

# Princípios de Tomografia por Coerência Óptica (OCT)

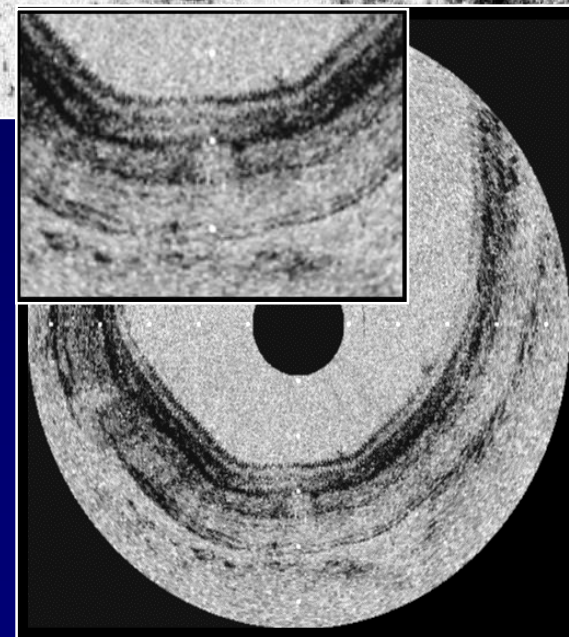
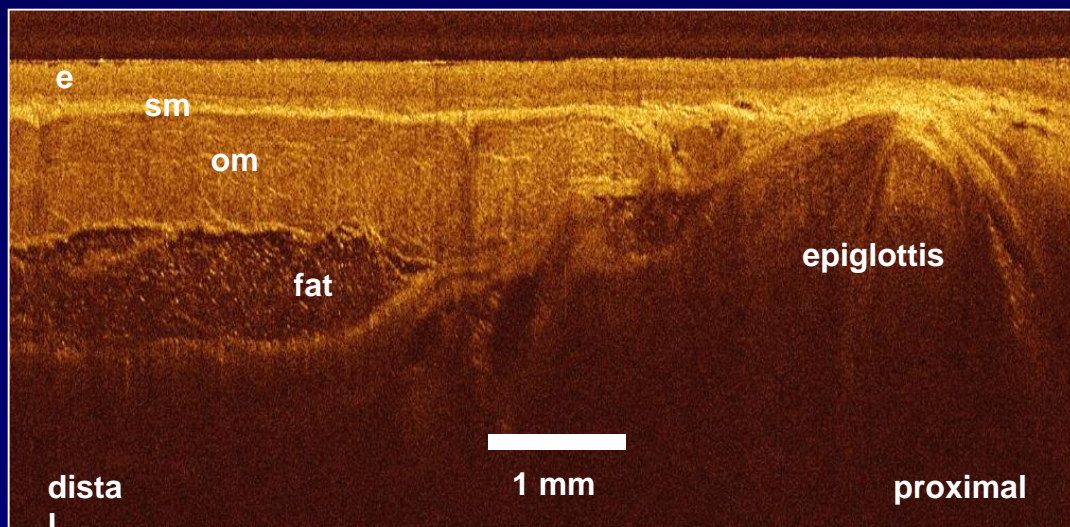
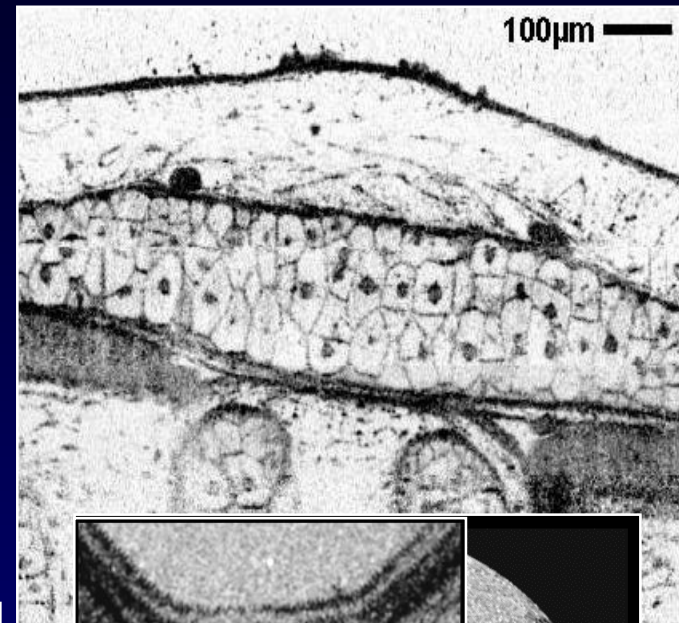
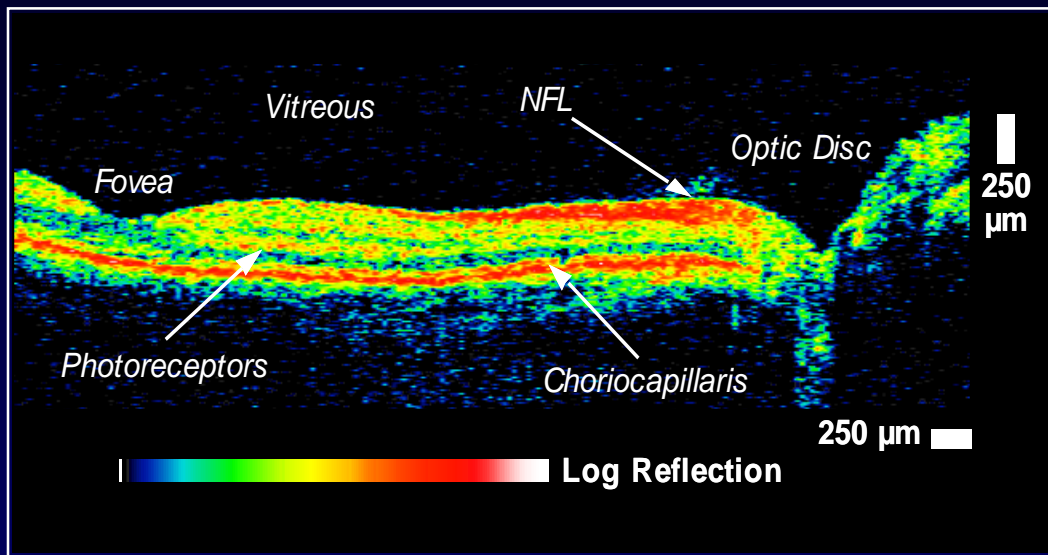
# OCT no diagnóstico não invasivo

