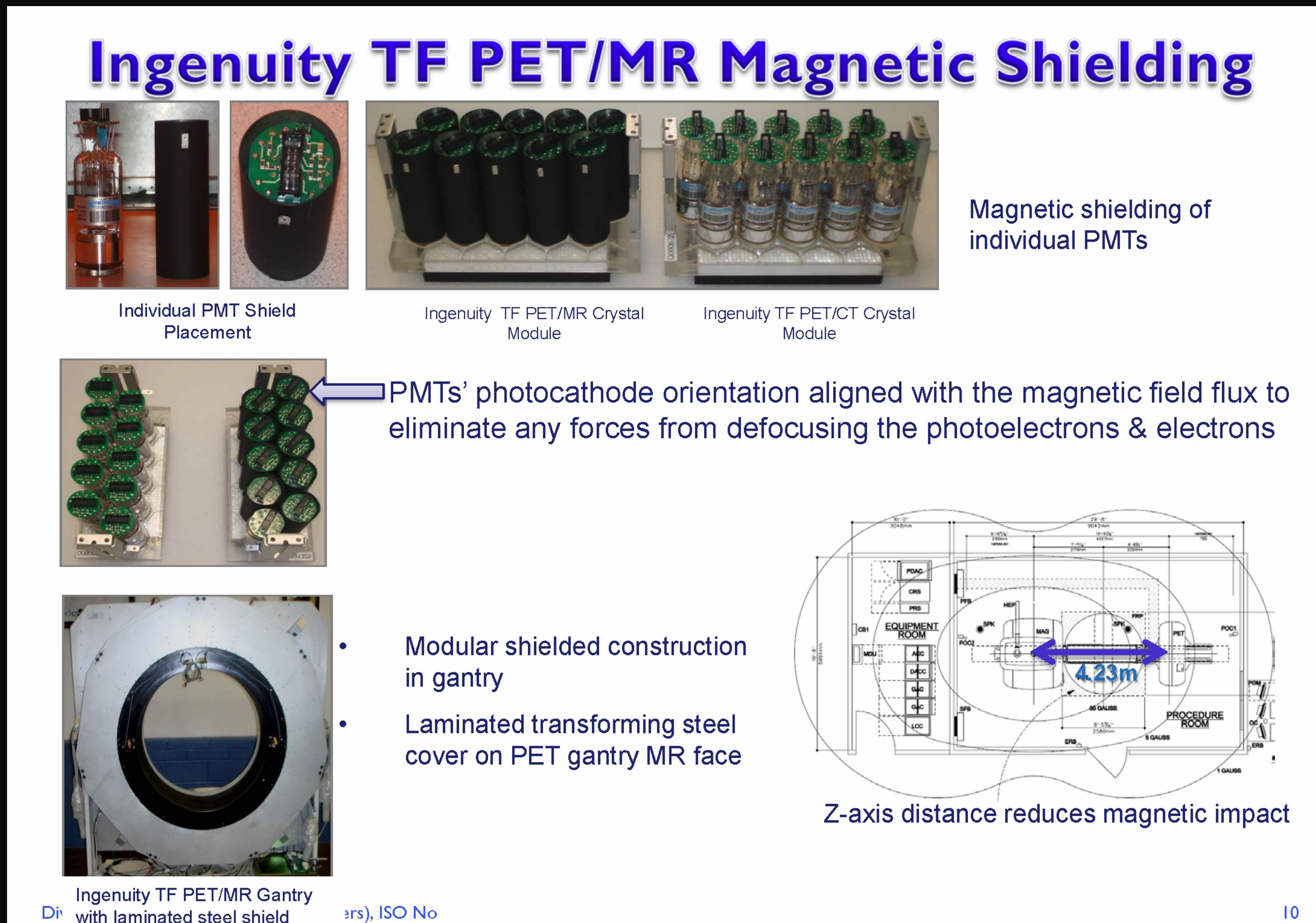
# Kilinik PET/MR Sistemler

| Uretici Firma ve Model | Philips Gemini TF | Siemens mMR | GE SIGNA |
|---|---|---|---|
| Görüntüleme metodu | Ardışık | Ayni anda | Ayni anda |
| Kristal | LSO | LYSO | LYSO |
| FDA Onayi | 2011 | 2011 | 2014 |
| Photodetector | PMT | APD | SiPM |
| Satilan (sipariş) (Mayis ‘15) | | | 7(10) |

# Ingenuity TF & Achieva 3T

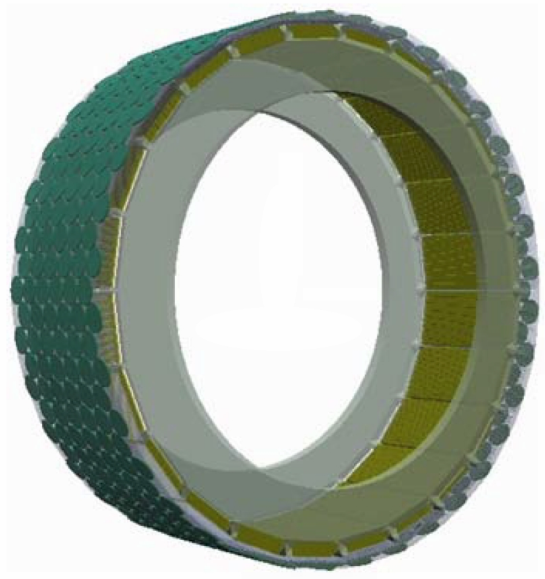


# Ingenuity TF & Achieva 3T



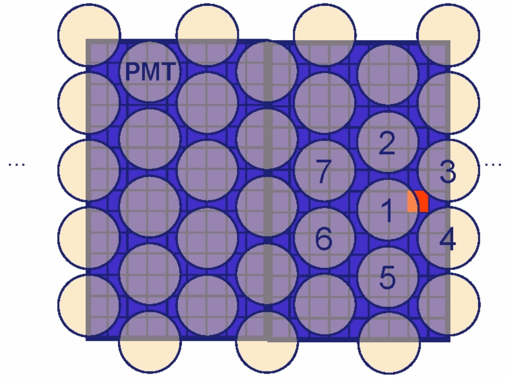
# PET system

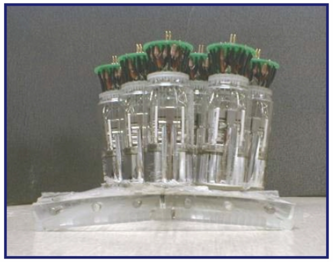
## New (2011) Astonish PET/CT



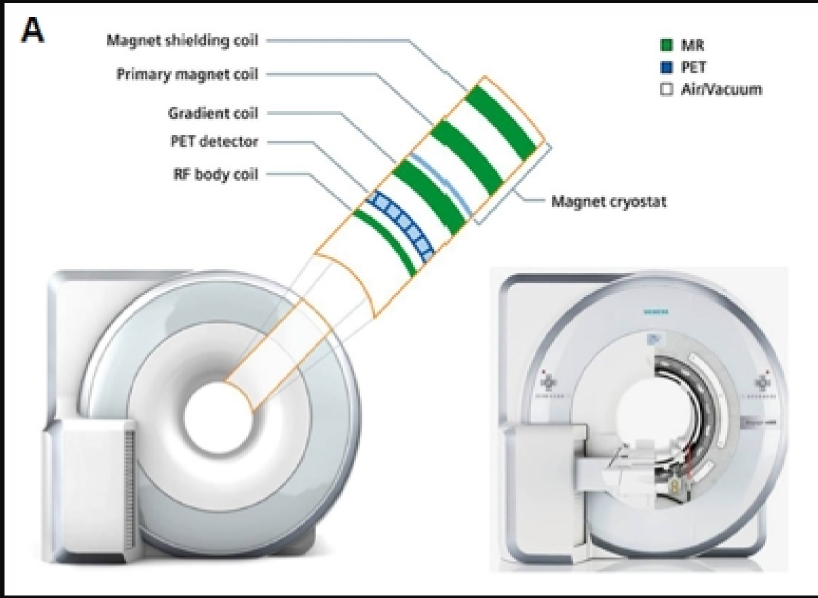
Philips' ***PIXELAR Detector***
- Continuous detector design
- 28,336 crystals of 4x4x22mm
- Optically connected panels via continuous light guide
- 5-7 PMTs used to localize each event.

***Outcome:***
- Homogeneous light collection
    - Energy Resolution of <12%
    - Increased timing resolution (495ps)
    - Scatter fraction 27%

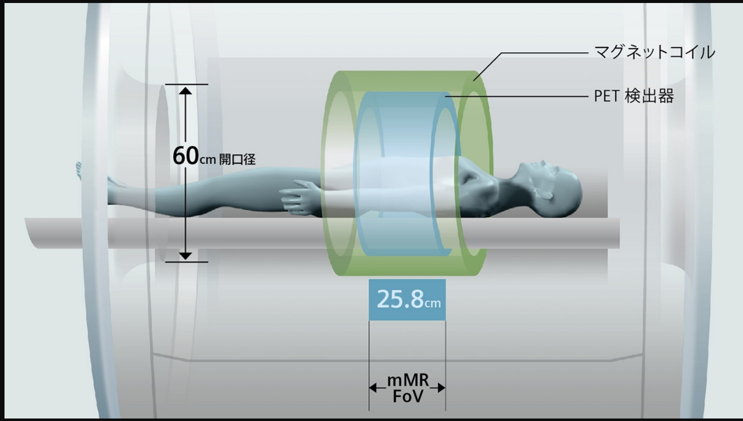


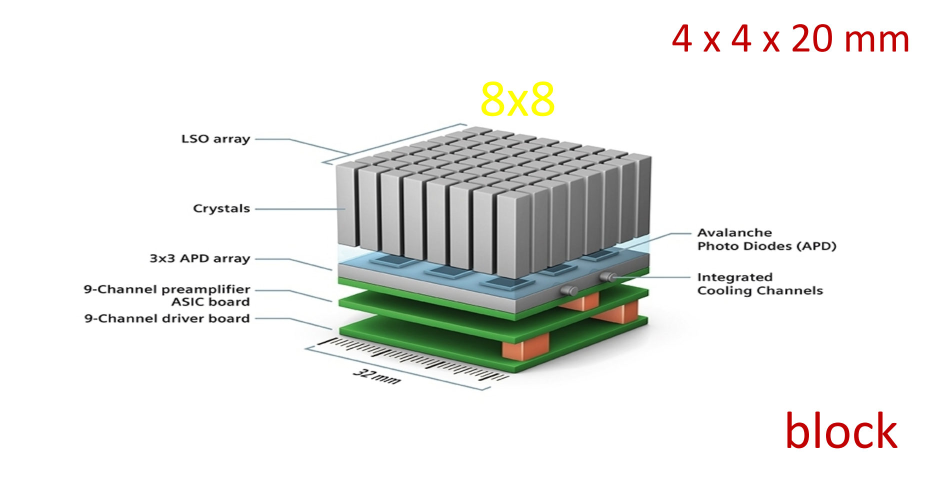
# Siemens Biograph mMR




Siemens Broshure (website)




