Medical Image Processing for Diagnostic Applications

Modalities – X-ray Computed Tomography

Online Course – Unit 51

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Topics

X-ray Computed Tomography

Summary

Take Home Messages

Further Readings

X-ray Imaging

- X-rays penetrate the object of interest.
- The amount of absorption and scattering allows the estimation of the object density.
- Energy is absorbed in the object.

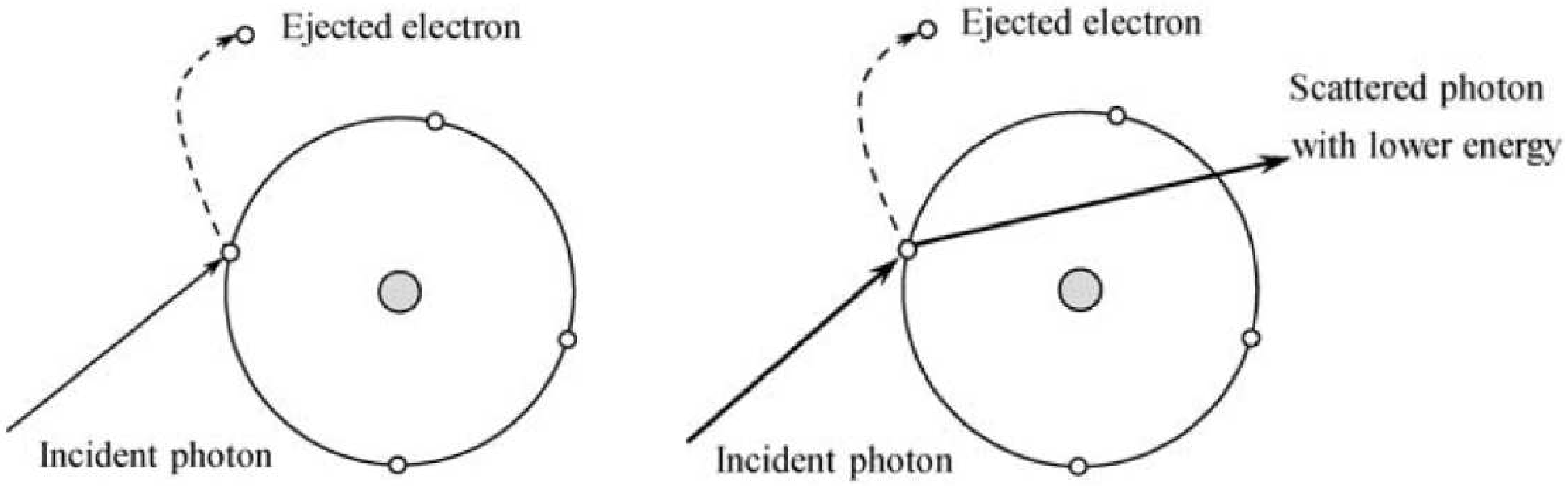

Figure 1: Photoelectric effect (left) and Compton scatter (right) (Zeng, 2009)

Parallel Beam Geometry

- Earliest acquisition scheme
- **Principle:** “Rotate & Translate”

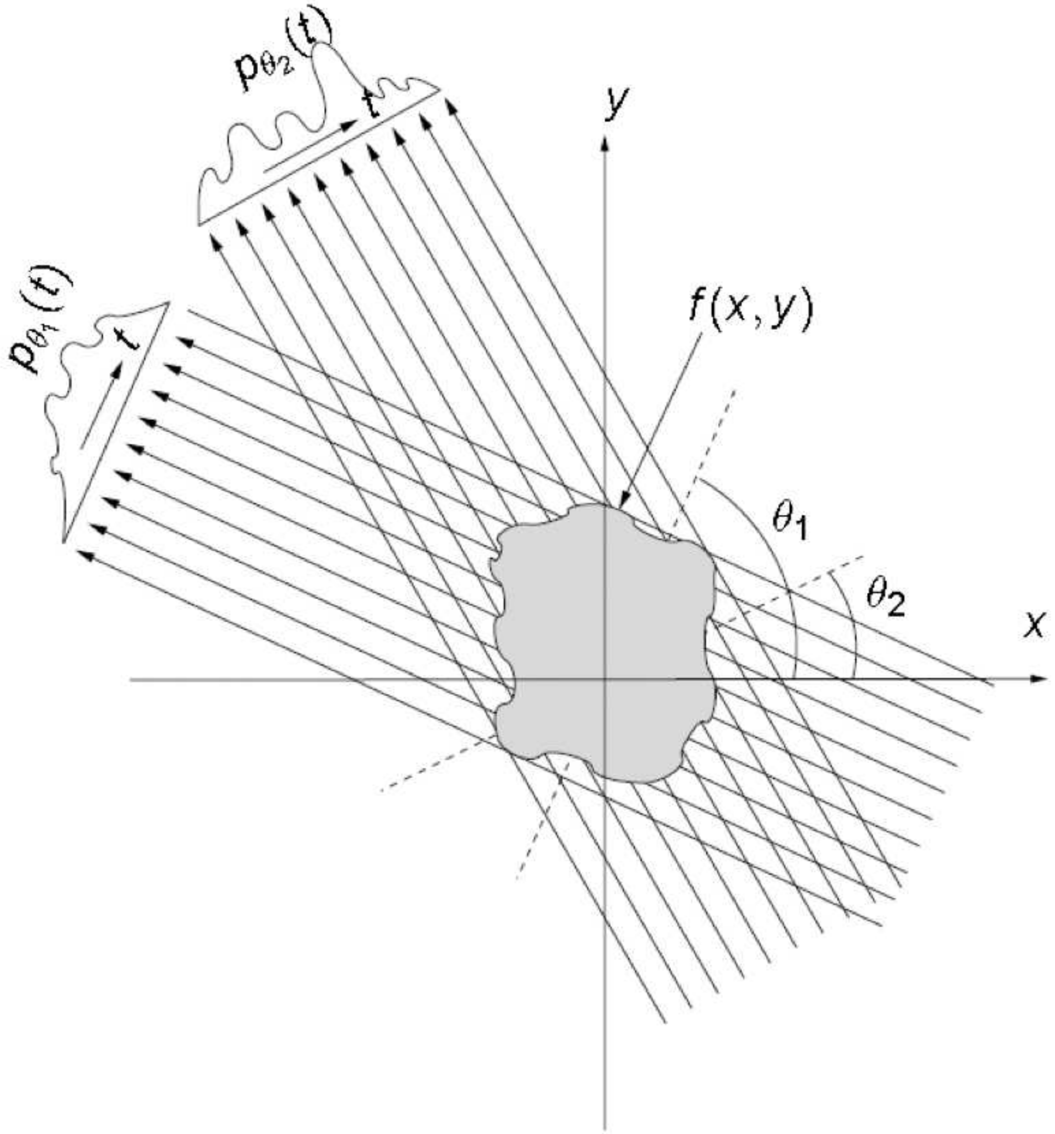

Figure 2: Parallel projection scheme with two different angles θ_1, θ_2 and the object $f(x, y)$

Fan Beam Geometry

- Fan covers the complete object.
- Continuous rotation is possible.

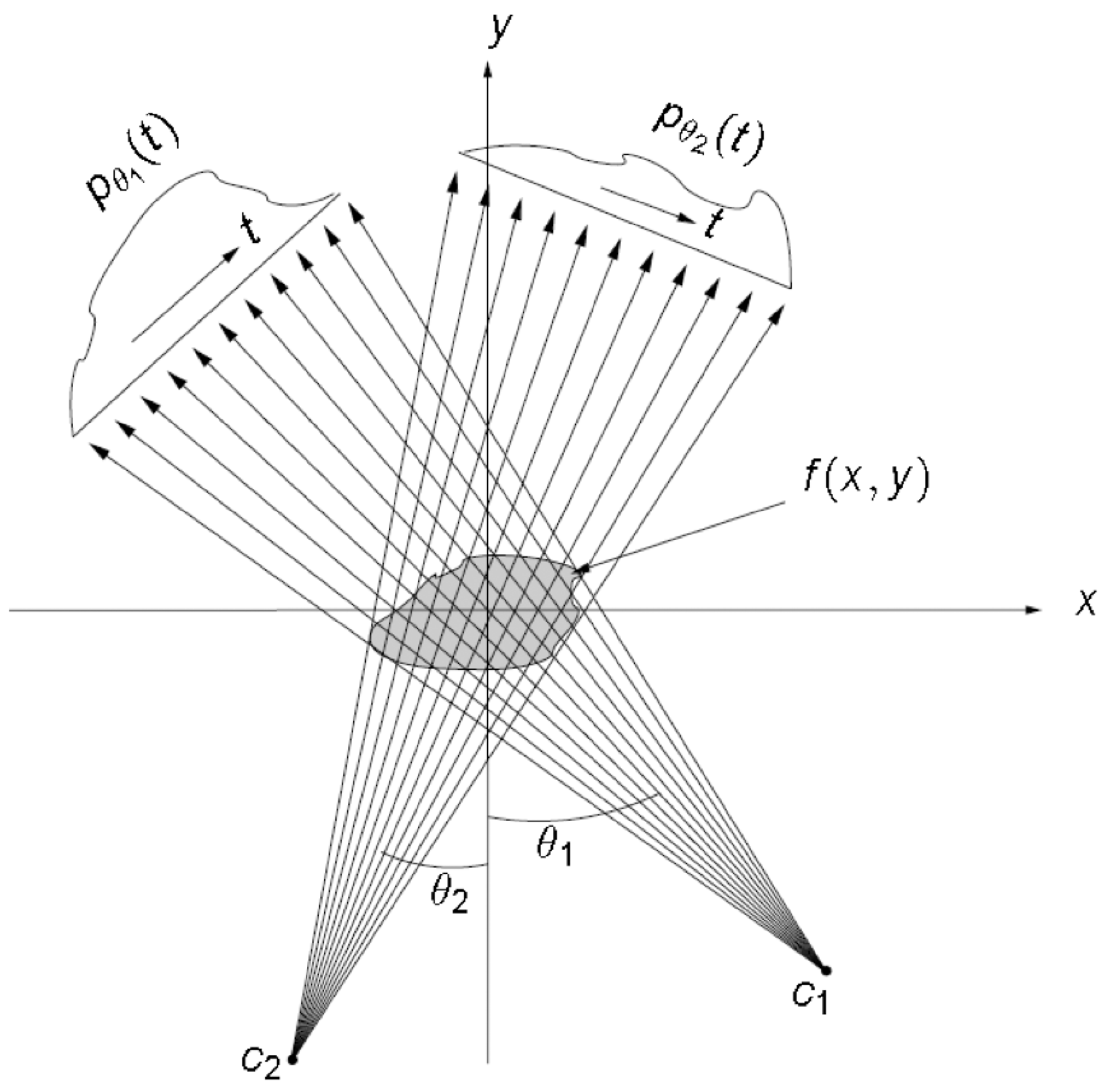

Figure 3: Fan beam projection scheme with two different angles θ_1, θ_2 and the object $f(x, y)$

Cone Beam Geometry

- Cone covers the complete object.
- Continuous rotation is possible.
- This geometry enables fast 3-D acquisition.
- Circular trajectory suffers from incomplete data.

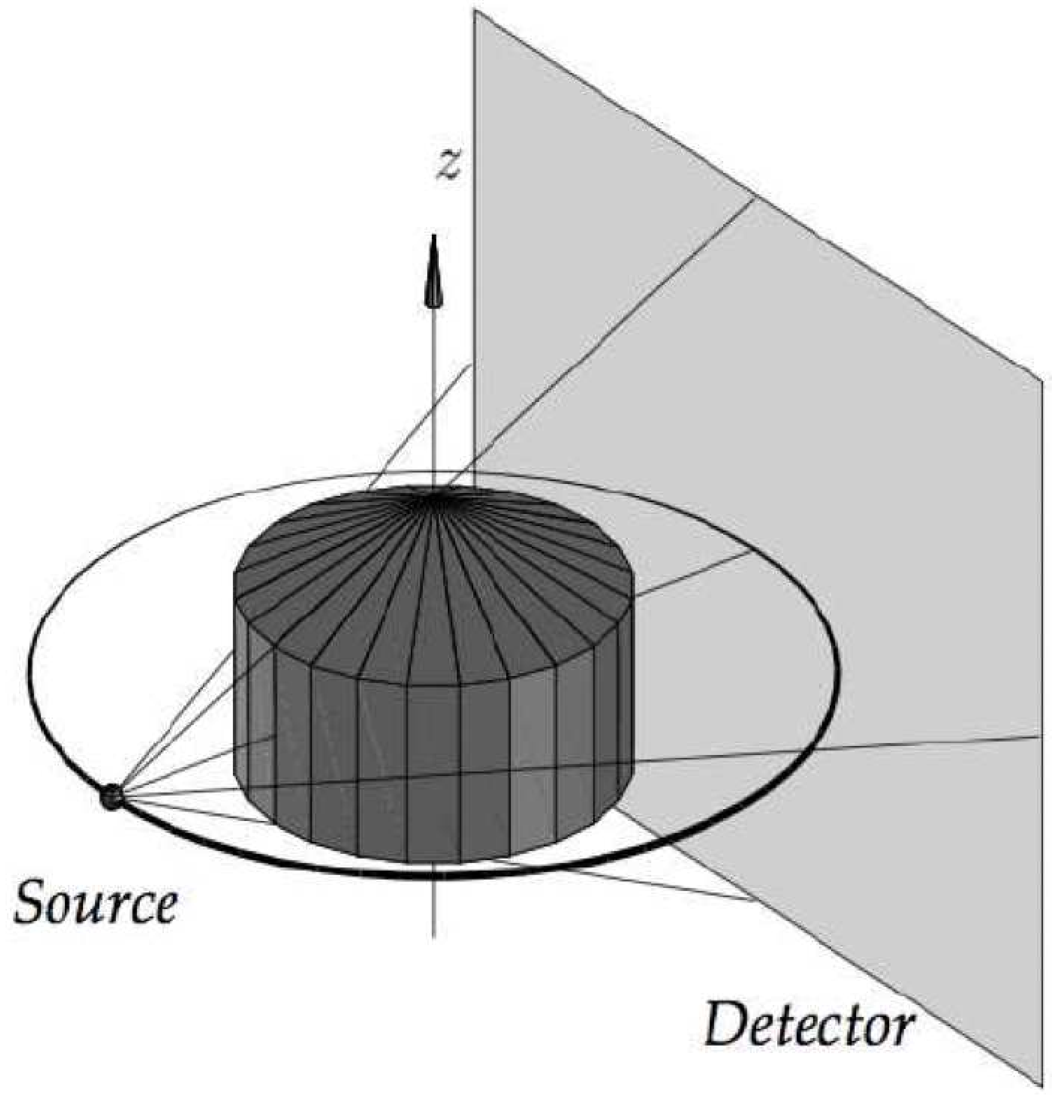

Figure 4: Cone beam scheme

Helical Scanning

- Helical scanning allows 3-D acquisition with complete data.
- The helix is created by a two-fold motion of a circular gantry rotation and a simultaneous table movement.