- Oftalmologia
  - Diagnóstico de doenças da retina.
- Dermatologia
  - Doenças da pele,
  - Estágios iniciais de câncer de pele.
- Doenças Cardiovasculares
  - Detecção de placas vulneráveis.
- Endoscopia (fiber-optic devices)
  - gastroenterologia
  - ginecologia
- Embriologia

- Imagens funcionais
  - Doppler OCT (blood flow)
  - Espectroscopia OCT (absorption, high speed)
  - Propriedades ópticas

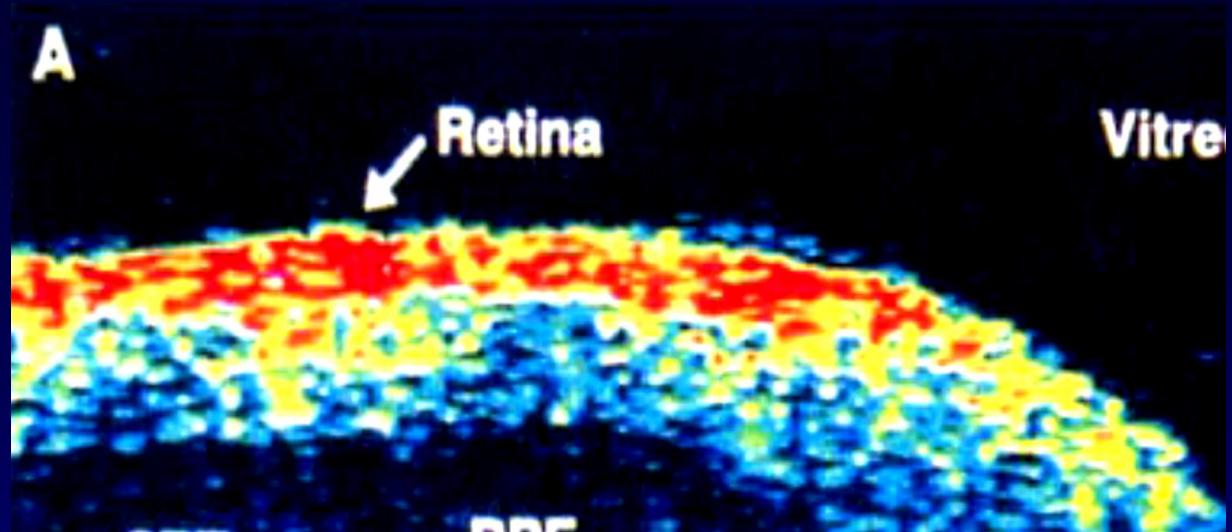
- Cirurgia guiada
  - Procedimentos delicados
    - Cirurgia do cérebro,
    - Cirurgia de articulações