8 Rings of 56 detector blocks

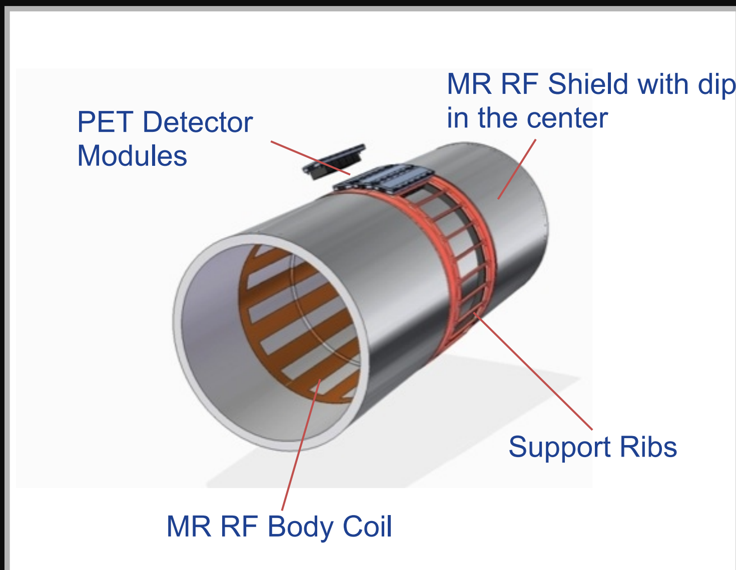


# Siemens mMR ve mCT

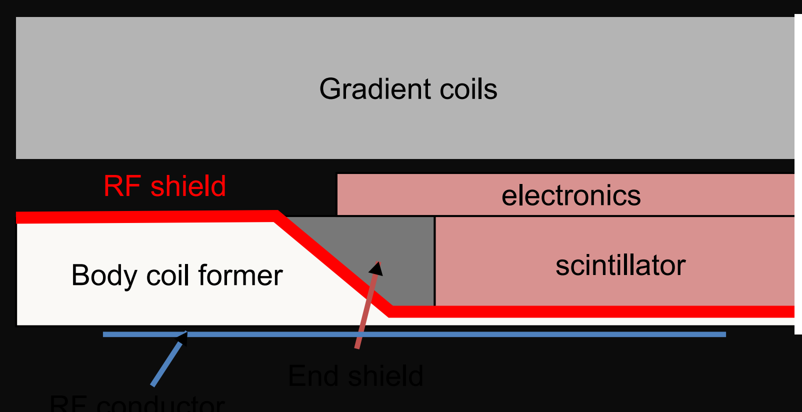
| Parameter | mMR | mCT |
|---|---|---|
| Transaxial FOV (cm) | 59.4 | 70 |
| AFOV (cm) | 25.8 | 21.8 |
| Ring Diameter (cm) | 65.6 | 84.2 |
| Energy Window | 430-610 | 435-650 |
| Energy Resolution | 14.5% | 11.5% |
| Timing Resolution | 2930 ps | 527 ps |
| Coincidence window | 5.9 | 4.1 |
| Transverse Resolution | 4.3 | 4.4 |
| Axial Resolution | 4.3 | 4.4 |
| Transverse Radial (mm) | 5.2 | 5.2 |
| Sensitivity (kcps/MBq) | 15 | 9.7 |
| Scatter fraction (%) | 36.7 | 33.2 |
| Peak NECR kcps | 183.5 @23.1 kBq/mL | 180.3 @28.3 kBq/mL |

JNM, vol. 52, No. 12, December, 2011

# GE SIGNA PET/MR System Design




- PET detector ring mounted between the RF shield and the gradient coil.
- Silicon PhotoMultipliers (SiPMs) for size and magnetic compatibility
- Detectors in ring on outer surface of novel RF body coil – 60 cm bore diameter

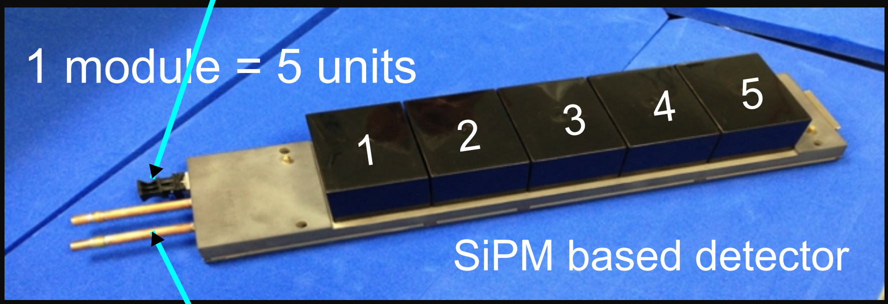





Slide Courtesy of Chuck Stern

# PET Detector Overview

Optical fiber communication

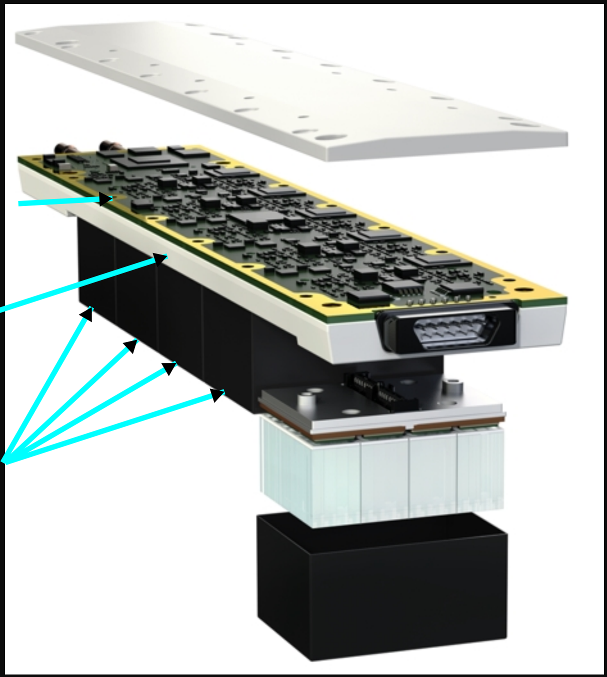



Liquid cooling

Digital electronics

Heat sink

Detector units

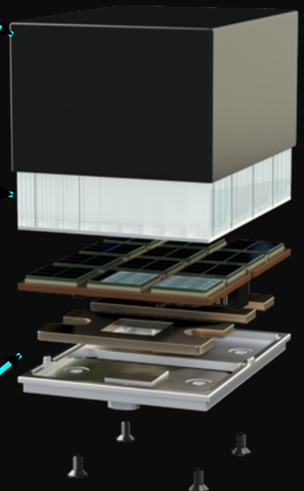


RF & light shield

LBS Scintillator Crystals (25 mm)

SiPM/ASIC Circuit Board

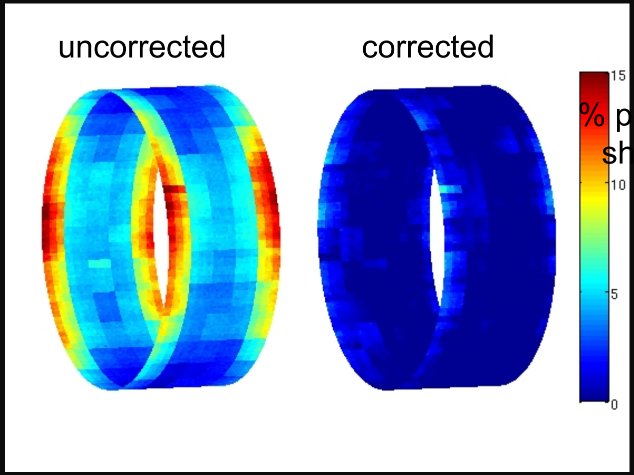
Thermal coupling



| PET/MR Detector Design | |
|---|---|
| Total PET modules | 28 |
| 1 detector module | 5 detector units |
| 1 detector unit | 4 detector blocks<br>2 temperature sensors |
| 1 detector block | 3x6 pixels of SiPMs<br>16 x 48 mm (4 x 9 crystals) |
| Module length | 25 cm |
| | |

# Some Design Features

- Dynamic temperature compensation
- Event processing pipeline optimization- max NECR
- Multiple RF shields for minimal interference