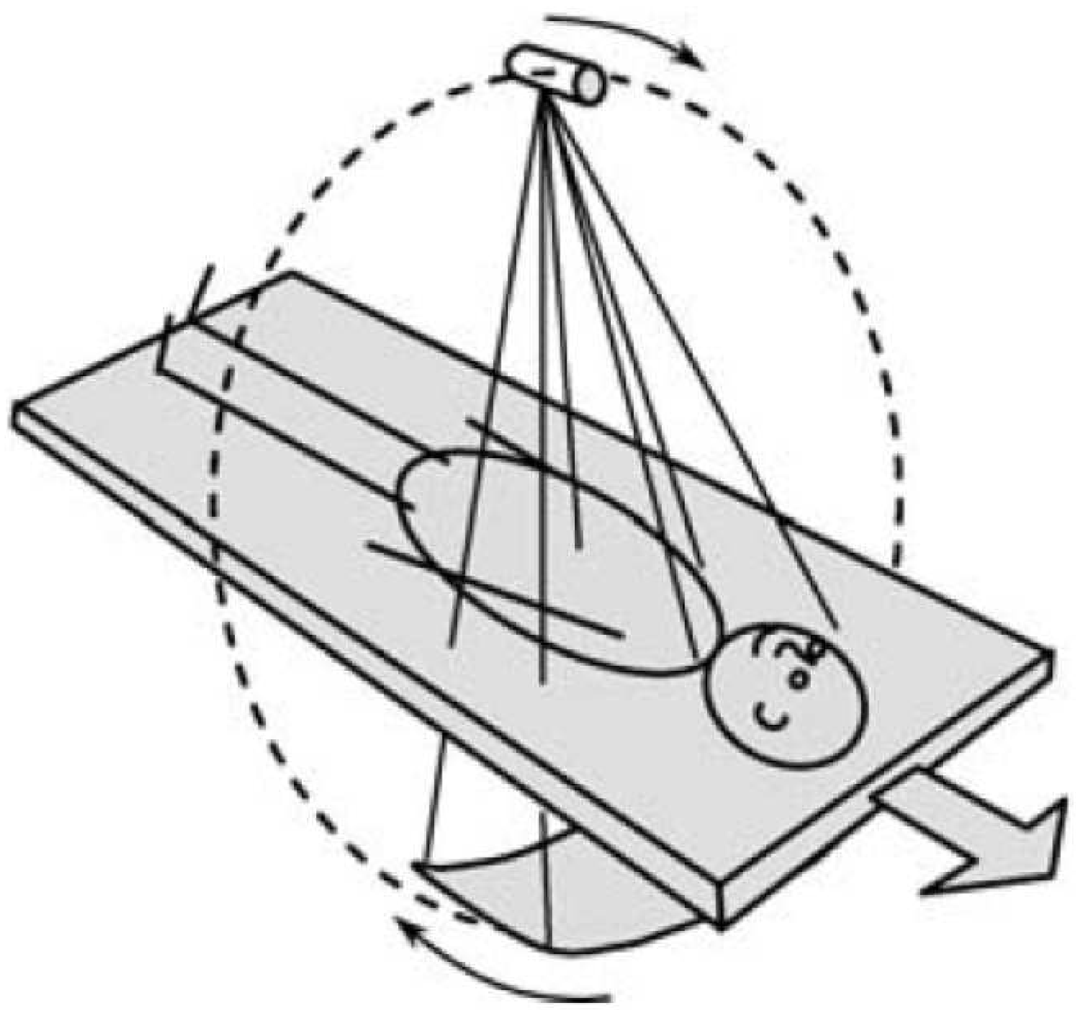

Figure 5: Sketch of an operational helical scan

Topics

X-ray Computed Tomography

Summary

Take Home Messages

Further Readings

Take Home Messages

- This unit was a reprise of the modality “X-ray computed tomography” and the common geometries.
- Every modality has its strengths and its weaknesses $\rightarrow$ X-ray imaging is the fastest acquisition technology.

Further Readings

Two reads for more insight into modalities:

Avinash C. Kak and Malcolm Slaney. *Principles of Computerized Tomographic Imaging*. Classics in Applied Mathematics. Accessed: 21. November 2016. Society of Industrial and Applied Mathematics, 2001. DOI: 10.1137/1.9780898719277. URL: http://www.slaney.org/pct/

Gengsheng Lawrence Zeng. *Medical Image Reconstruction – A Conceptual Tutorial*. Springer-Verlag Berlin Heidelberg, 2010. DOI: 10.1007/978-3-642-05368-9

Medical Image Processing for Diagnostic Applications

Modalities – PET and SPECT

Online Course – Unit 52
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Topics

Positron Emission Tomography

Single Photon Emission Computed Tomography

Summary

Take Home Messages

Further Readings

Positron Emission Tomography (PET)

- PET is based on the insertion of a radioactive substance (e. g., isotopes $^{15}\mathrm{O}$, $^{11}\mathrm{C}$, $^{13}\mathrm{N}$, or $^{18}\mathrm{F}$) into the patient's body via injection, inhalation, or ingestion.
- The radioactive substance is bound to a molecule that is of interest for the diagnostic task (e. g., sugar for analysis of the patient's metabolism).
- The imaging task delivers a map of the distribution of the radioactive tracer.

Positron Emission Tomography: Concept

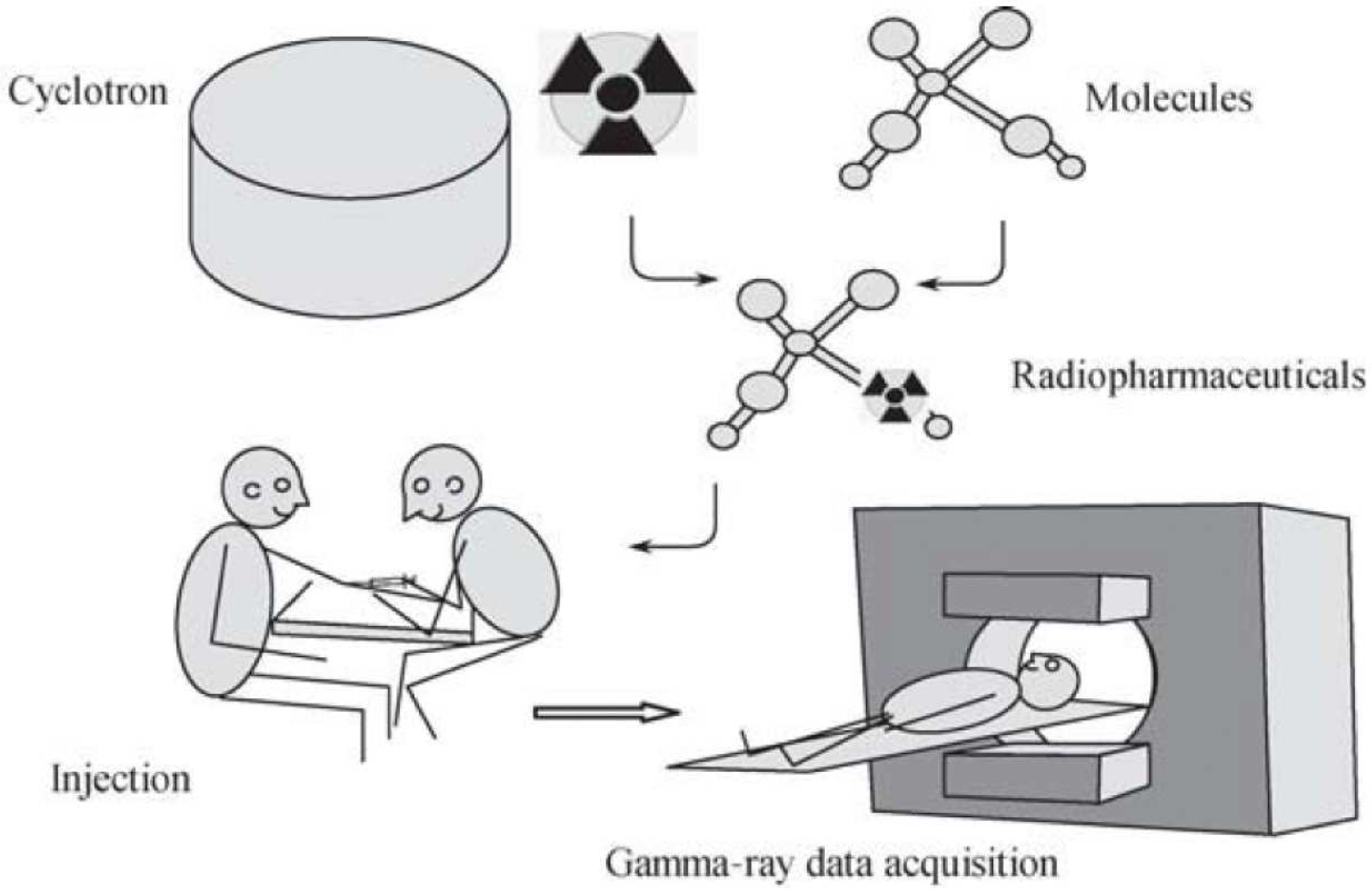


Figure 1: Scheme of a PET scan workflow (Zeng, 2009)

Positron Emission Tomography: Physics

- The radio decay of the isotopes causes the creation of positrons.
- As soon as a positron hits an electron, their masses are annihilated, and two photons of 511 keV each are emitted into opposite directions.

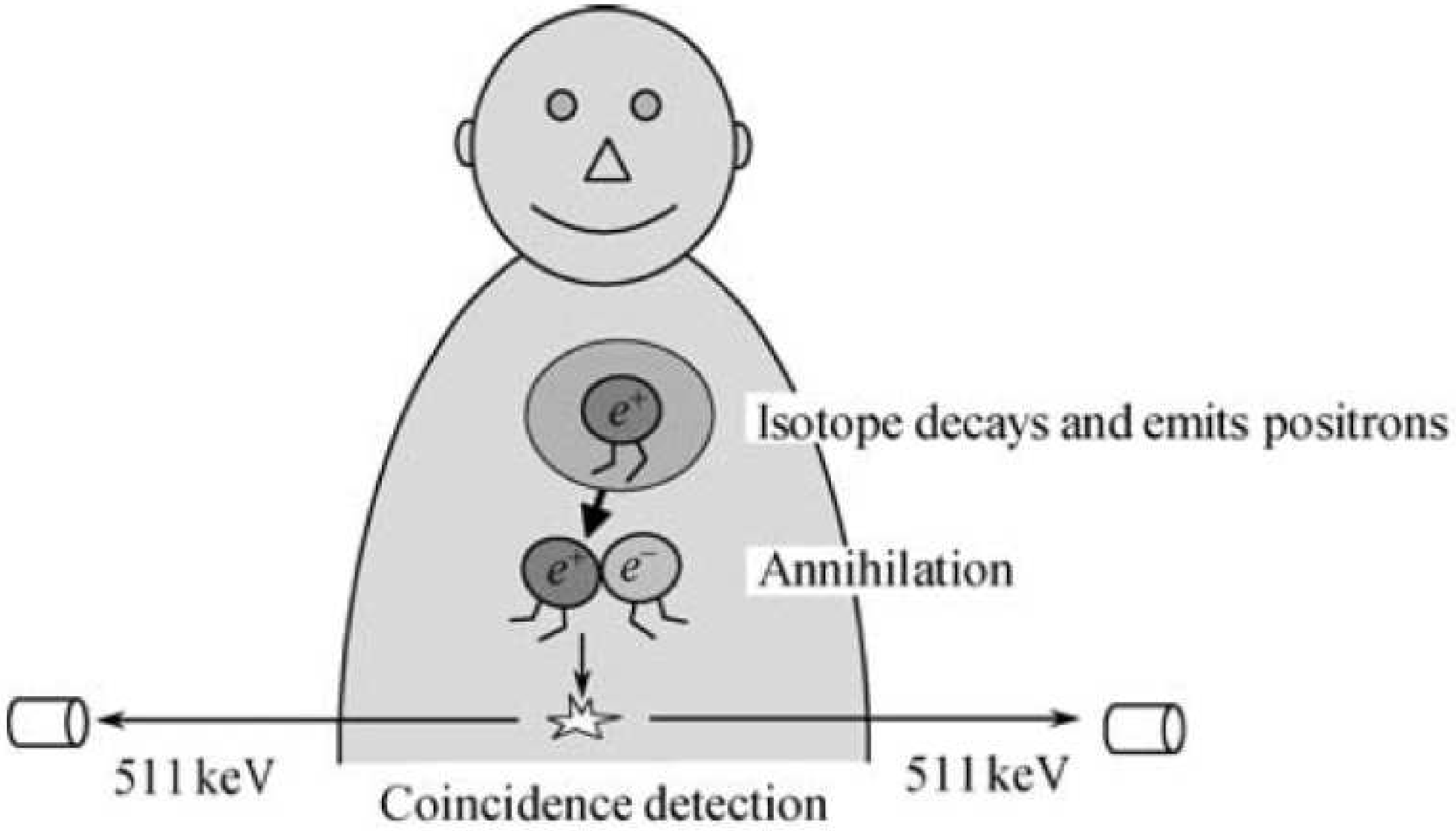


Figure 2: Illustration of positron annihilation (Zeng, 2009)

Positron Emission Tomography: Acquisition Geometry

- Simultaneous events have to be detected in order to find a pair annihilation.
- As the direction of the gamma rays is on the same line, but in opposite direction, a parallel imaging geometry emerges.