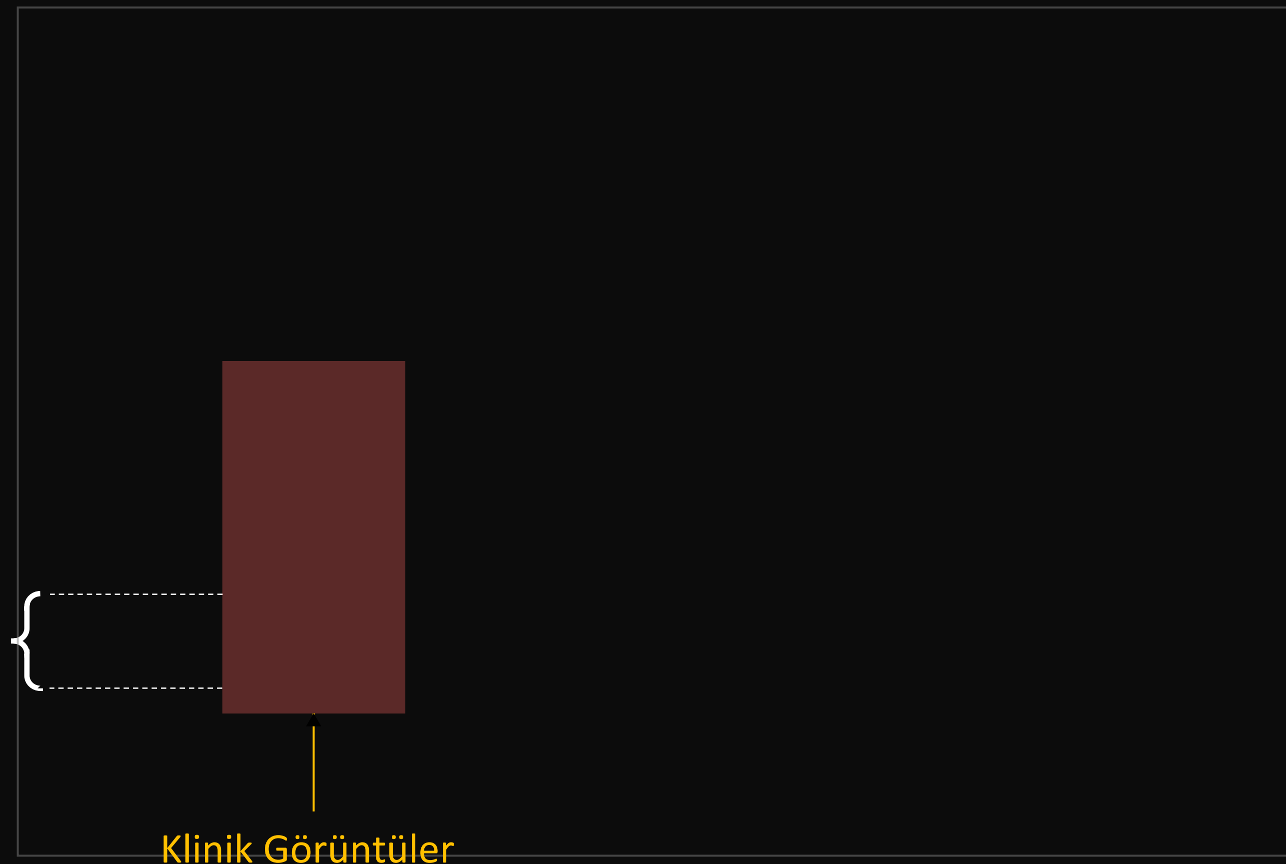



Slide Courtesy of Chuck Stern, GE PET Scientist

# PET Energy and Timing Resolution

| Sequence | ΔE FHWM |
|---|---|
| Off | 10.3% |
| LAVA-FLEX | 10.5% |
| GRE-EPI | 10.5% |
| FR-FSE-XL | 10.5% |

$\Delta t_{max}$ = 11 ps



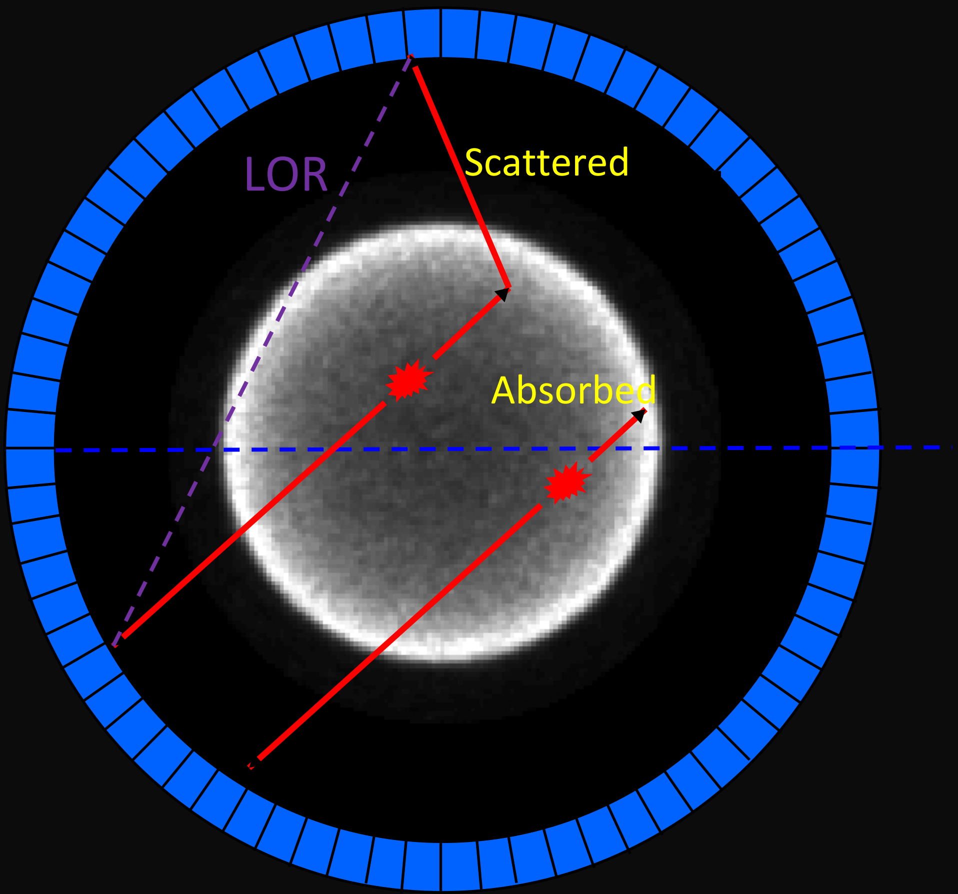

Source geometry: line source

Slide Courtesy of Chuck Stern, GE PET Scientist

| | GE SIGNA [1] | Siemens Biograph mMR | Philips Ingenuity TF |
|---|---|---|---|
| Trans. FOV | 60 | 59.4 | 70.7 |
| Sensitivity (kcps/MBq) | 21 | 15 | 7 |
| Peak NECR (kcps) | 210 | 183.5 | 90 |
| Energy resolution (%) | 11 | 14.5 | 12 |
| Timing resolution (ps) | 400 | 2930 | 520 |
| Axial FOV (cm) | 25 | 25.8 | 18 |
| Spatial resolution | | | |
| Transaxial (@1 cm, 10 cm) | 3.7, 4.5 (Iterative) | 4.3 | 4.7, 5.1 |
| Axial (@ 1 cm, 10 cm) | 4.8, 4.7 | 4.3 | 5 |
| Reconstruction | TOF and PSF | NO TOF and PSF | TOF and PSF |

[1] Chuck Stern, GE PET Scientist

# Foton Zayiflamasi (Attenuation)

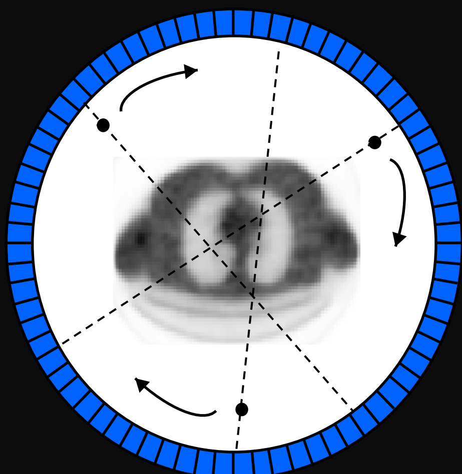



Homojen phantomdan bir kesit
Düzeltmeden önce

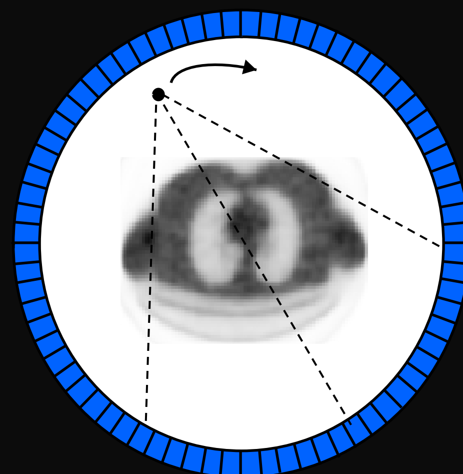
Kesitten bir profil

# Aktarma (Transmission) Görüntü

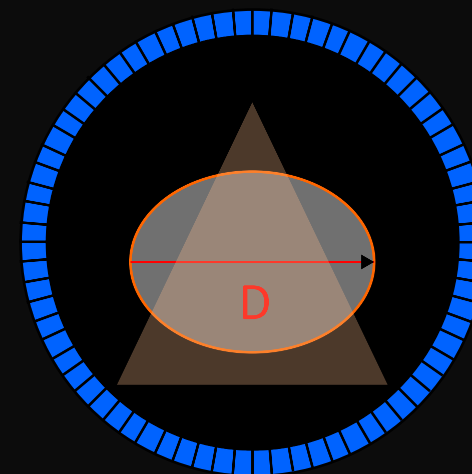
$^{68}$Ge/ $^{68}$Ga source



$^{137}$Cs source



X-ray source

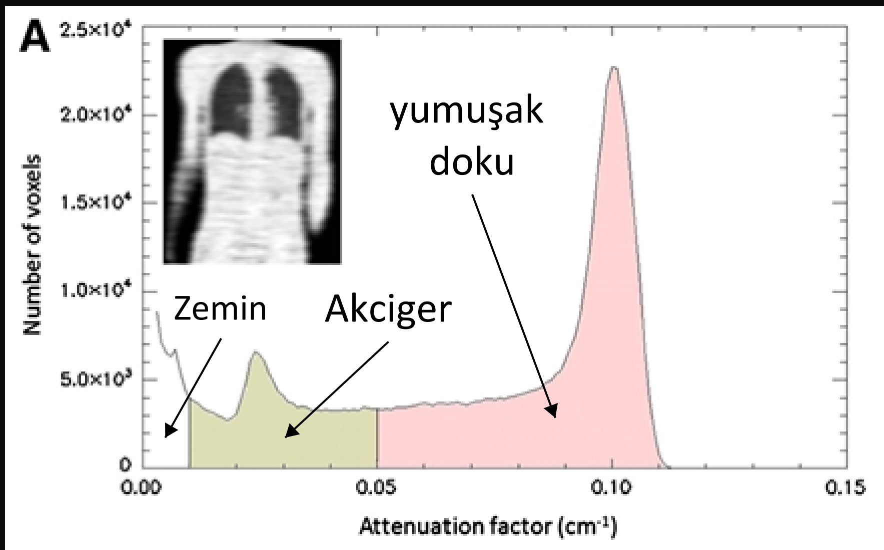



$$ACF = \frac{I_o}{I} = \frac{Blank}{Transmission} = e^{\mu D}$$

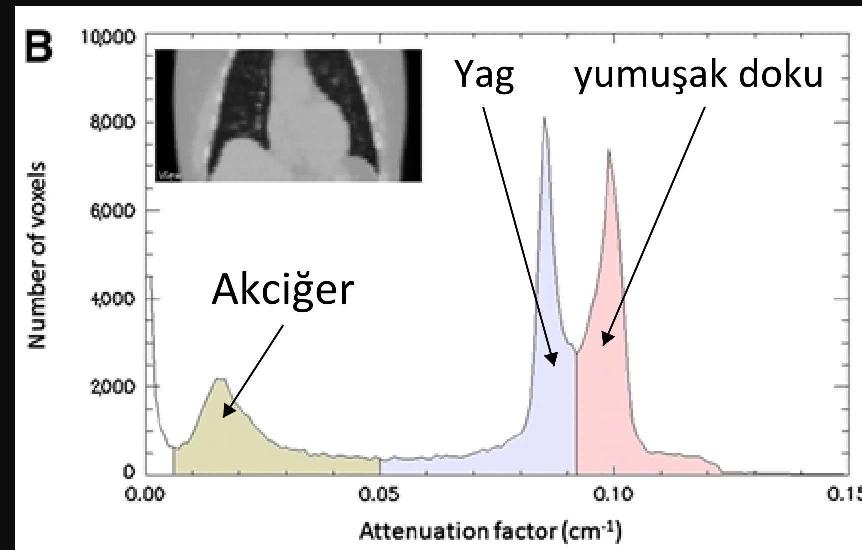
ACF: Attenuation Correction Factor

Kinahan et al. Sem Nucl. Med (2003)

## Ge68/Ga68 Transmission Scan




## Low Dose CT-based Attenuation



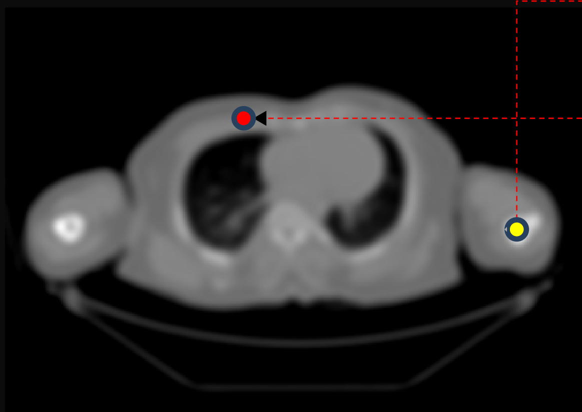

> 0.105 $cm^{-1}$ : Kemik veya kemik ve yumuşak doku karışımı

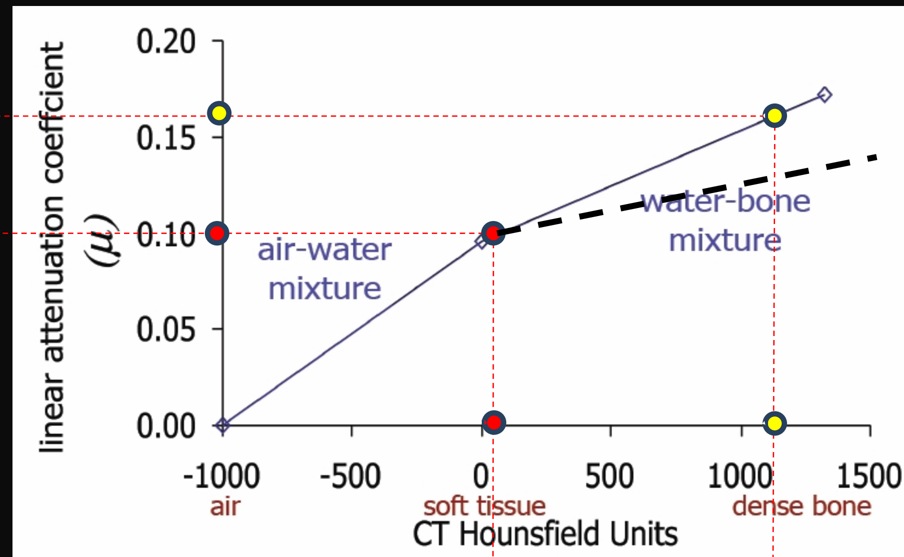
Kemik ve yumuşak doku arasinda ki fark 30% lara kadar çıkabilir