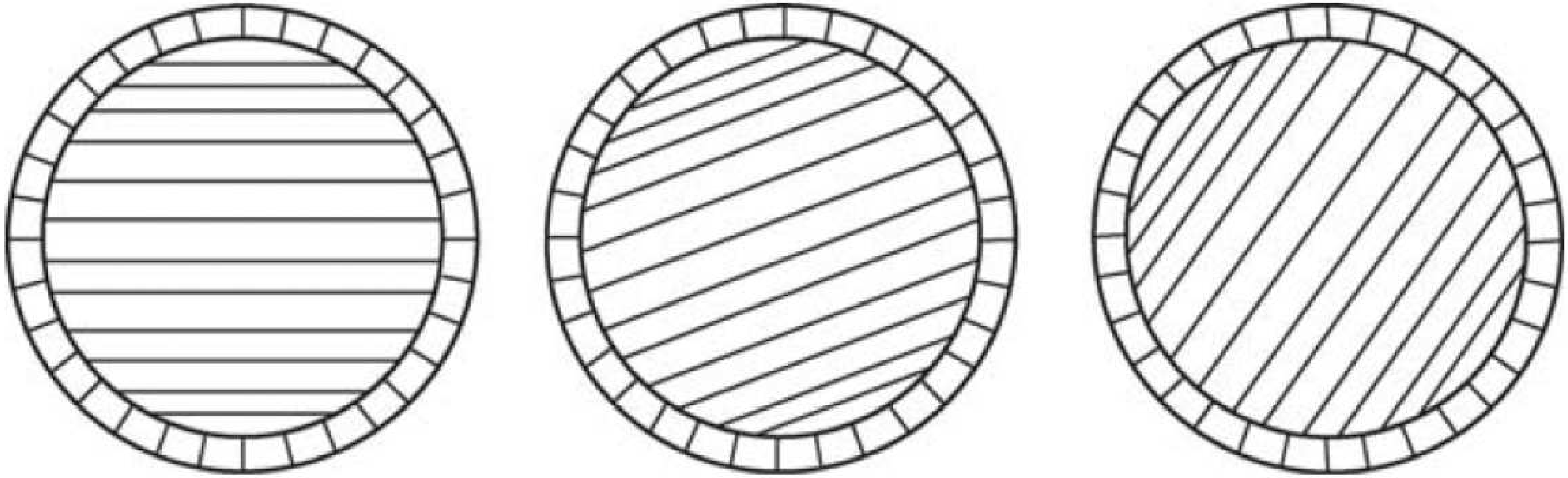


Figure 3: Illustration of the parallel line acquisition in PET (Zeng, 2009)

Positron Emission Tomography

- PET imaging has lower resolution than X-ray imaging.
- PET scans show the concentration of the tracer substance.
- Time-of-flight imaging helps to increase the spatial resolution of PET scans.
- Attenuation correction helps to reduce image distortions.

Figure 4: PET torso image (inverse gray scale, Zeng, 2009)

Positron Emission Tomography: Attenuation Correction

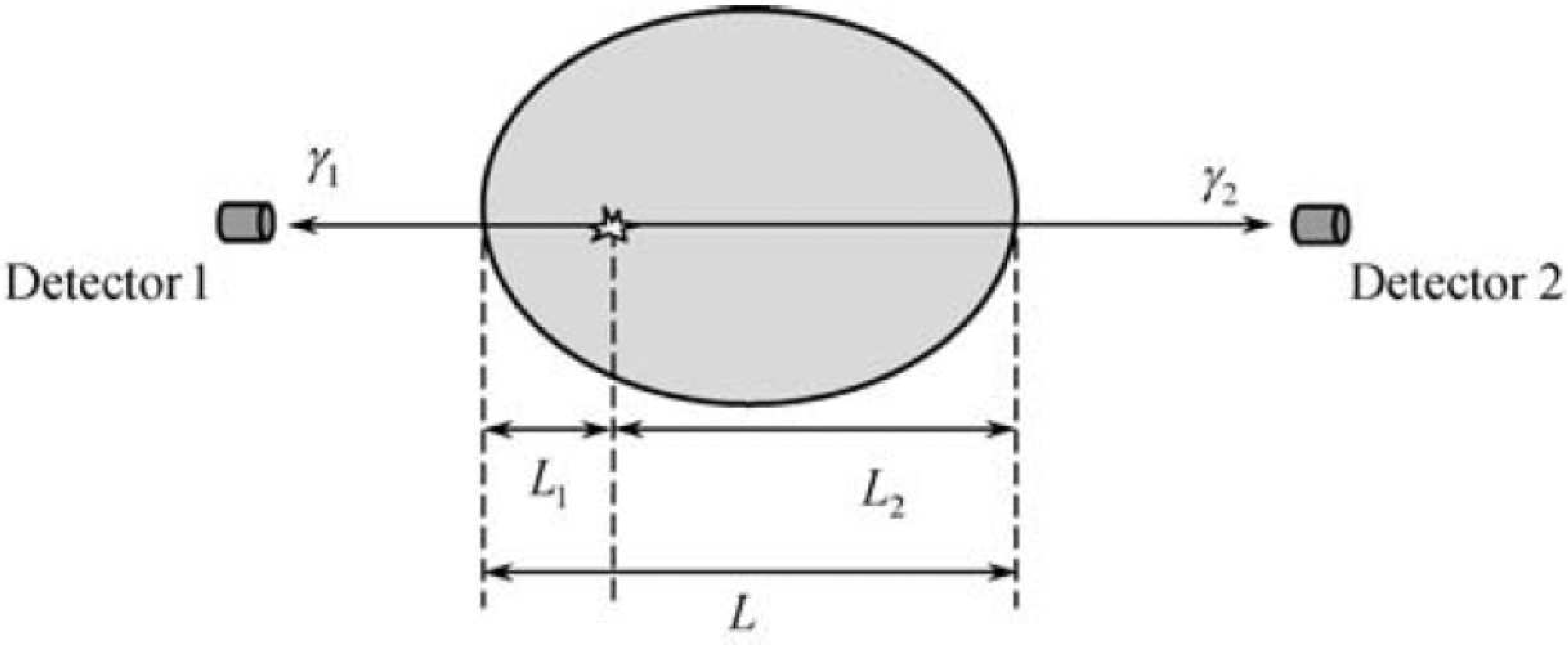


Figure 5: Depending on the point of emission, the positrons may have different path length to the detectors (Zeng, 2009).

Topics

Positron Emission Tomography

Single Photon Emission Computed Tomography

Summary

- Take Home Messages
- Further Readings

Single Photon Emission Computed Tomography (SPECT)

- SPECT (like PET) is based on the insertion of a radioactive substance into the patient's body via injection, inhalation, or ingestion.
- Analogously, the radioactive substance is bound to a molecule that is of interest for the diagnostic task (e. g., sugar for analysis of the patient's metabolism).
- The imaging task also delivers a map of the distribution of the radioactive tracer.
- However, the detected ray energy consists of collimated gamma rays in contrast to PET where coincident photons are measured, induced by positron annihilation.

Single Photon Emission Computed Tomography: Principle

- Radioactive decay causes the emission of gamma rays.
- The emitted gamma quanta are detected by a gamma camera.
- Only single gamma rays are seen by the camera.
- The imaging geometry is determined by the system’s collimator.

Single Photon Emission Computed Tomography: Principle

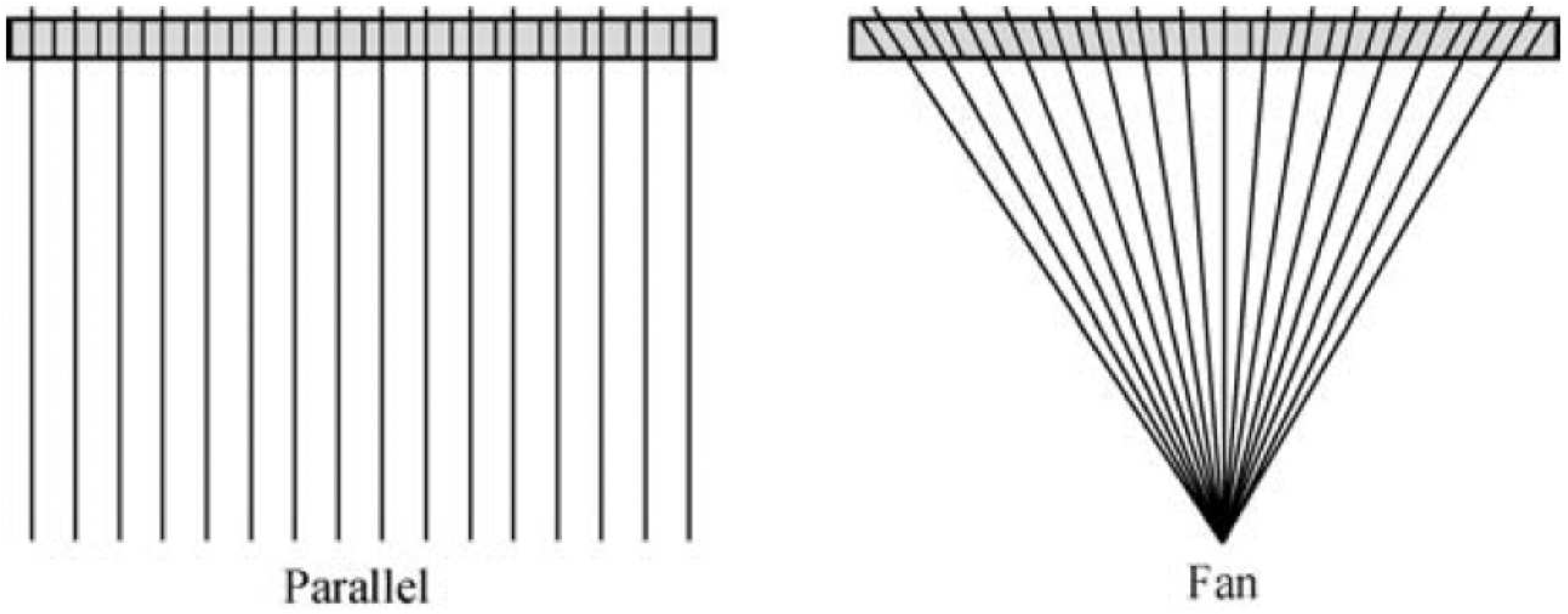


Figure 6: Among others, there are parallel and fan beam collimators for SPECT (Zeng, 2009).

Single Photon Emission Computed Tomography: Collimators

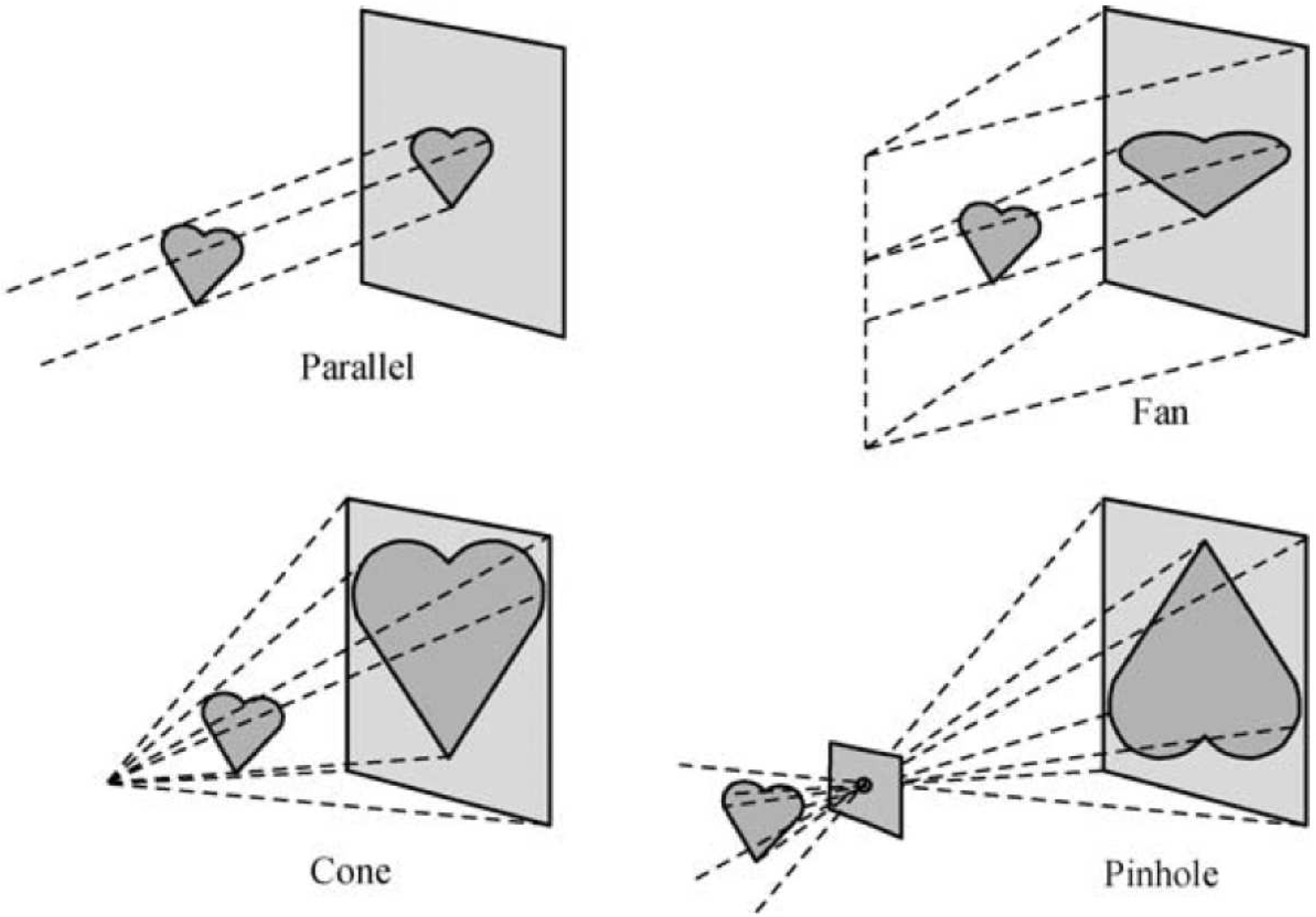


Figure 7: The imaging result is dependent on the collimator type (Zeng, 2009).

Single Photon Emission Computed Tomography

- SPECT imaging has a lower resolution than PET imaging.
- SPECT scans show the concentration of the tracer substance.
- Attenuation correction helps to reduce image distortions.