Martinez-Moller et al. JNM, Vol. 50, No. 4, April 2009

# PET/CT'de Foton Zayiflamanin Duzeltilmesi

Scaled Map @511 keV

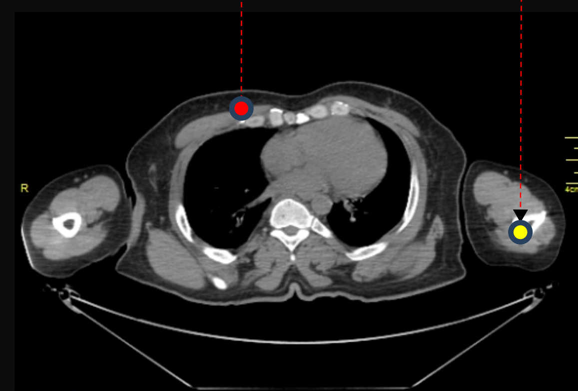





Linear Attenuation Coefficient

Lineer Azaltma Katsayisi

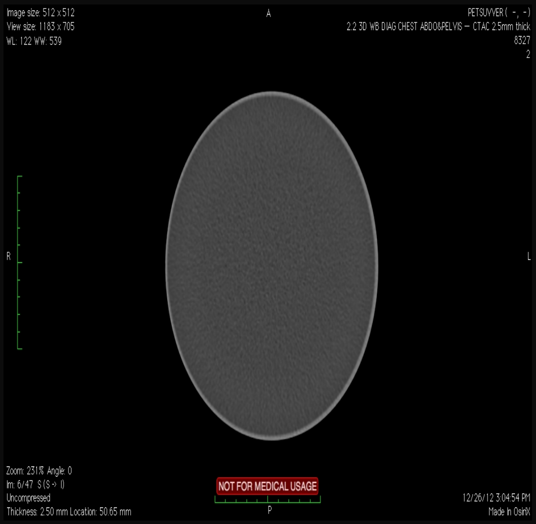
CT: 70-80 keV



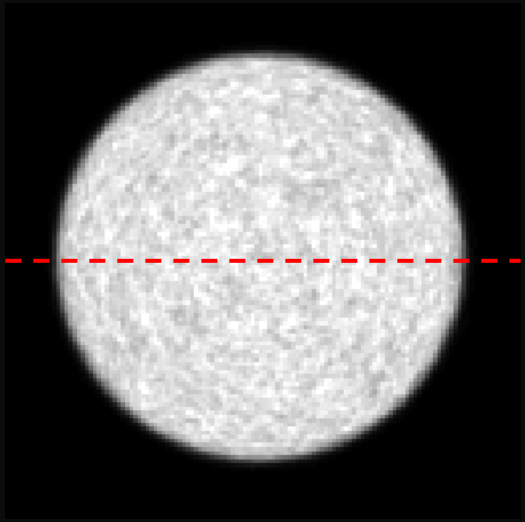

Modified from Kinahan's slide

# PET/CT'de Foton Zayiflamasinin Duzeltilmesi

CT Slice




CT-based AC



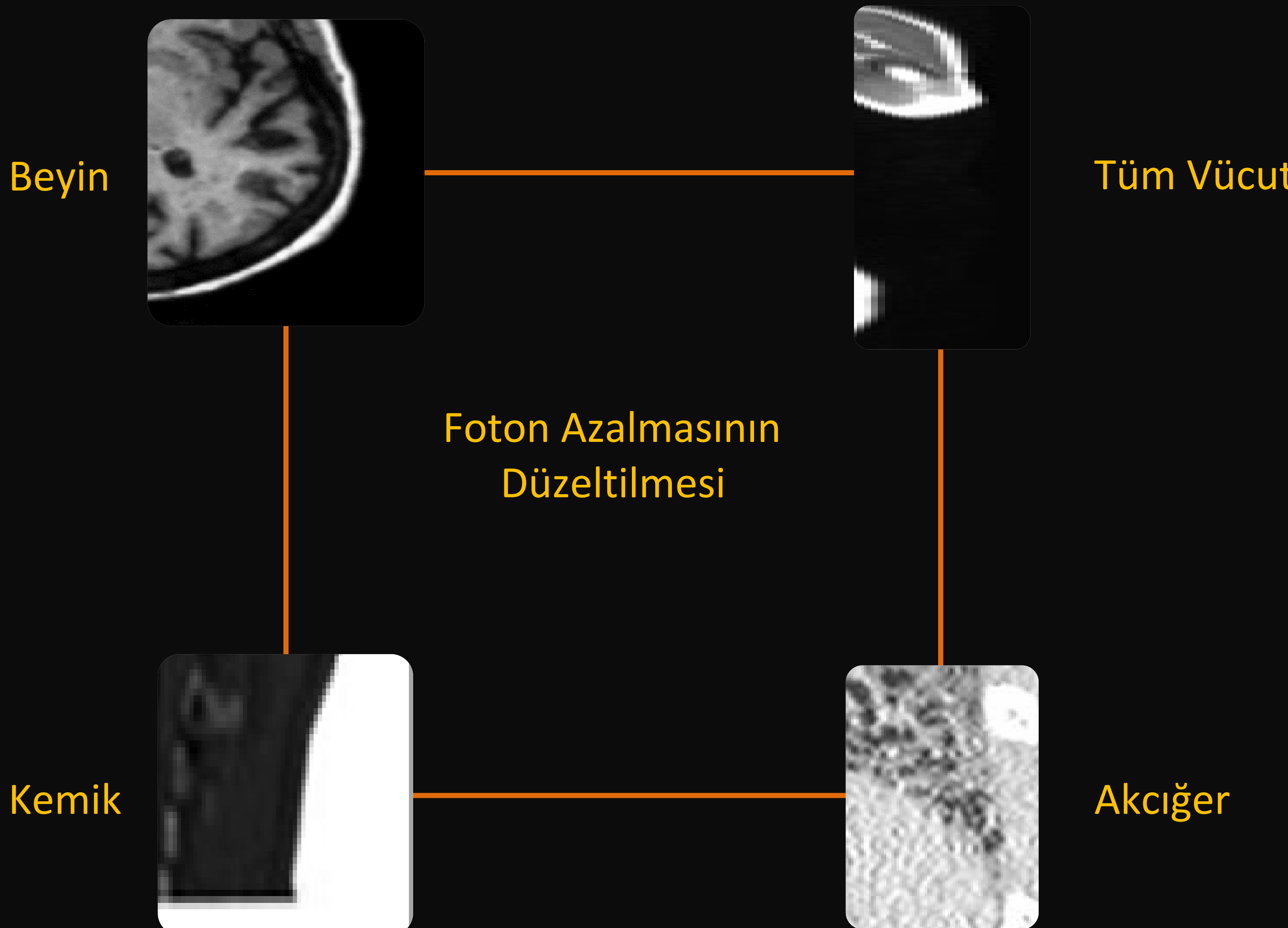
Düzletmeden sonra

Intensity Profile

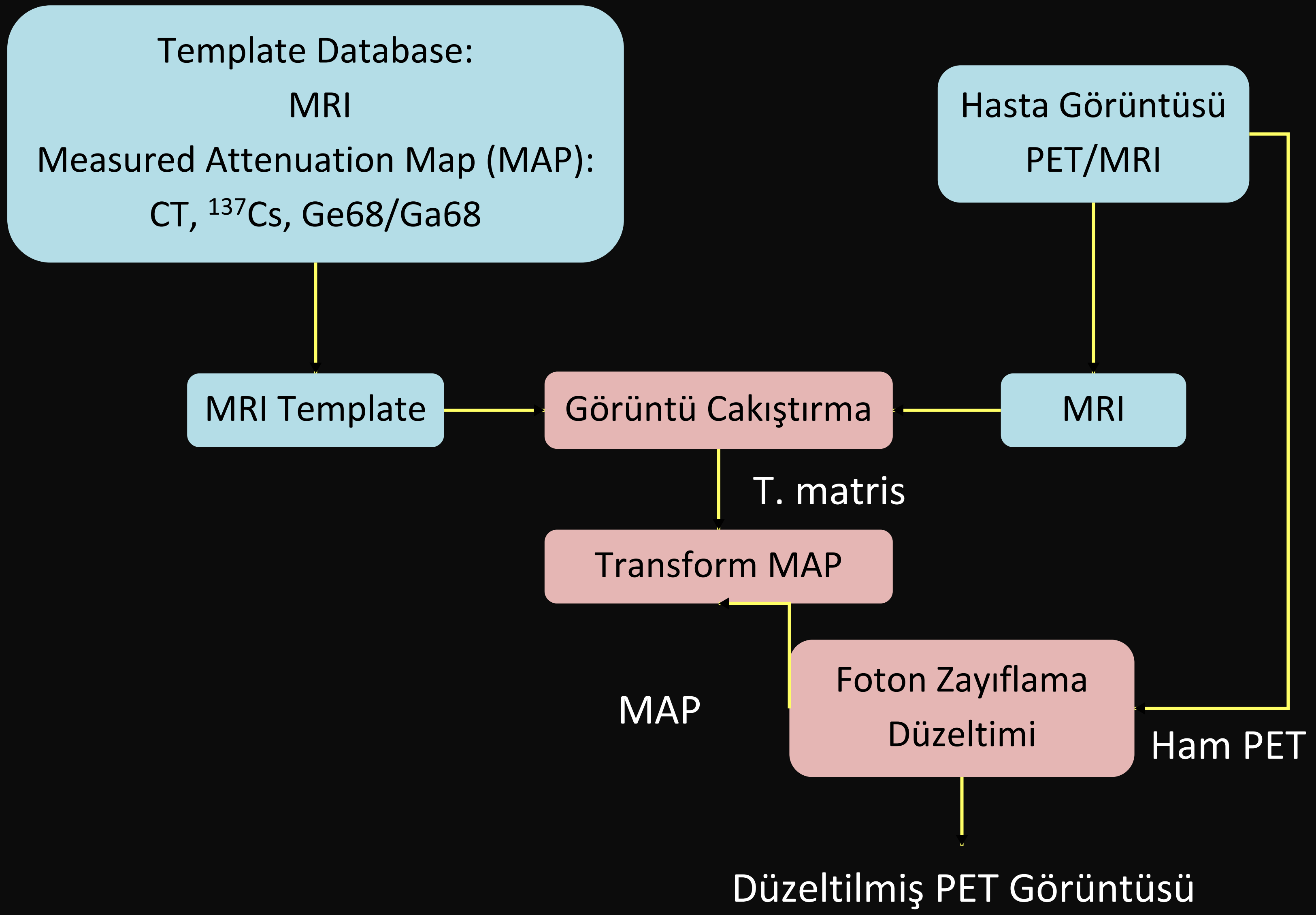
# PET/MR'da Foton Zayiflama Düzeltme Teknikleri

- MR Segmentasyon (bölütleme) tabanlı teknikler
  - Vücut dokusunu farklı doku ceşitlerine ayrıştırır.
  - Her doku tipine sabit lineer azaltma katsayisi verir
  - Uygulamasi kolay ve hizli
- Template veya atlas tabanlı teknikler
- Emisyon ve transmisyon görüntüleri kullanilarak

Foton azalma haritası (map) foton azalmasını ve scatter fotonları duzeltmek icin kullanılır


Beyin
Tüm Vücut
Foton Azalmasının Düzeltilmesi
Kemik
Akciğer

# Atlas Tabanlı Düzeltme Teknikleri



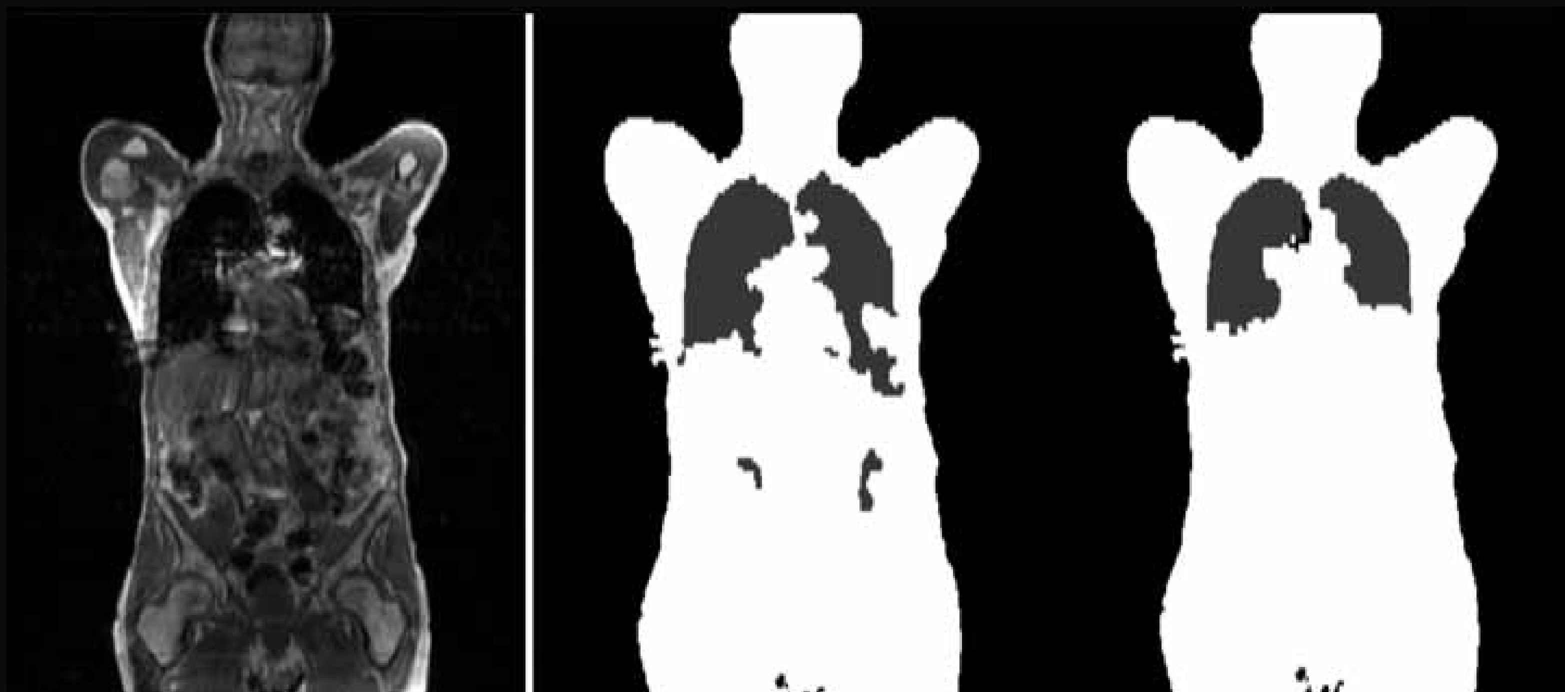
# Philips Ingenuity PET/MR

- MR FOV = 46 cm
- T1 weighted MR
- Multi-station protocol (her station, 6 cm)
- Normal bir insan (170 cm) yaklaşık 5 dakika

- 3 doku sınıfı : Hava (air), yumuşak doku (soft tissue), Akciğer (Lungs)
- Kemik dokusu hesaba katılmıyor
- Atomotik segmentasyon: Thresholding + Region growing + Deformable model for the lungs from a set of 20 High res. CT.

Z. Hu et al., Philips Ingenuity TF PET/MR attenuation correction.

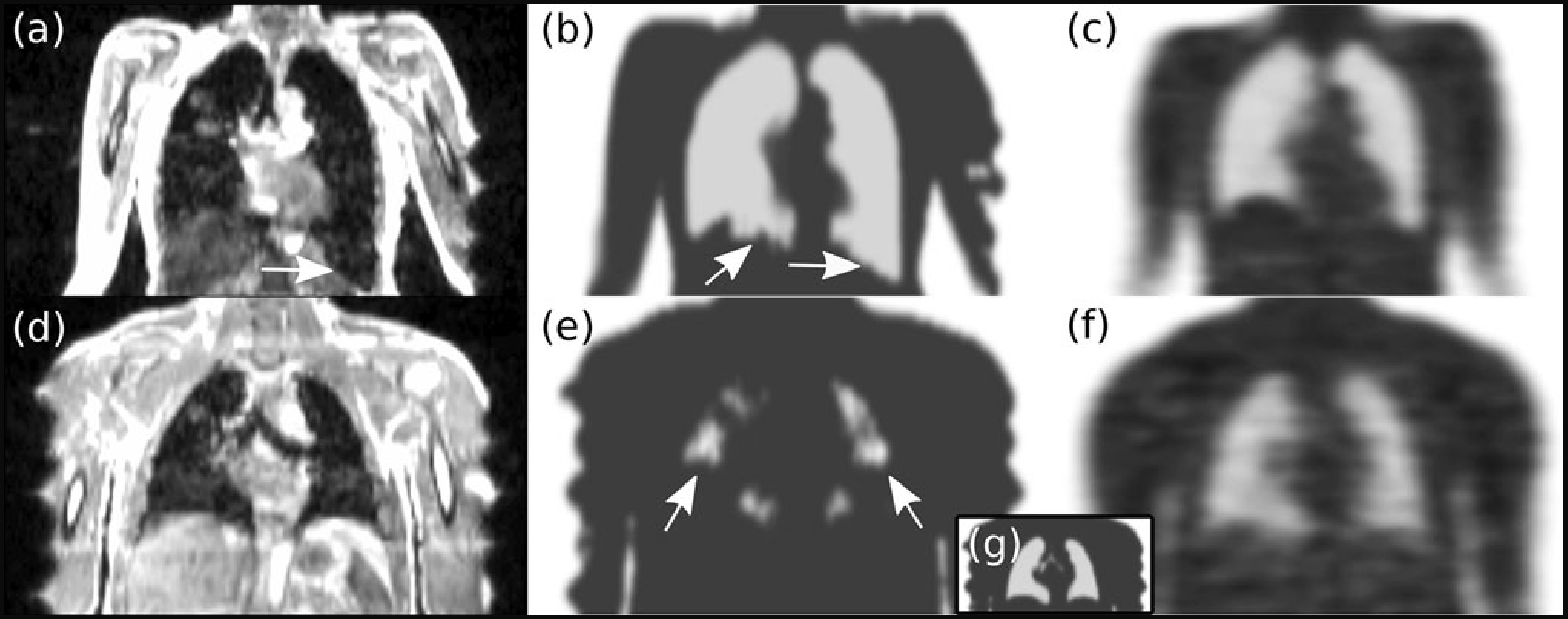
# Philips Ingenuity PET/MR



MR Bölütlenmiş Düzeltmeden sonra

Z. Hu et al., Philips Ingenuity TF PET/MR attenuation correction.

# Akciğerde örnek bir problem




MR

MRmap

Radyoaktif kaynak
Kullanılarak

Iki hastada (üst ve alt sıra) yanlış bölütleme (beyaz oklar). bölütleme parametreleri değiştirilerek daha dogru bir bölütleme elde edilebilir(g). Ingenuity TF PET/MR

Magn Reson Mater Phy (2013) 26:115–126

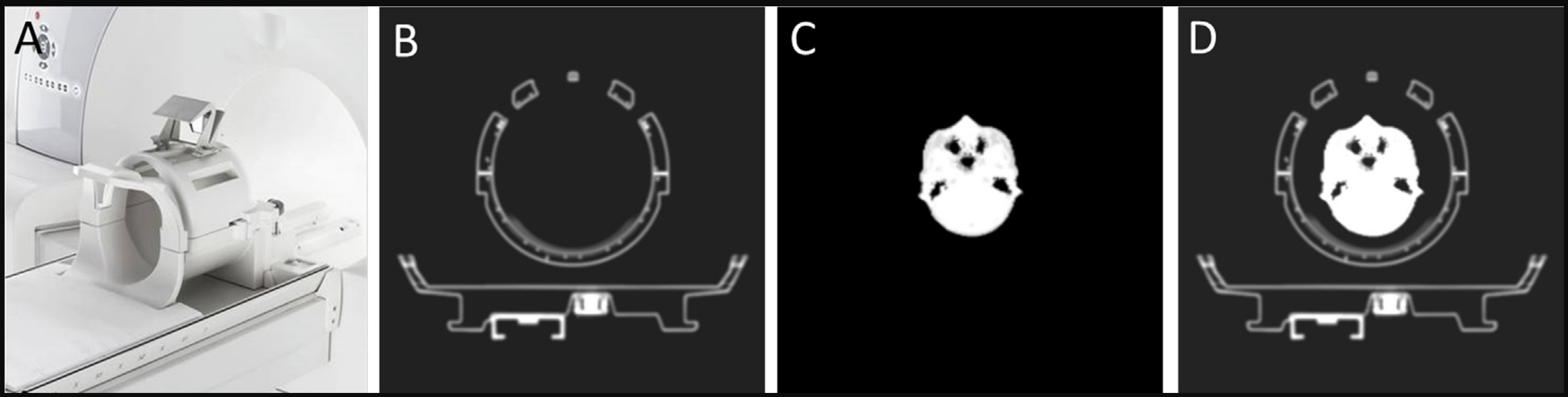
# Biograph mMR

- 4 doku sınıfı  (hava, yağ dokusu, yumuşak doku ve Akciğer) kullanılmakta
- Cok yakinda buna kemik dokusunu da dahil etmek icin calisiyorlar.
- 2-point DIXON sequence kullanılarak yağ ve su dokuları ayrıştırılıyor
- Coil ve yatak foton azaltılması duzeltilmekte
- Truncation artifact “HUGE” algoritması kullanılarak MR FOV,  PET FOV kadar genişletiyor.

Bu bilgiler kişisel iletişimle elde edildi

# Donanım (Hardware) Etkisi

Donanım kısmı MR görüntülerde gözükmediği için transmisyon tabanlı görüntülerden elde edilen azalma haritaları kullanılır



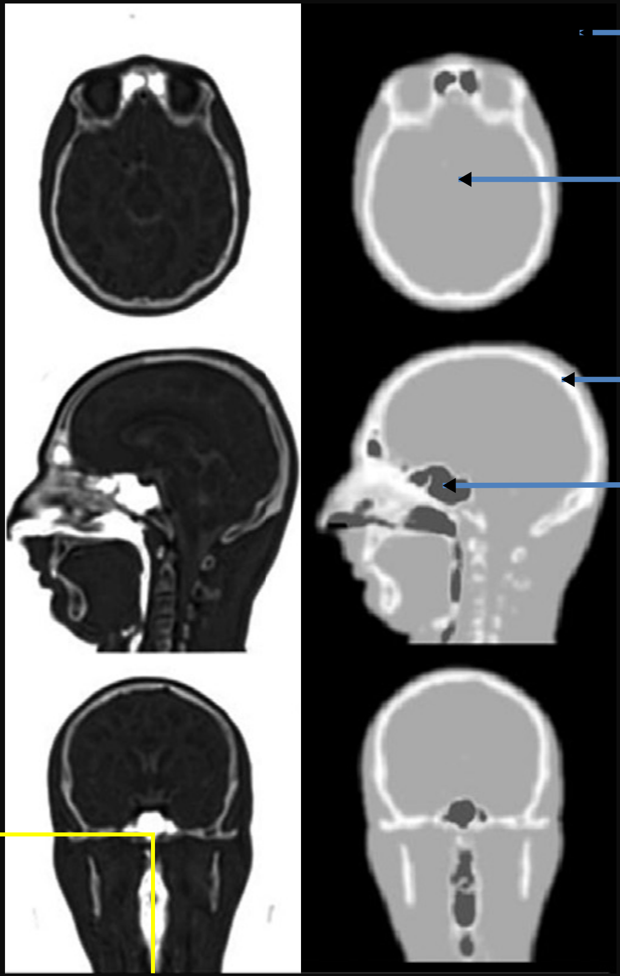

| Boyun-bogaz RF Coil | PET/MR 3D Tabanlı CT-Tabanlı azalma haritası | MR-Tabanlı yumuşak doku azalma haritası | MR-Tabanlı Yumuşak doku, masa ve RF coil |
|---|---|---|---|