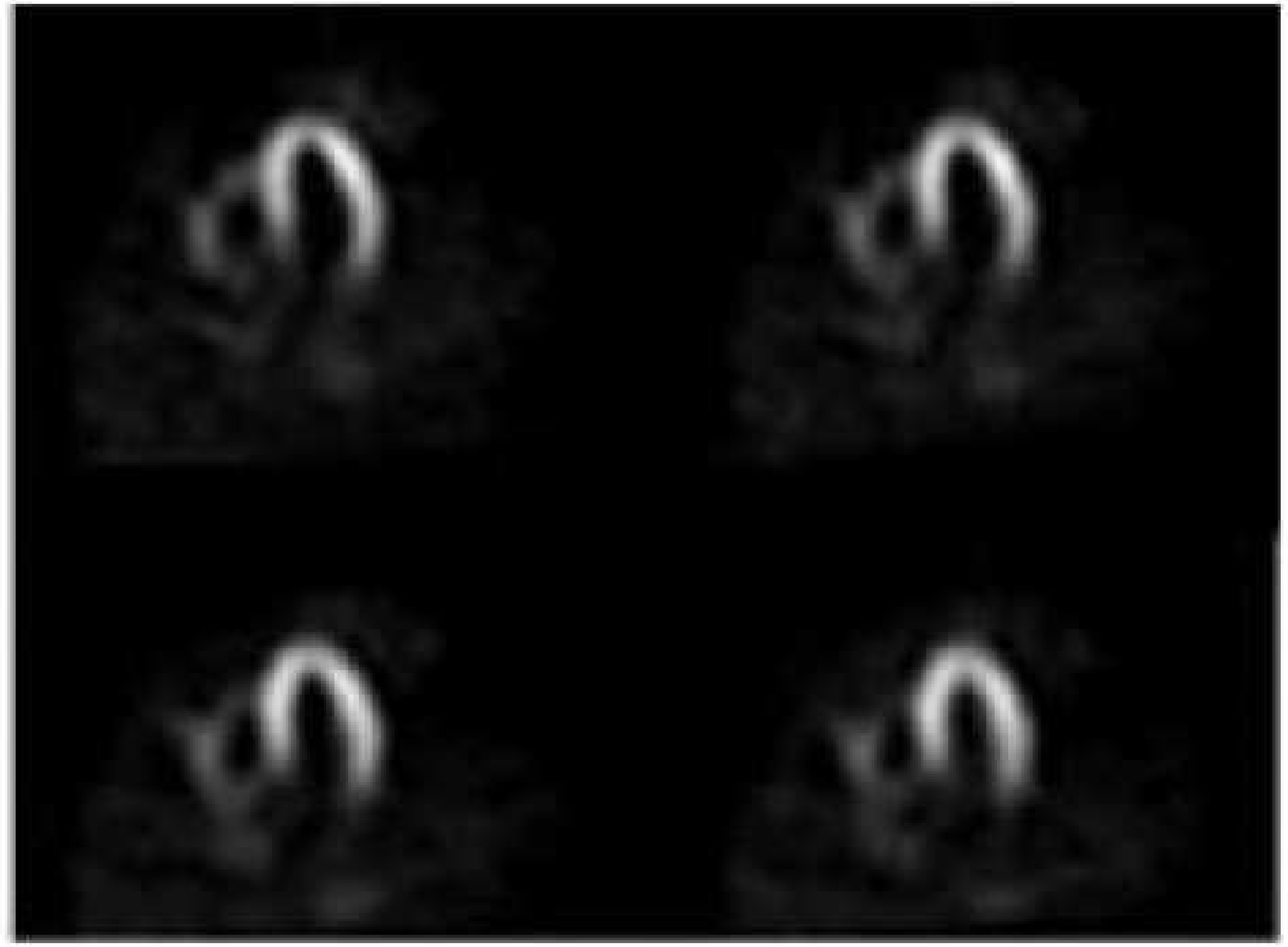
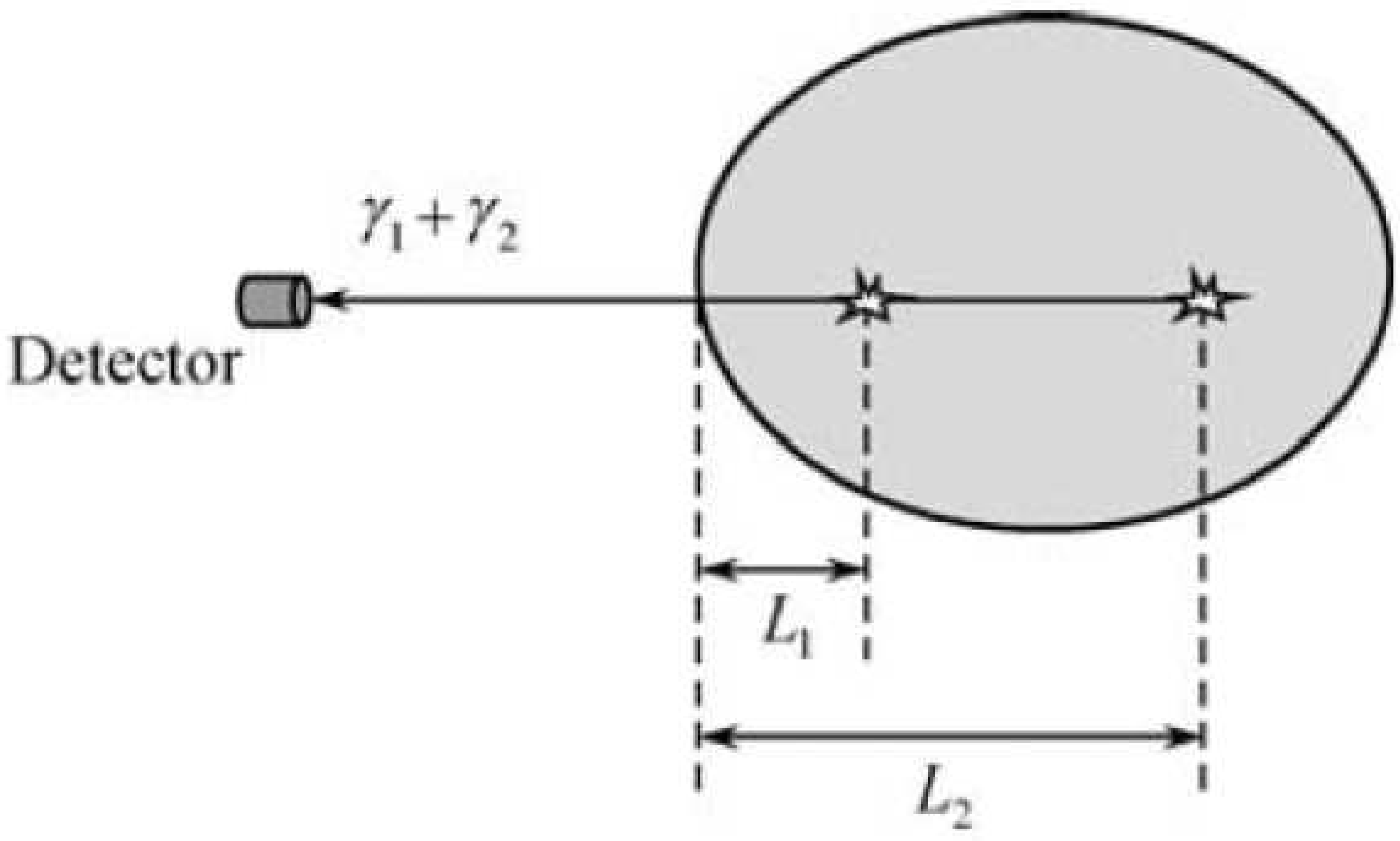


Figure 8: SPECT cardiac images (Zeng, 2009)

Single Photon Emission Computed Tomography: Attenuation Correction



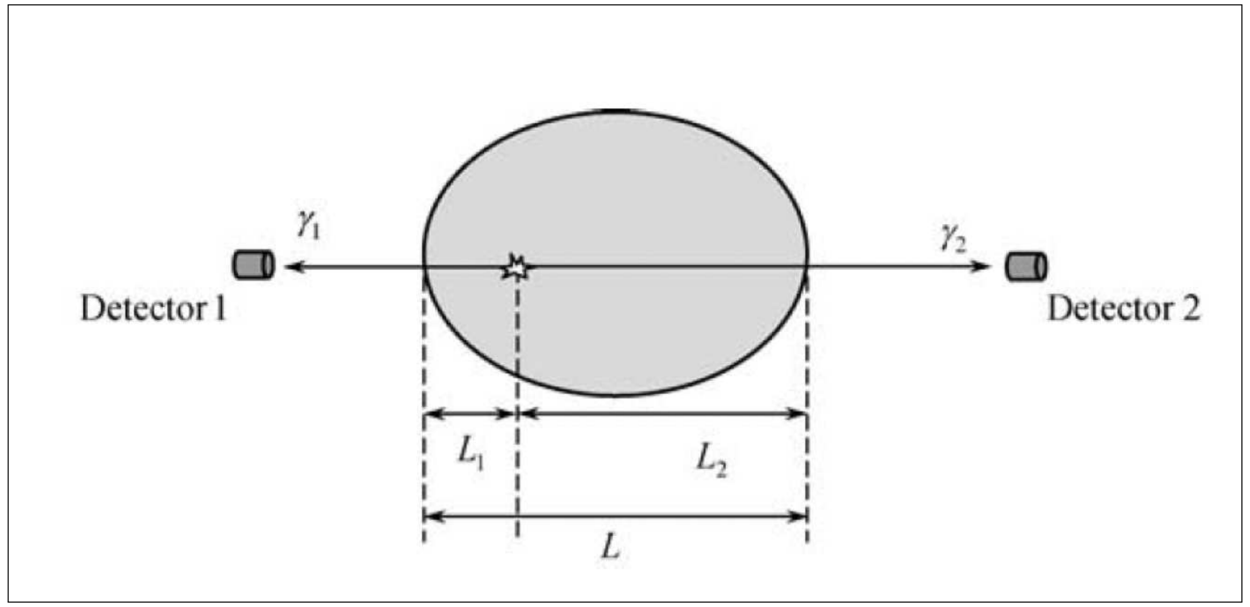


Figure 9: Attenuation correction for SPECT (left) vs. attenuation correction for PET (right box) (Zeng, 2009)

Topics

Positron Emission Tomography

Single Photon Emission Computed Tomography

Summary
- Take Home Messages
- Further Readings

Take Home Messages

- PET and SPECT both are based on the detection of gamma rays emitted from radioactive substances *inside* the patient's body.
- Every modality has its strengths and its weaknesses $\rightarrow$ PET and SPECT show functional images.
- Combination of modalities helps to alleviate particular problems $\rightarrow$ hybrid systems, e. g., SPECT/CT and PET/MR, are emerging technologies.

Further Readings

Two reads for more insight into modalities:

Avinash C. Kak and Malcolm Slaney. *Principles of Computerized Tomographic Imaging*. Classics in Applied Mathematics. Accessed: 21. November 2016. Society of Industrial and Applied Mathematics, 2001. DOI: 10.1137/1.9780898719277. URL: http://www.slaney.org/pct/

Gengsheng Lawrence Zeng. *Medical Image Reconstruction – A Conceptual Tutorial*. Springer-Verlag Berlin Heidelberg, 2010. DOI: 10.1007/978-3-642-05368-9

Medical Image Processing for Diagnostic Applications

Modalities – Magnetic Resonance Imaging - Part 1

Online Course – Unit 53
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Topics

Magnetic Resonance Imaging

Summary

Take Home Messages

Further Readings

Magnetic Resonance Imaging (MRI) ...

- ... used to be called “Nuclear Magnetic Resonance Imaging” (NMRI).
- ... measures the distribution of hydrogen atoms:

$\rightarrow$ it yields very good soft tissue contrast,

$\rightarrow$ and it yields low contrast for other materials such as bone or air.

Figure 1: Brain MRI (Zeng, 2009)

Magnetic Resonance Imaging: Proton Spin

Spinning protons act like tiny magnets:

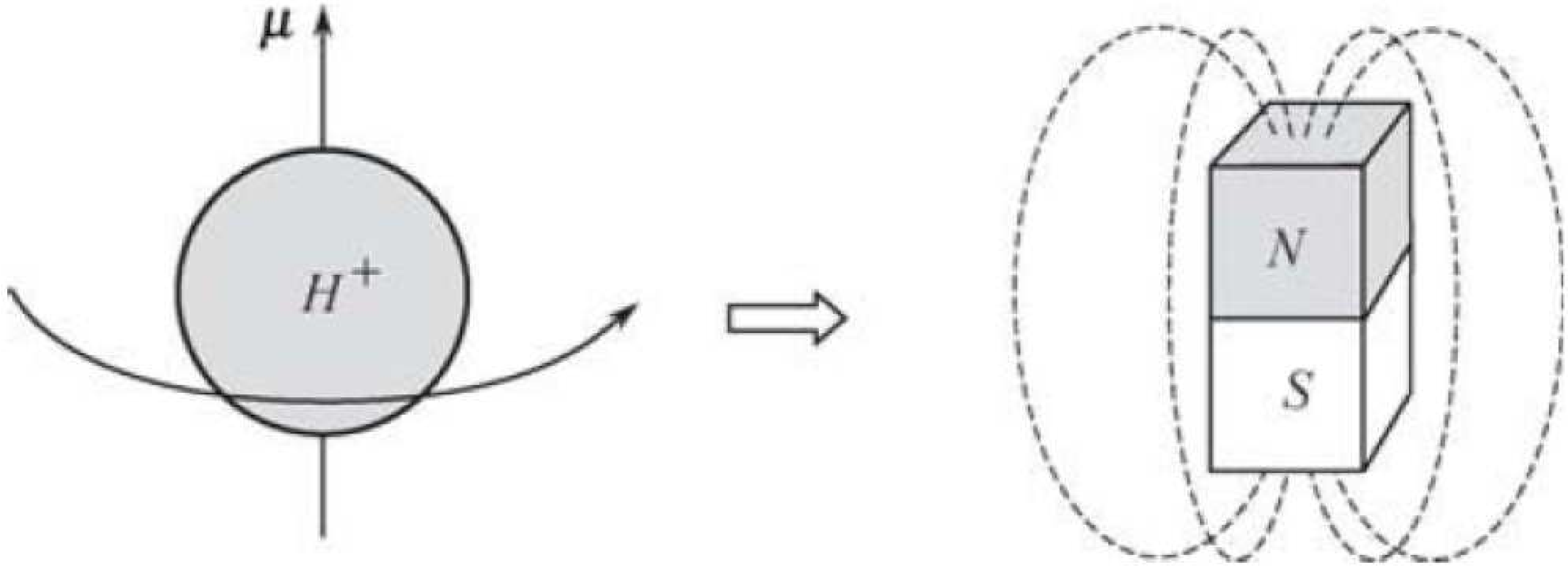

Figure 2: Illustration of the proton spin (Zeng, 2009)

Magnetic Resonance Imaging: Proton Spin

As the protons are oriented in random directions the net magnetic moment is zero:

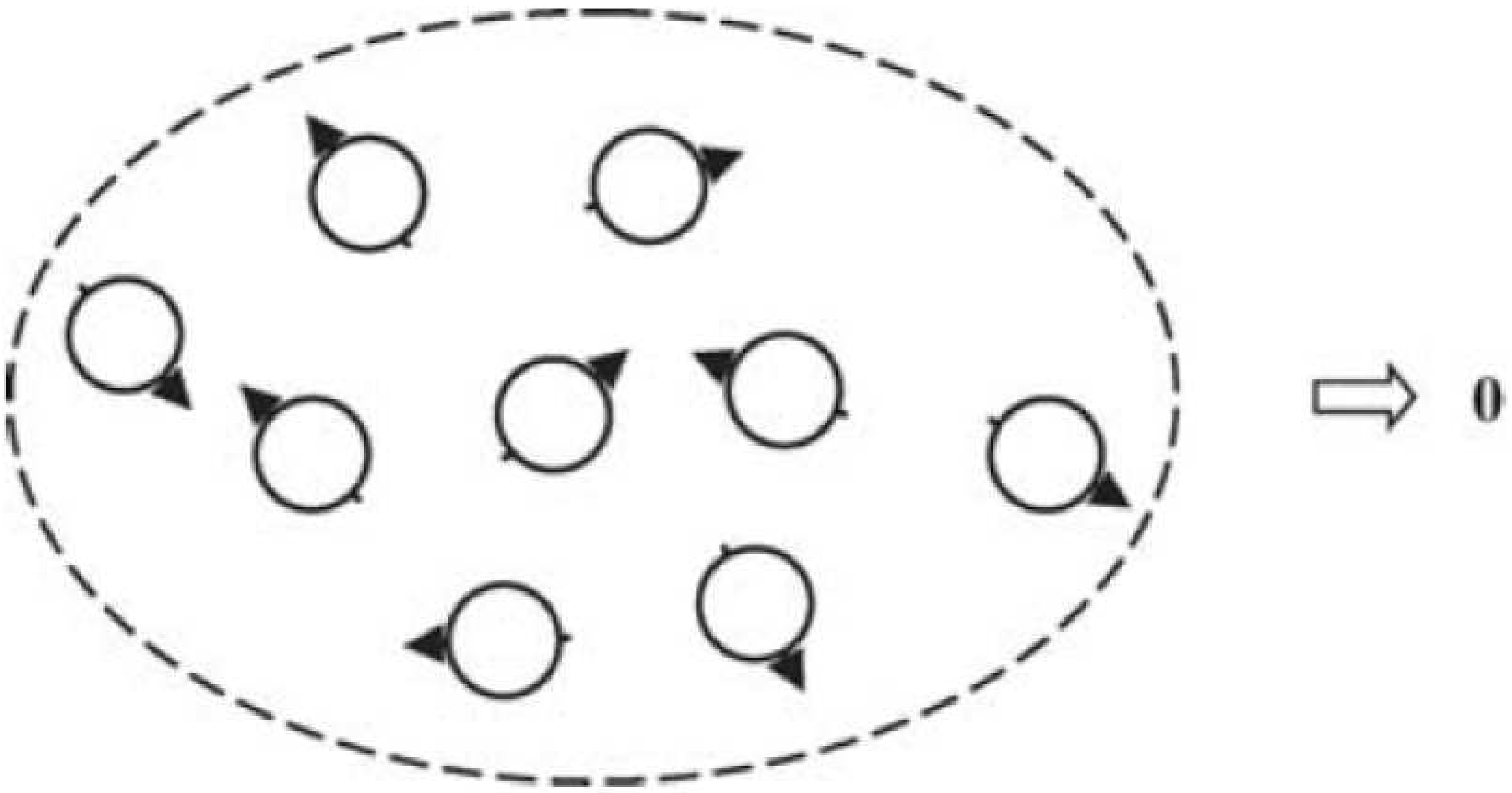

Figure 3: Spins are equalized without external interaction (Zeng, 2009).

Magnetic Resonance Imaging: Spin Orientation

- If an external magnetic field is applied, the protons orient along this field.
- About half of them point towards the south pole of the field, while the others point towards the north pole.
- Due to this imbalance, a small magnetic moment is created.
- The magnitude M of the net magnetic moment $\boldsymbol{M}$ is proportional to

$$M \sim \frac{\gamma \hbar B_0}{2 k_B T}.$$

T is the temperature (in K),
$k_B \approx 8.617 \times 10^{-5}\,\mathrm{eV\,K^{-1}}$ is the Boltzmann constant,
$\hbar \approx 1.055 \times 10^{-34}\,\mathrm{J\,s}$ is the reduced Planck constant,
γ is the atom-dependent gyromagnetic ratio
(e. g., $42.58\,\mathrm{MHz\,T^{-1}}$ for hydrogen nuclei),

B_0 is the strength of the external magnetic field.

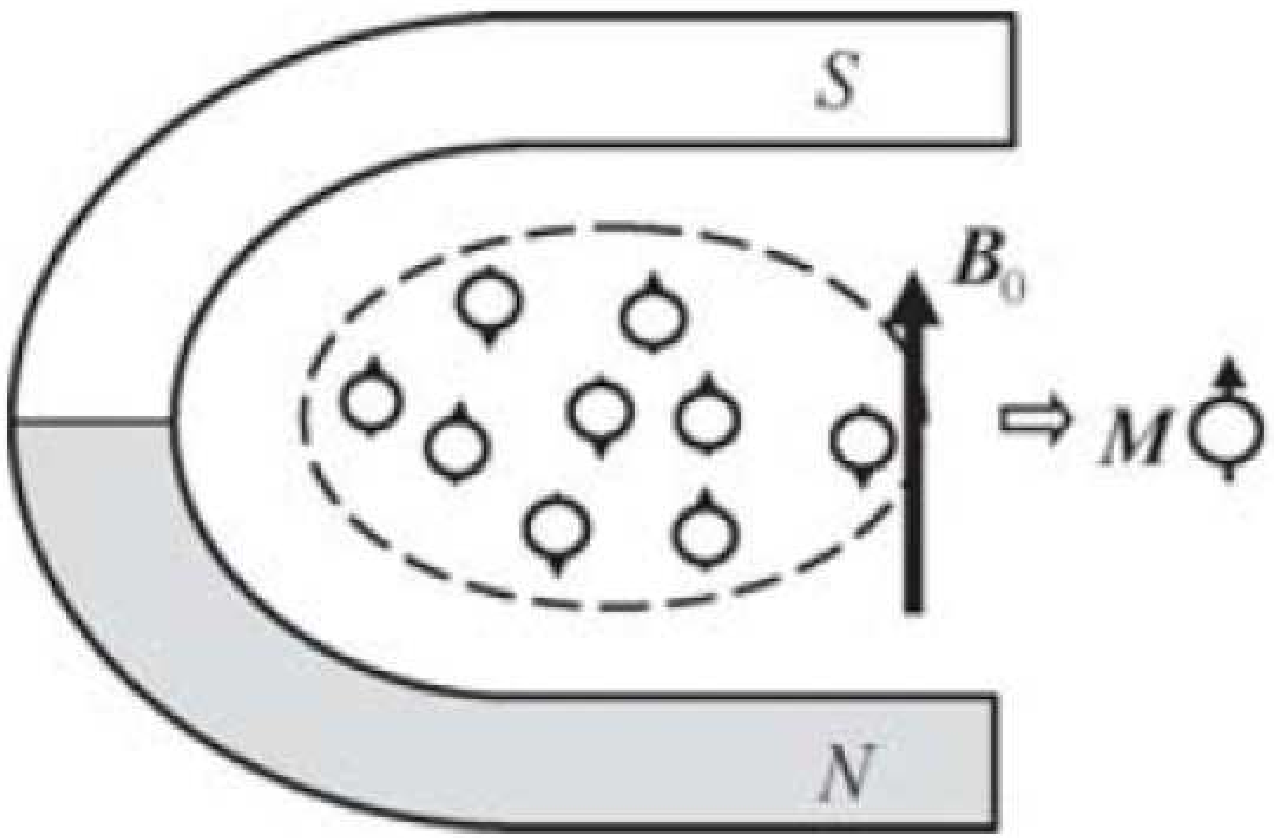

Figure 4: There is a magnetic field due to two different spin types (Zeng, 2009).

Magnetic Resonance Imaging: Precession

- Each of the hydrogen atoms is spinning.
- If the spin axis is not along the external magnetic field axis, **precession** happens.

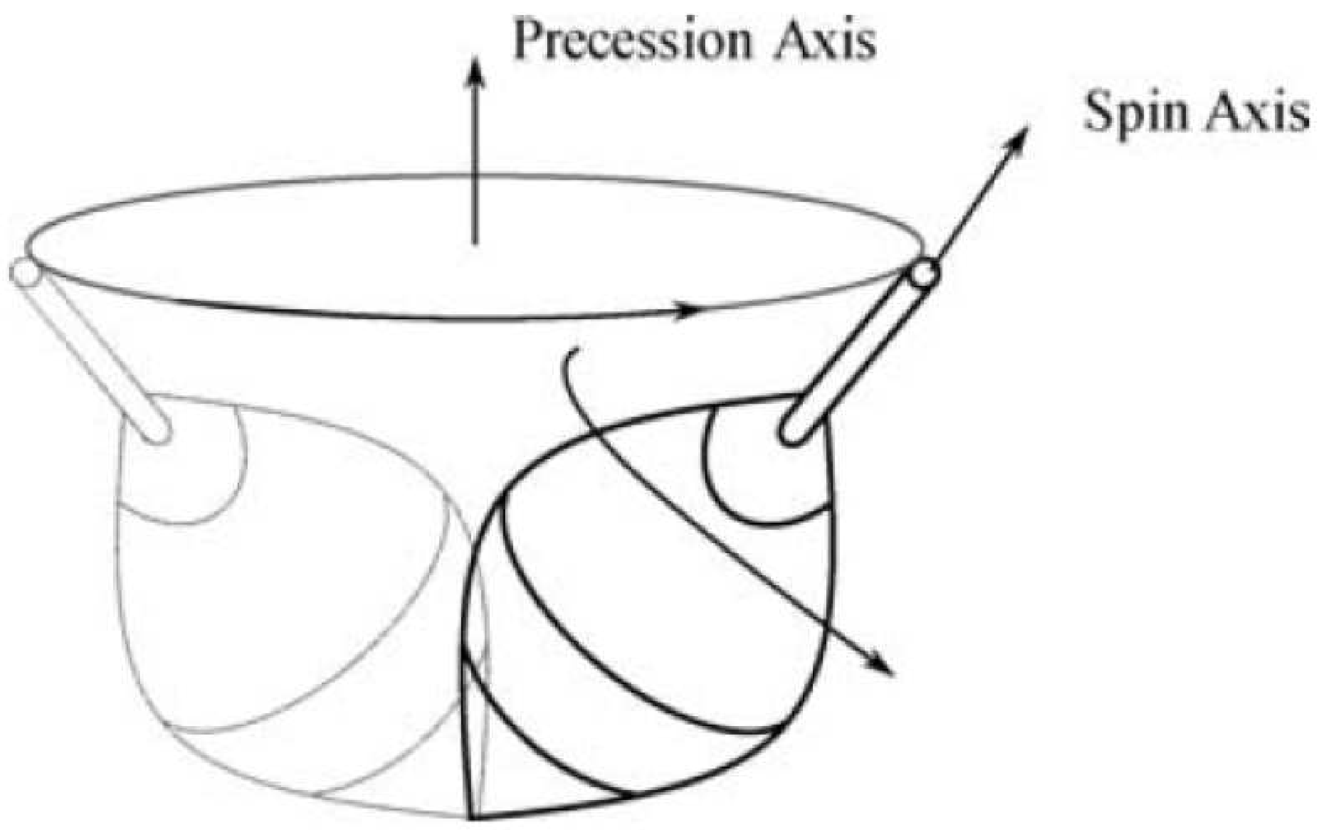

Figure 5: Illustration of precession (Zeng, 2009)

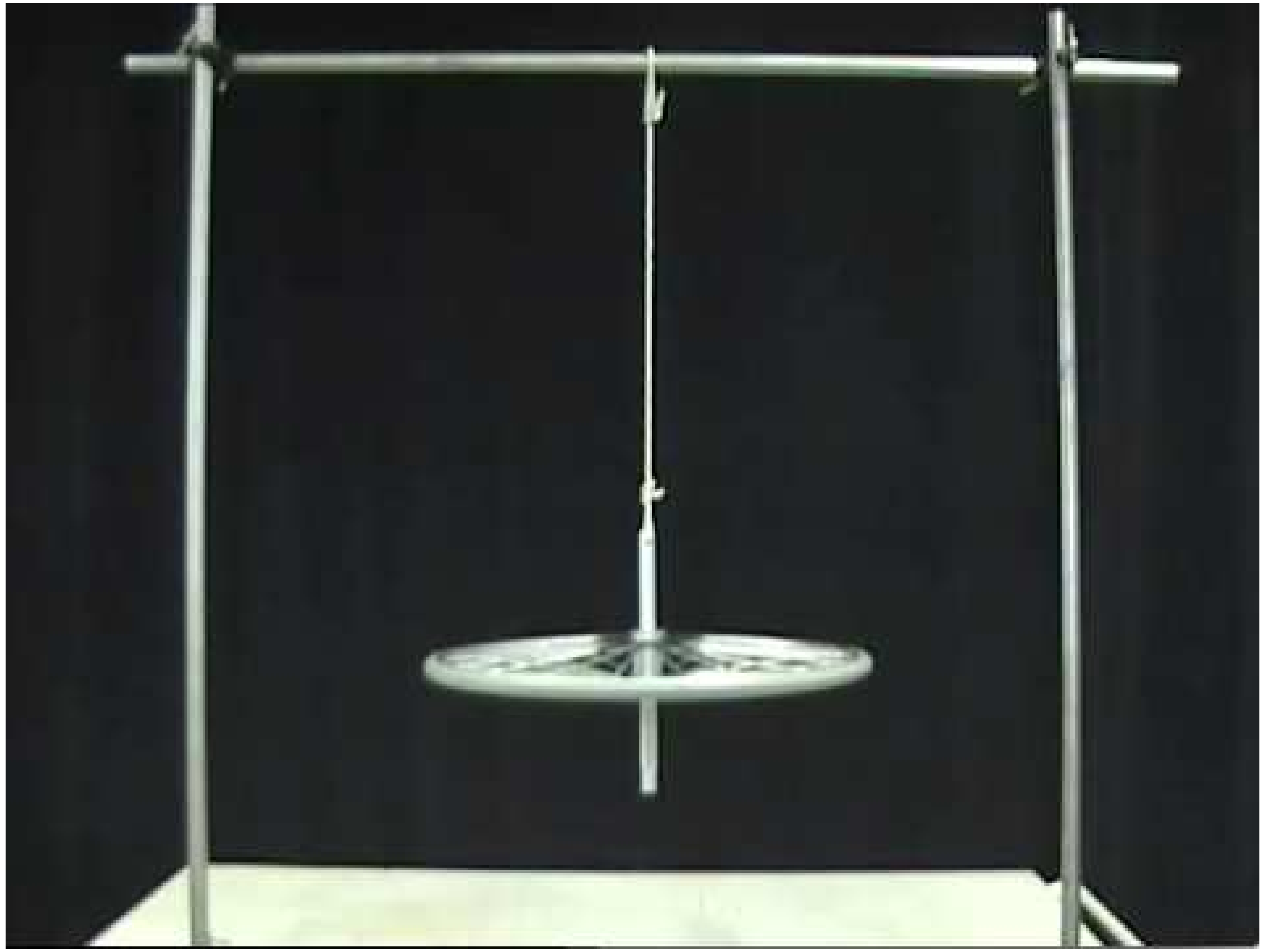

Figure 6: Bicycle wheel gyroscope, MIT Physics Demo, link: http://www.youtube.com/watch?v=8H98BgRzpOM

Magnetic Resonance Imaging: Precession

If the atom is “knocked off balance”, afterwards it returns to its equilibrium position:

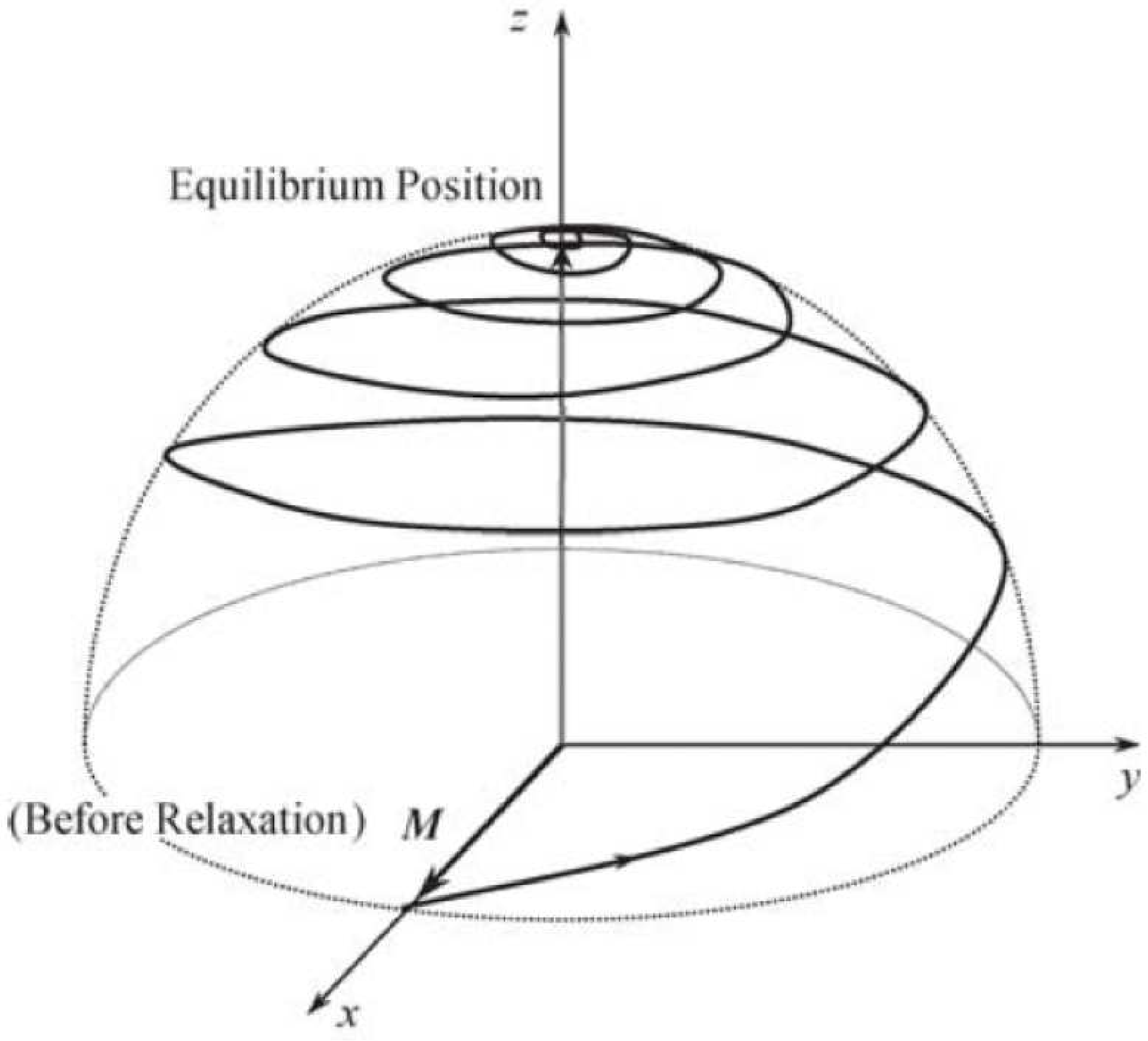

Figure 7: Excitated protons align with the magnetic field with precession (Zeng, 2009).

Magnetic Resonance Imaging: Precession

- The precession of Hydrogen protons is at the Larmor frequency

$$\omega_0 = \gamma B_0,$$

  where γ is the atom-dependent gyromagnetic ratio (42.58 MHz T^{-1} for hydrogen), and B_0 is the strength of the external magnetic field.
- This frequency is in the range of FM radio ($\sim$ 64 MHz at 1.5 T).

Magnetic Resonance Imaging: Frame of Reference

- Consider a second coordinate system that rotates at the Larmor frequency.
- In this coordinate system, there is no precession.

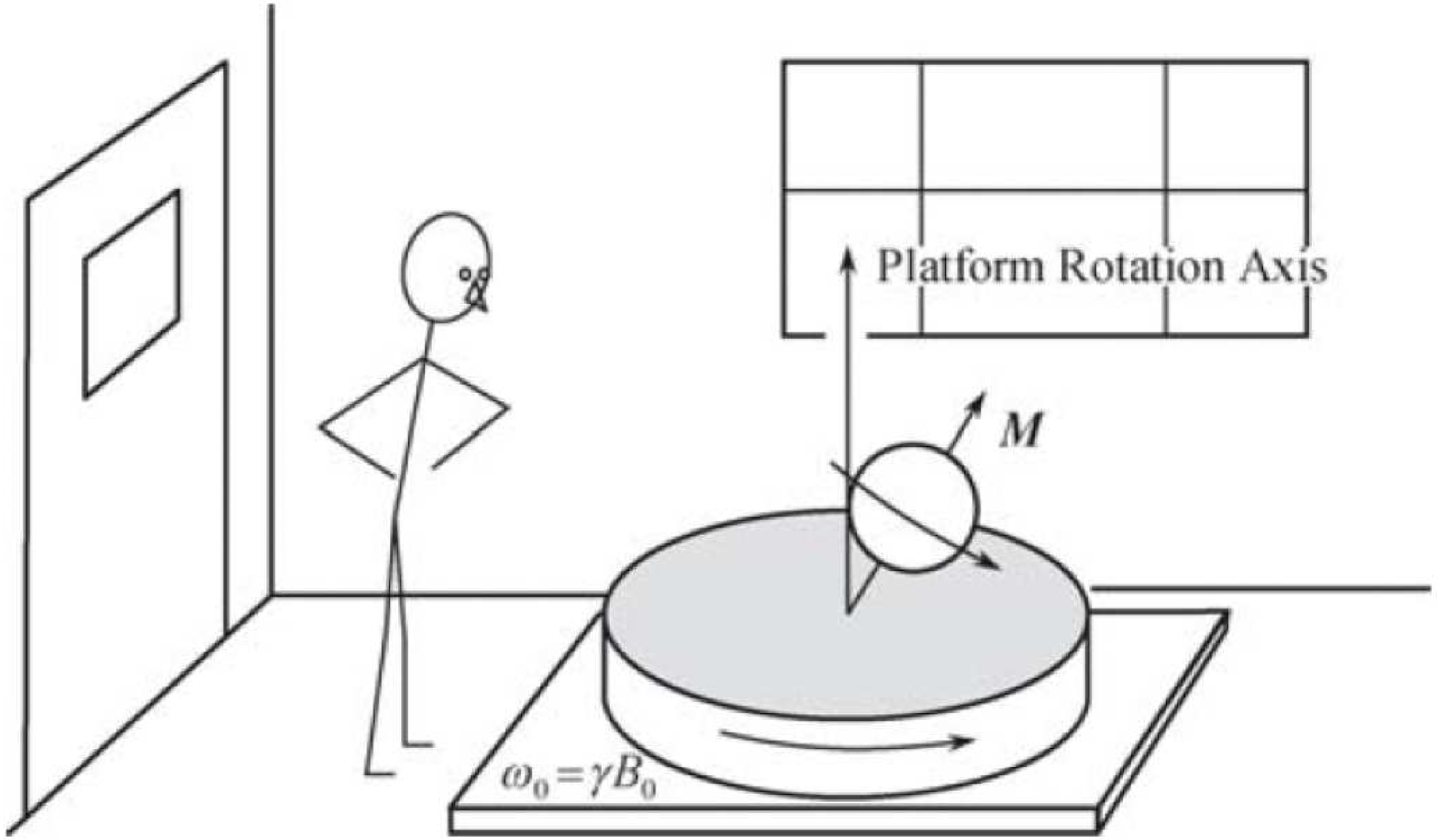

Figure 8: Initial coordinate system (Zeng, 2009)

Magnetic Resonance Imaging: Frame of Reference

- In this new coordinate system, we can apply another field $\boldsymbol{B}_1$ to knock the spin axis off balance.
- After excitation, the field can be turned off again.

$\rightarrow$ The spin axis will return to its equilibrium position.

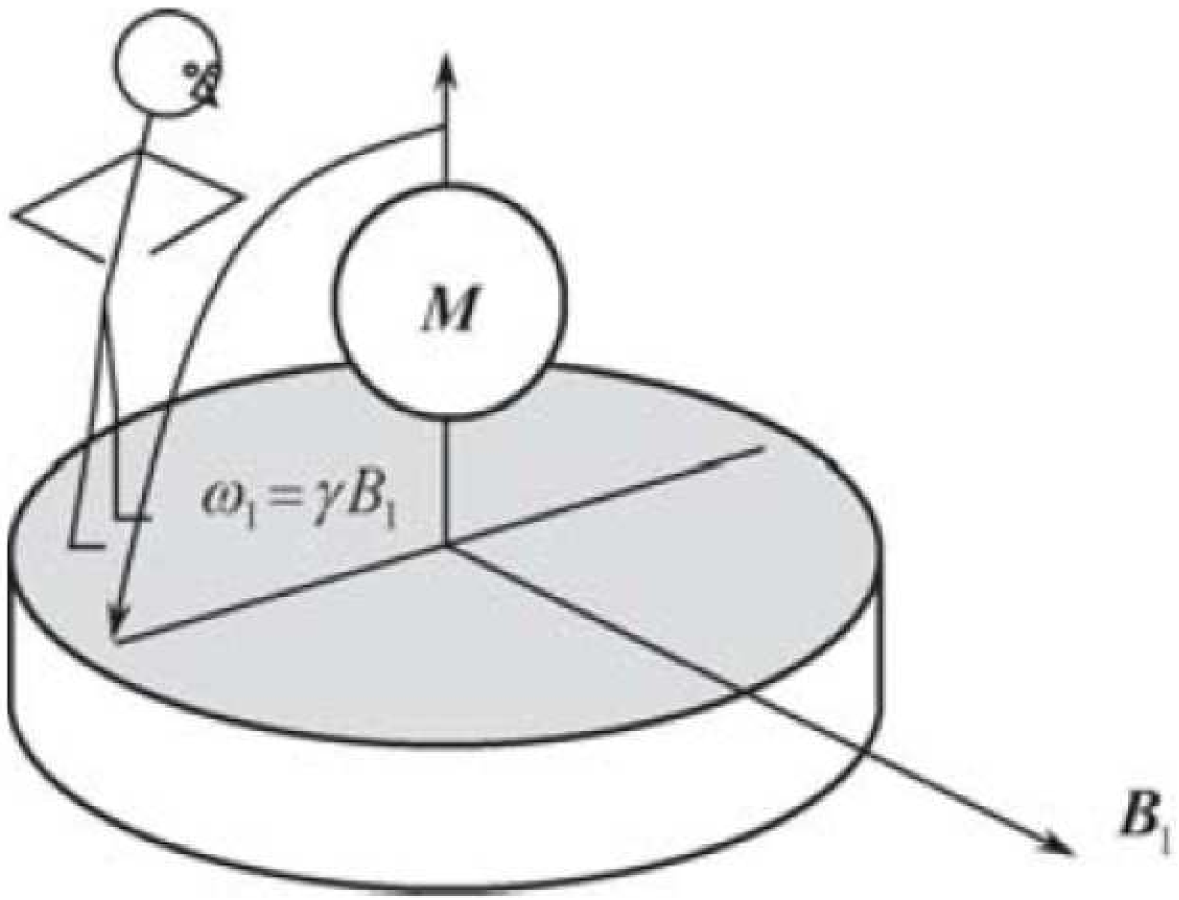

Figure 9: Frame of reference aligned with the magnetic moment $\boldsymbol{M}$ (Zeng, 2009)

Magnetic Resonance Imaging: Principle

- The constant magnetic field in the virtual rotating coordinate system is generated by a varying the field in the constant coordinate system.
- The varying field corresponds to a radio frequency pulse at the Larmor frequency.
- This “knock-off” pulse is also called a 90° pulse.
- During the return to the equilibrium state, a resonance pulse at the Larmor frequency can be measured.

$\rightarrow$ For imaging the hydrogen atoms are knocked off balance and the resonance signal is measured.

Problem: We have not yet discussed localization.
Learn more about that in the next unit.

Topics

Magnetic Resonance Imaging

Summary

Take Home Messages

Further Readings

Take Home Messages

- We learned about the general working mechanism of MRI.
- Excitation of atom nuclei in a magnetic field causes them to emit a resonance signal which can be measured.

Further Readings

Two reads for more insight into modalities:

Avinash C. Kak and Malcolm Slaney. *Principles of Computerized Tomographic Imaging*. Classics in Applied Mathematics. Accessed: 21. November 2016. Society of Industrial and Applied Mathematics, 2001. DOI: 10.1137/1.9780898719277. URL: http://www.slaney.org/pct/

Gengsheng Lawrence Zeng. *Medical Image Reconstruction – A Conceptual Tutorial*. Springer-Verlag Berlin Heidelberg, 2010. DOI: 10.1007/978-3-642-05368-9

Medical Image Processing for Diagnostic Applications

Modalities – Magnetic Resonance Imaging - Part 2

Online Course – Unit 54

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Topics

Magnetic Resonance Imaging

Summary

Take Home Messages

Further Readings

Magnetic Resonance Imaging: Gradient Coils

With the theory of the last unit, we can only measure a combined signal of the complete object.