Ronald Boellaard, PhD,* and Harald H. Quick, Semin Nucl Med 45:192-200, 2015

PD-weighted ZTE Acquisition:

Bölütlenmiş Görüntü

FOV = 260 mm
flip angle = 1.21,
Resolution = 1.35 mm
TE = 0
Scan time = 173 seconds



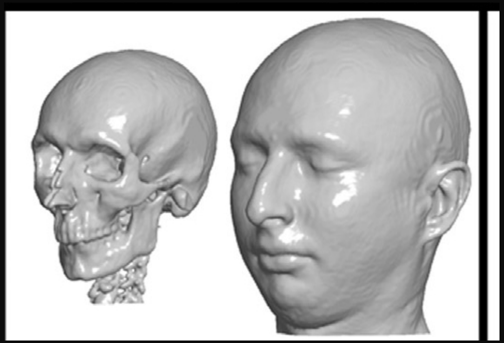
Zemin

Yumuşak doku

Kemik

Hava boşluğu

RF-bias corrected,
inverse log- scaled
MR images



Andreas Boss et al, Semin. Nucl. Med, 45:201-211, 2015

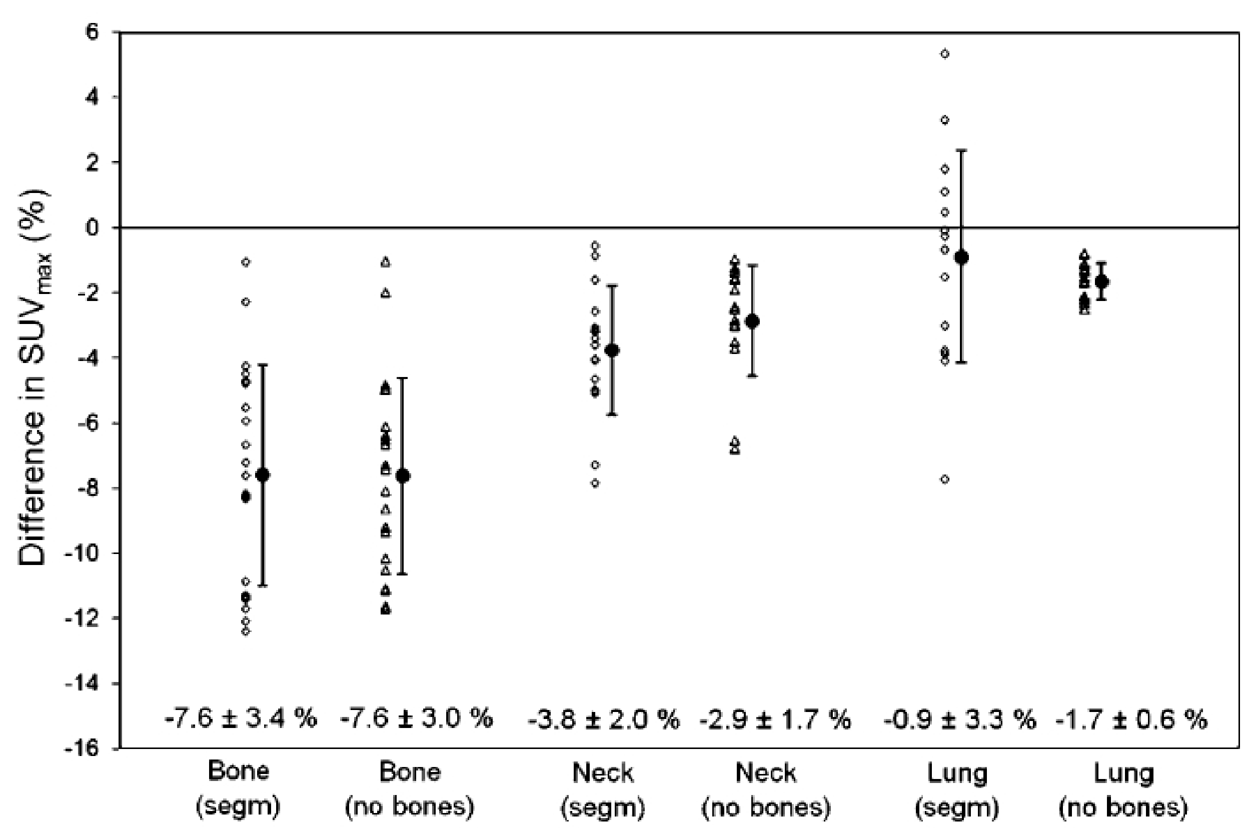
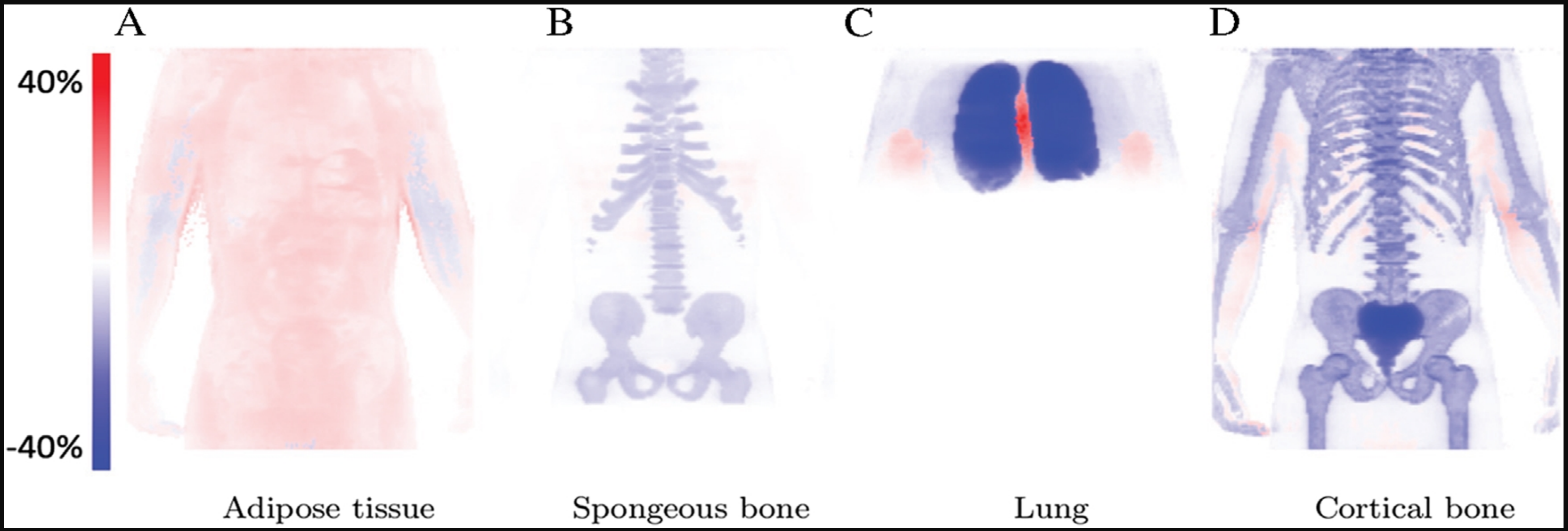



**FIGURE 4.** Differences in mean SUVs (top) and maximum SUVs (bottom) for each group of lesions produced by AC with segmented attenuation map (segm, ◇) and attenuation map with bone removed (no bones, △) relative to AC with original map. Vertical bars indicate mean ± SD.

Absence of lung tumor in the attenuation map: in SUV 35%.

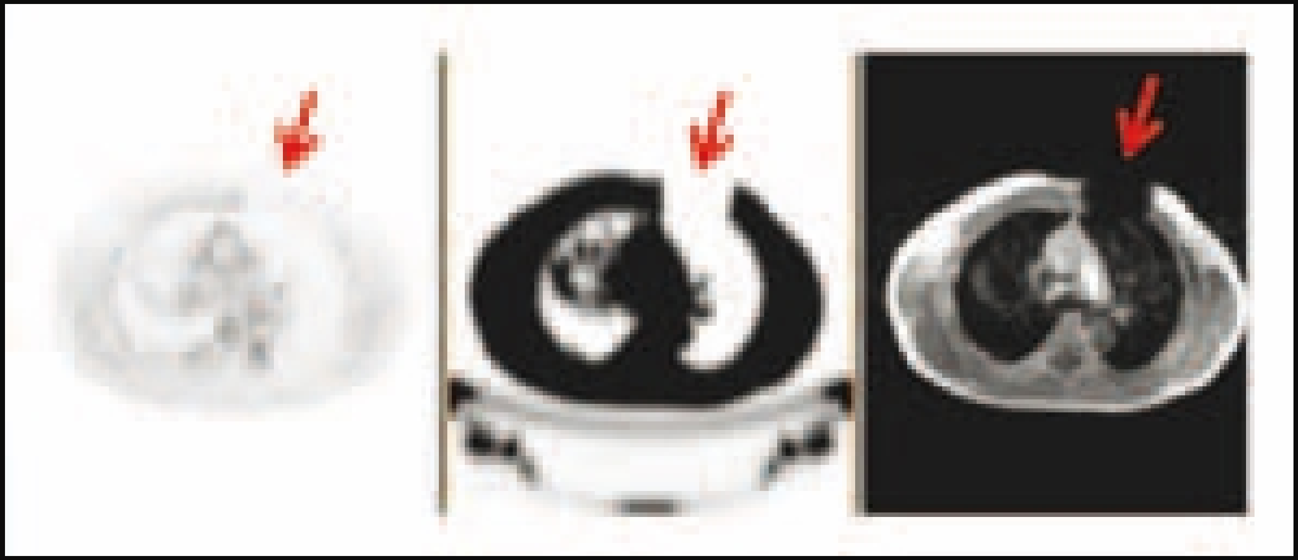
Martinez-Moller et al. JNM, Vol. 50, No. 4, April 2009




Maximum intensity projections (MIP) of relative PET quantitation errors induced by ignoring a certain tis*su*e type in the segmented attenuation map.