$\rightarrow$ A method is required to encode different locations differently.
$\rightarrow$ This is achieved by so-called **gradient coils**.

Magnetic Resonance Imaging: Gradient Coils

- In z-direction two coils are used with currents running in opposite direction.
- This creates a gradient within the magnetic field.

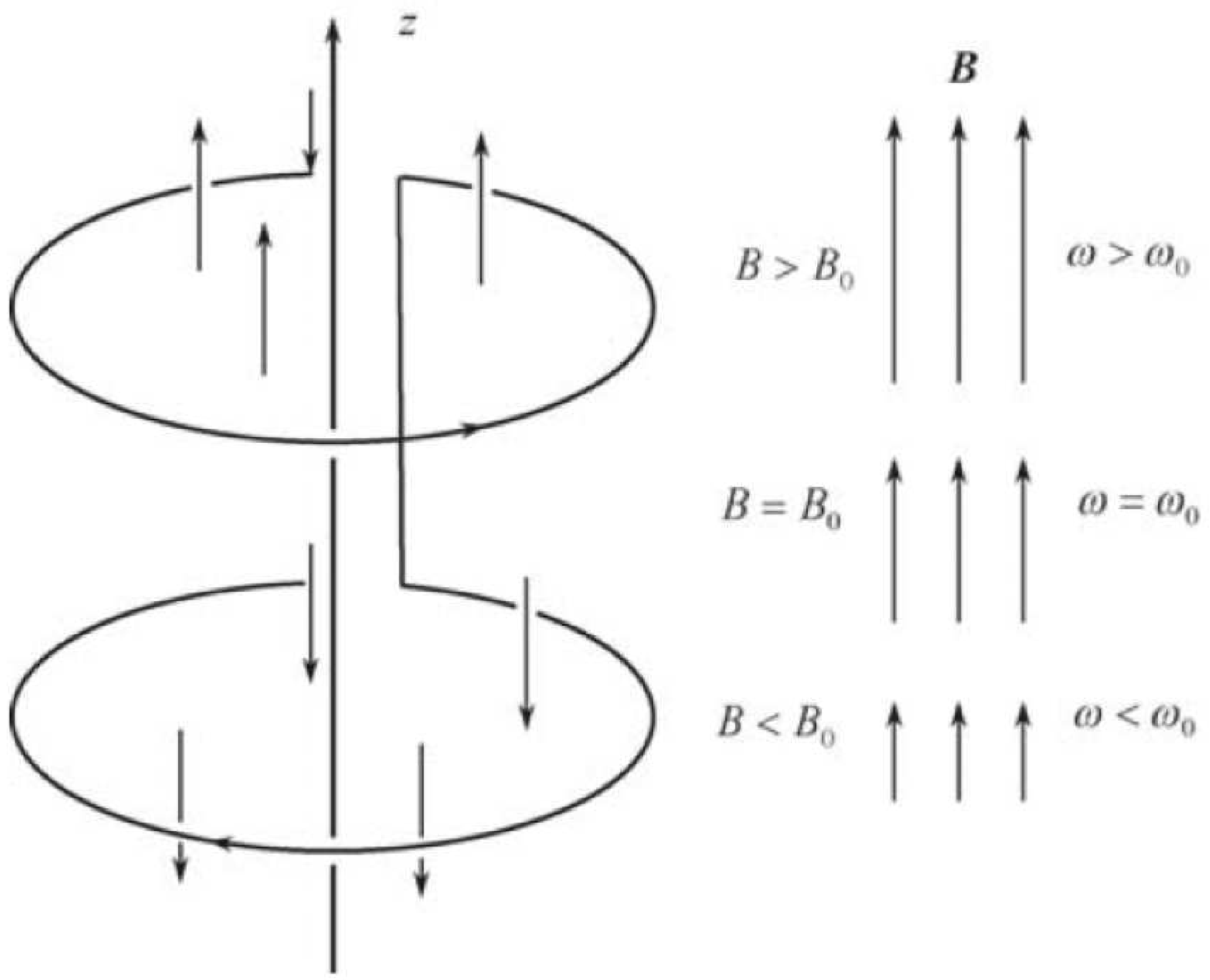


Figure 1: Scheme of two coils in z-direction (Zeng, 2009)

Magnetic Resonance Imaging: RF Pulse

If we use an RF pulse at only one frequency, we can excite only one layer of the object:

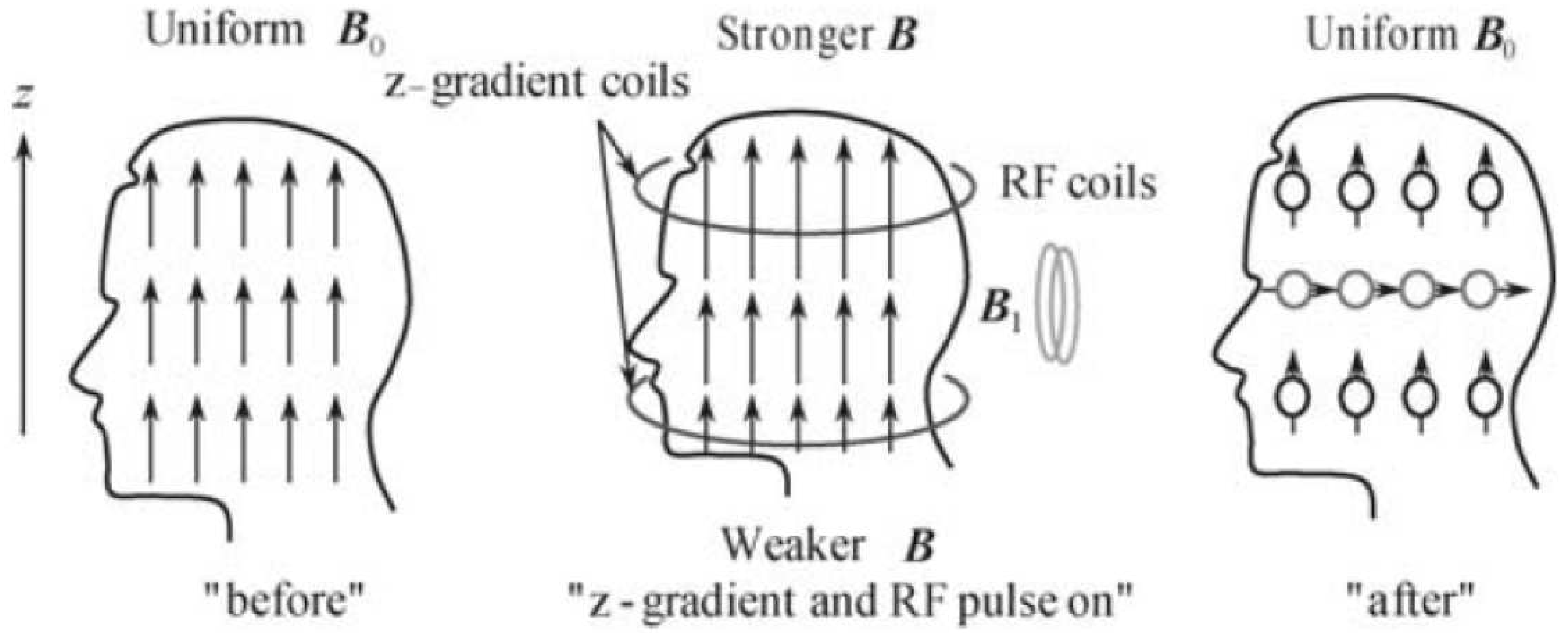


Figure 2: Illustration of single layer excitation (Zeng, 2009)

Magnetic Resonance Imaging: Encoding in y-Direction

- Encoding in y-direction is performed by varying the phase of the spins.
- This is achieved by turning on a gradient in y-direction for a short time.

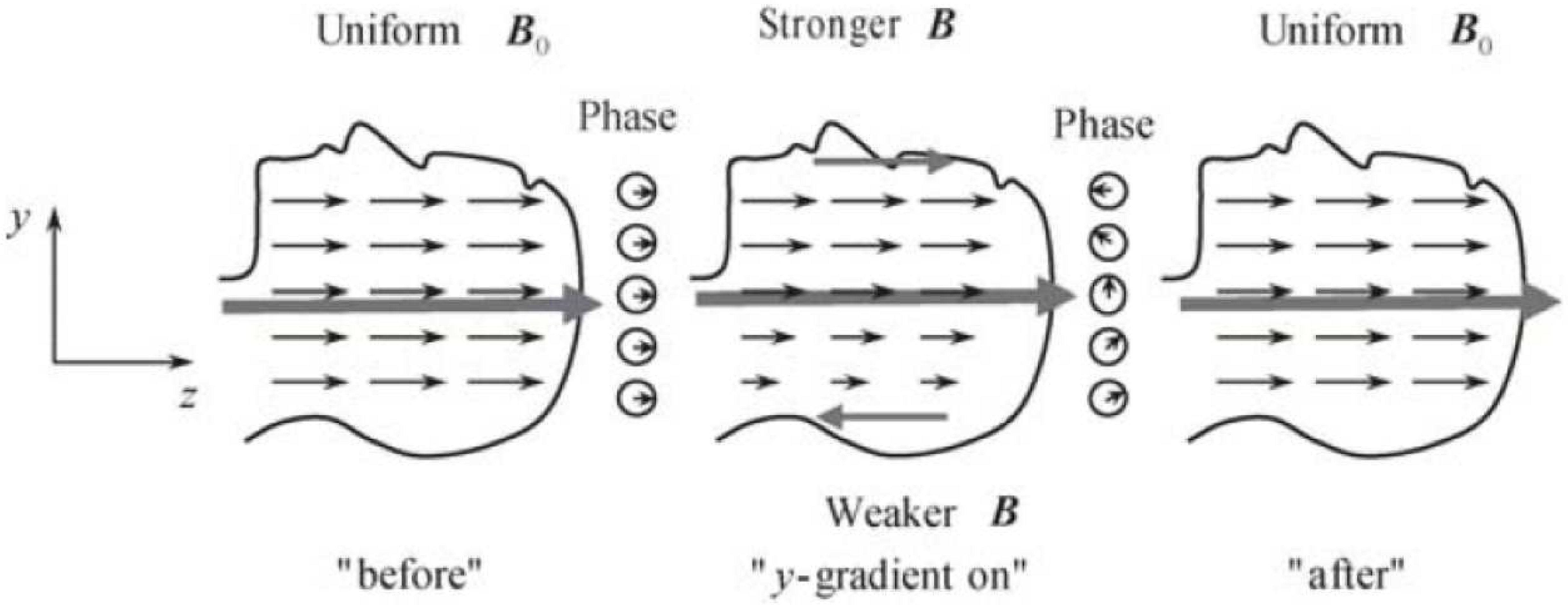


Figure 3: Modulating the spin phase (Zeng, 2009)

Magnetic Resonance Imaging: Encoding in x-Direction

Encoding in *x*-direction is performed by varying the magnetic field during the read-out of the RF pulse:

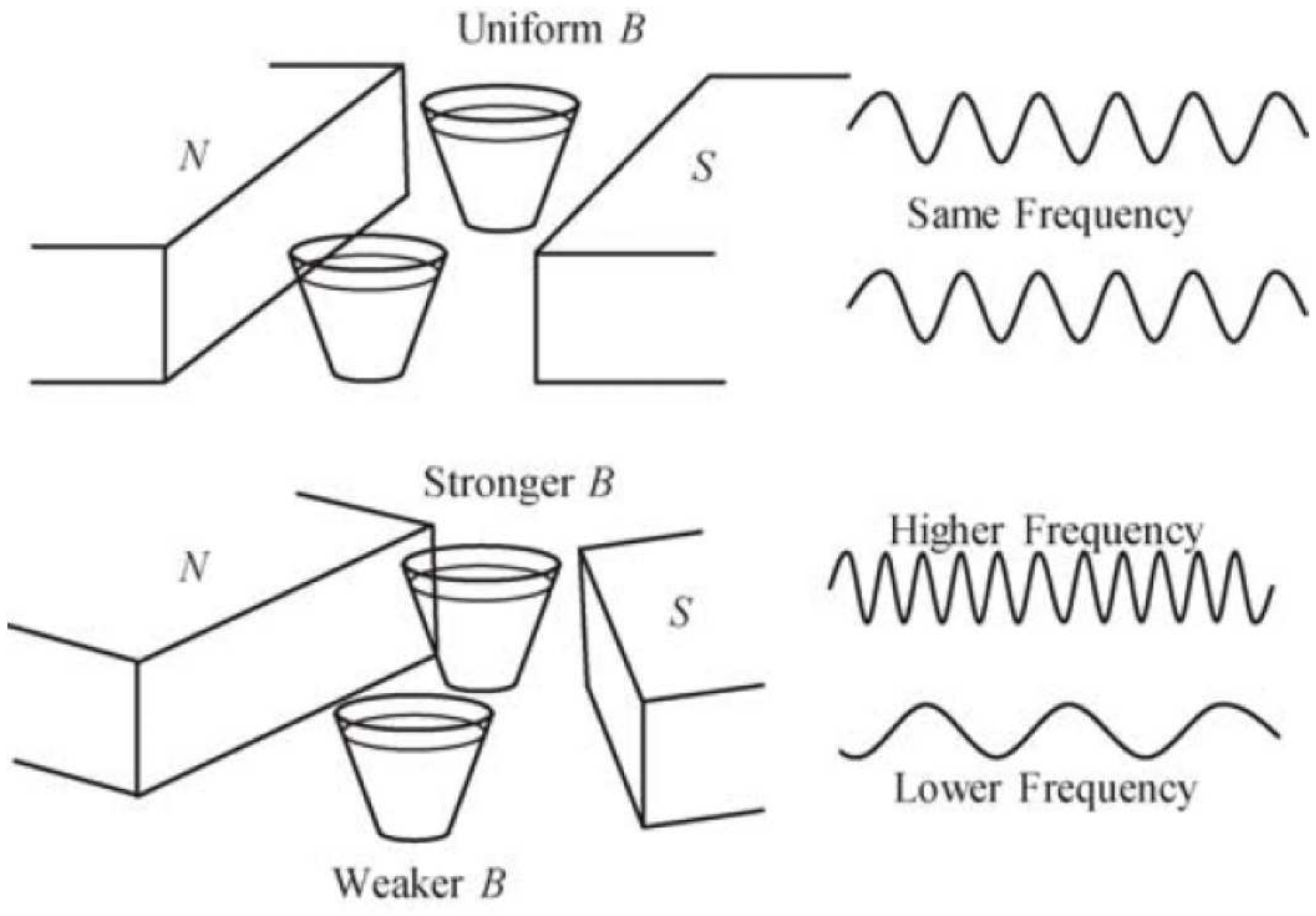
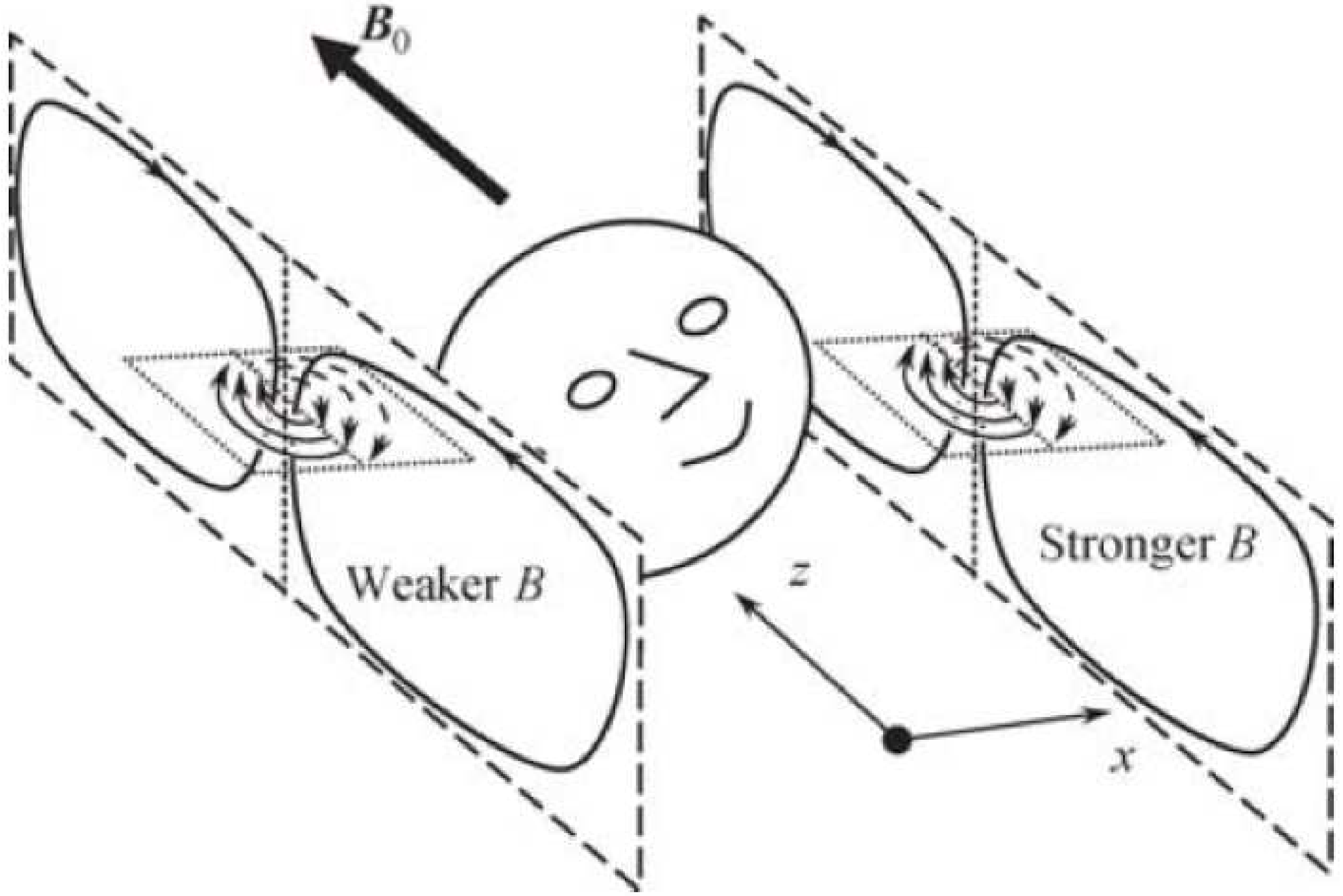


Figure 4: Scheme of magnetic field variation (Zeng, 2009)

Magnetic Resonance Imaging: Encoding in x-Direction

Encoding in *x*-direction is performed by varying the magnetic field during the read-out of the RF pulse:



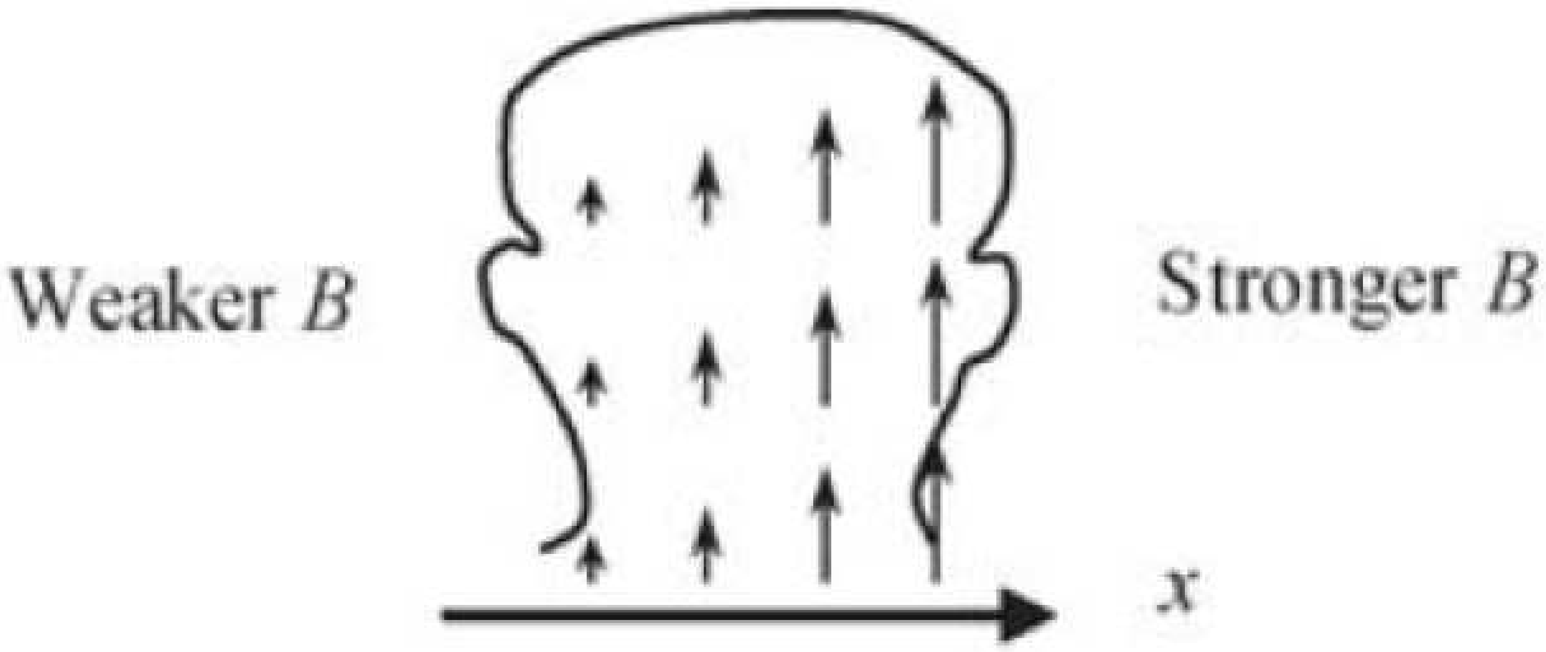


Figure 5: Illustration of the field variation during read-out (Zeng, 2009)

Magnetic Resonance Imaging: Sequence

Each step has to be performed in the right sequence:

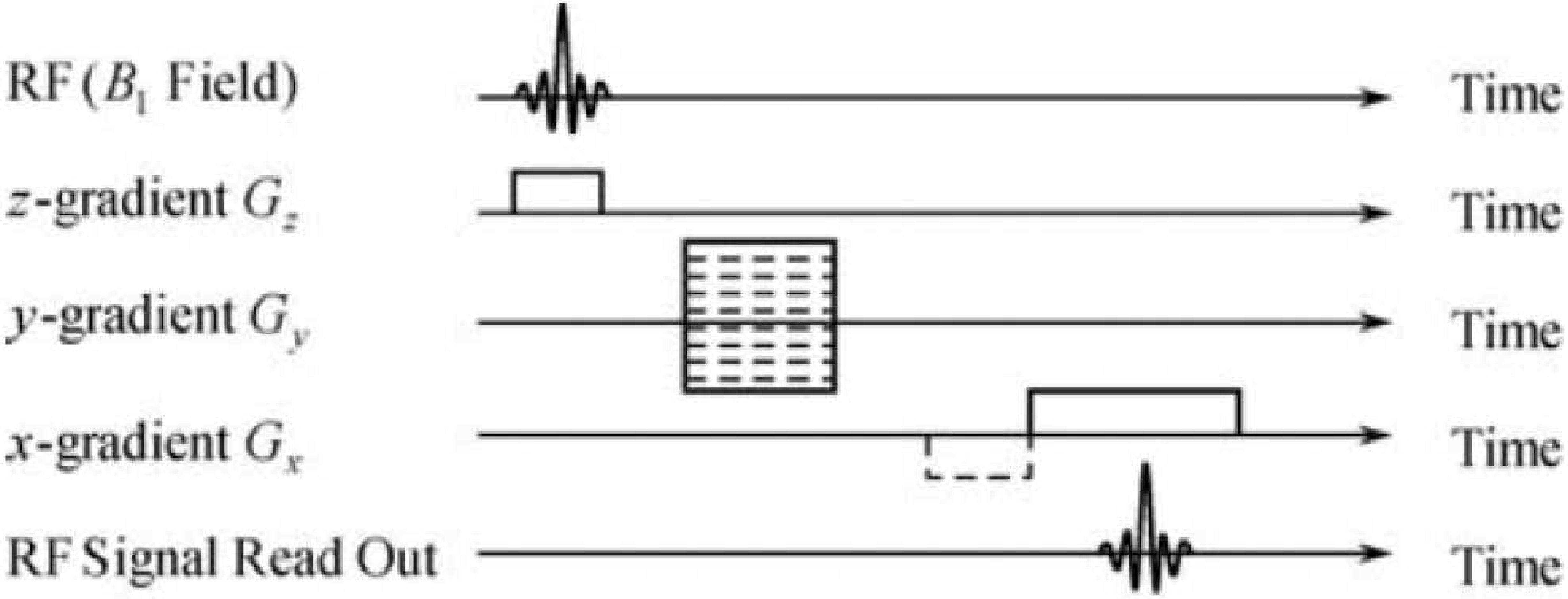


Figure 6: Timing diagram (Zeng, 2009)

Magnetic Resonance Imaging: Read-out

- Read-out data contains the sum over all locations for each frequency.
- Reconstruction is performed by an inverse Fourier transform.
- The read-out space is referred to as ***k-space***.
- *k*-space can be read out arbitrarily with different timing of pulses and gradients.

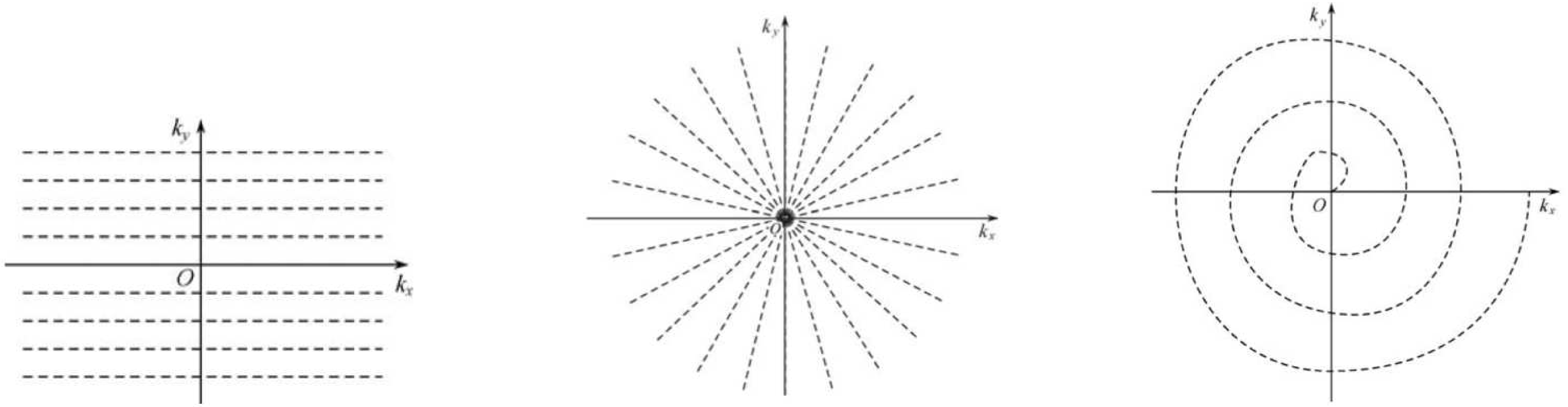


Figure 7: Examples for *k*-space sampling (Zeng, 2009)

Magnetic Resonance Imaging

- MRI enables high contrast imaging of soft tissue $\rightarrow$ excellent for diagnostic purposes.
- Magnetic labeling enables the marking of certain protons $\rightarrow$ blood flow can be visualized.
- Magnetic resonance is dependent on the amount of oxygen in the blood $\rightarrow$ oxygen consumption can be visualized.
- Many more possibilities ...

Topics

Magnetic Resonance Imaging

Summary

- Take Home Messages
- Further Readings

Take Home Messages

- Tissue localization is enabled by using gradient coils and a specific read-out sequence.
- The read-out space for MRI is called *k*-space, and reconstruction is done from Fourier space (in contrast to CT where we start in the spatial domain).
- Every modality has its strengths and its weaknesses $\rightarrow$ MRI supports many acquisition modes.
- Combination of modalities helps to alleviate particular problems $\rightarrow$ hybrid systems, e. g., SPECT/CT and PET/MR, are emerging technologies.

Further Readings

Two reads for more insight into modalities:

Avinash C. Kak and Malcolm Slaney. *Principles of Computerized Tomographic Imaging*. Classics in Applied Mathematics. Accessed: 21. November 2016. Society of Industrial and Applied Mathematics, 2001. DOI: 10.1137/1.9780898719277. URL: http://www.slaney.org/pct/

Gengsheng Lawrence Zeng. *Medical Image Reconstruction – A Conceptual Tutorial*. Springer-Verlag Berlin Heidelberg, 2010. DOI: 10.1007/978-3-642-05368-9