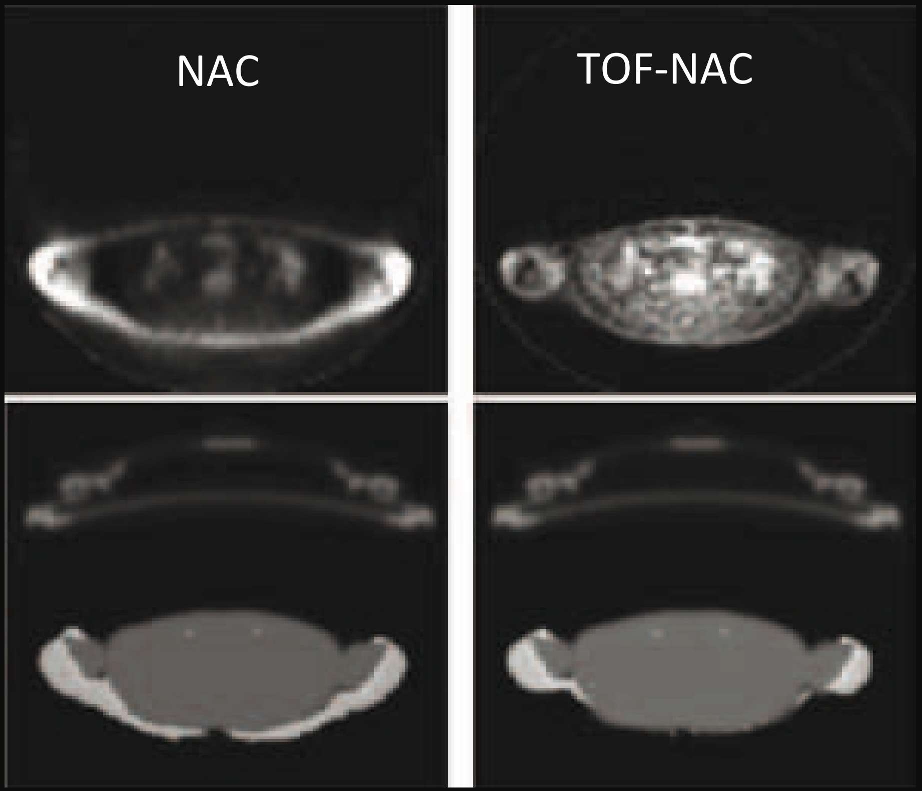
Keereman et al, Medical Physics, **38**, 6010 (2011)

# Metal Artifact



MR görüntüdeki (sag)  buyuk delik göğüsteki kalp stentinden kaynaklanmaktadır.

# Truncation Artifact



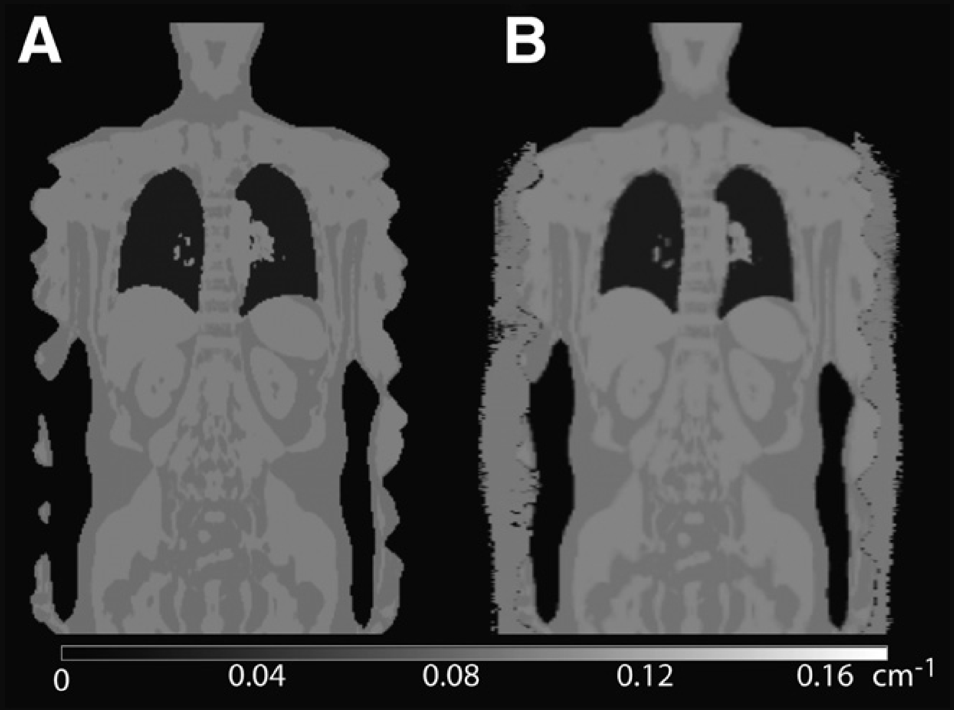

NAC kullanılarak duzeltilmiş map

TOF-NAC kullanilarak duzeltilmiş map

Truncation artifact sadece $^{18}$F-FDG lere uygulanabilir. Normal dokuda toplanmayan radyoizleyiclere uygulanamaz.

Z. Hu et al., Philips Ingenuity TF PET/MR attenuation correction.

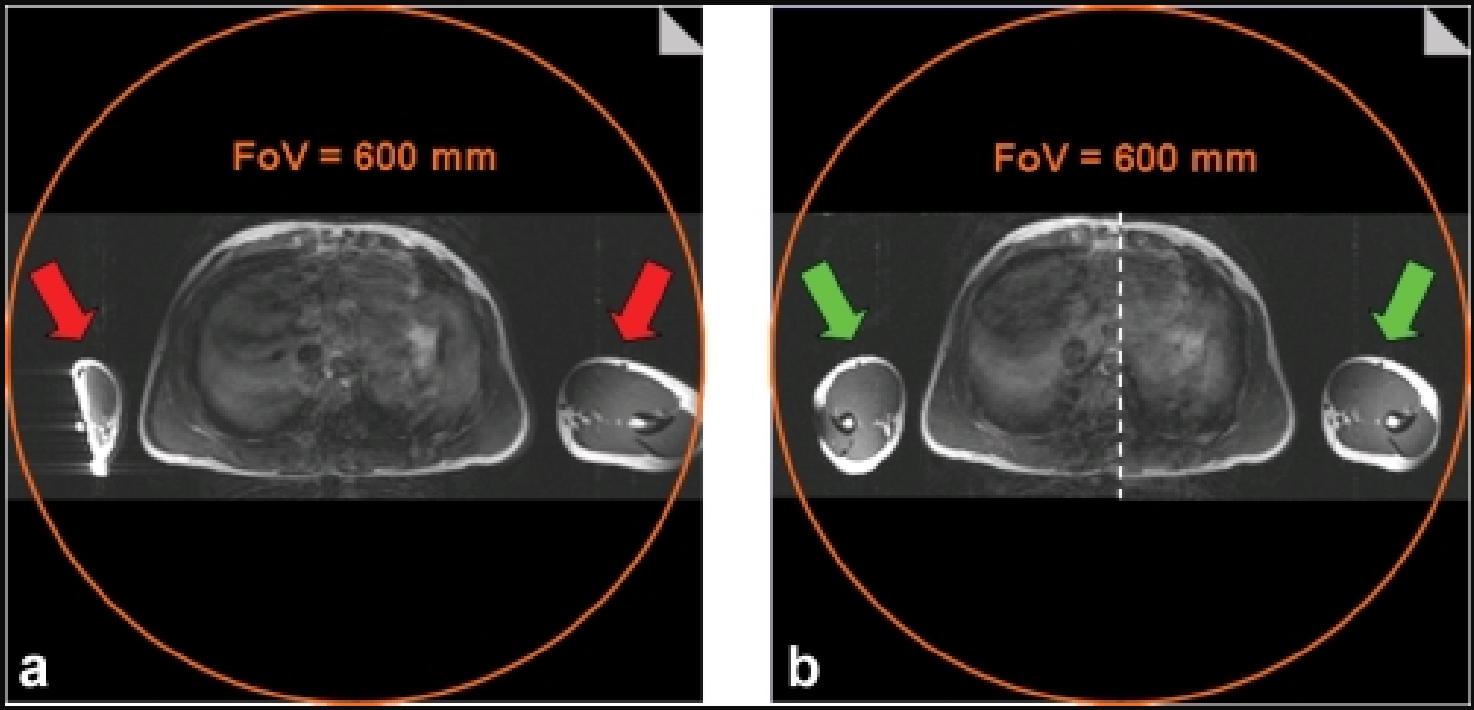
# Truncation Artifact




- A truncated attenuation map created from MR data using the segmentation method based on Martinez-Möller et al.

- An attenuation map corrected for truncation using the method described in Nuyts et al. on the Biograph mMR.

# Truncation Artifact




**MR-based field-of-view extension in MR/PET: $B_0$ homogenization using gradient enhancement (HUGE)**

Magnetic Resonance in Medicine
Volume 70, Issue 4, pages 1047-1057, 30 NOV 2012 DOI: 10.1002/mrm.24555
http://onlinelibrary.wiley.com/doi/10.1002/mrm.24555/full#mrm24555-fig-0008

# Tartışma ve Sonuçlar

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# TESEKKURLER