# Imagem em OCT



# Primeira demonstração de OCT (1991)

Retina humana  
*ex vivo* e histologia  
correspondente



David Huang, et al,  
*Science* 254, 1178  
(1991)

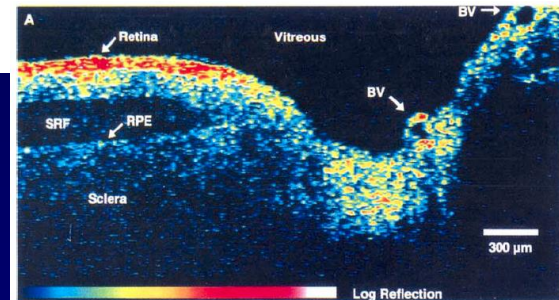
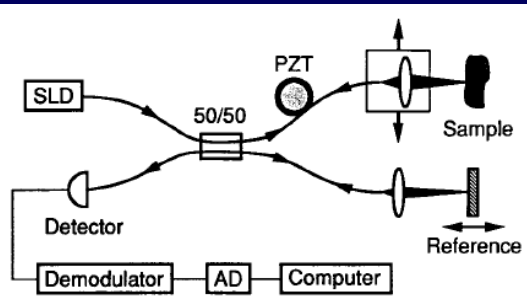


# Optical Coherence Tomography

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 MICHAEL R. HEE, THOMAS FLOTTE, KENTON GREGORY,  
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A technique called optical coherence tomography (OCT) has been developed for noninvasive cross-sectional imaging in biological systems. OCT uses low-coherence interferometry to produce a two-dimensional image of optical scattering from internal tissue microstructures in a way that is analogous to ultrasonic pulse-echo imaging. OCT has longitudinal and lateral spatial resolutions of a few micrometers and can detect reflected signals as small as  $\sim 10^{-10}$  of the incident optical power. Tomographic imaging is demonstrated in vitro in the peripapillary area of the retina and in the coronary artery, two clinically relevant examples that are representative of transparent and turbid media, respectively.

**Fig. 1.** Schematic of the OCT scanner. The SLD output is coupled into a single mode fiber and split at the 50/50 coupler into sample and reference arms. Reflections from the two arms are combined at the coupler and detected by the photodiode. Longitudinal scanning is performed by translating the reference mirror with a stepper motor stage at  $1.6 \text{ mm s}^{-1}$ , generating a 3.8-kHz Doppler shift. The piezoelectric transducer (PZT) in the sample arm further provides 21.2-kHz phase modulation to the interferometric signal. Interferometric modulation of the output intensity is detected by the photodetector when the reference and sample arm delays are nearly matched. The detector output is demodulated at the sum modulation frequency of 25 kHz to produce the envelope of the interferometric signal, which is then digitized (AD) and stored on computer. A series of longitudinal scans are performed. The lateral beam position is translated after each longitudinal scan.



**Fig. 2.** Optical coherence tomograph of human retina and optic disk in vitro (A) and histologic section of the same specimen (B). Eye bank specimens were kept at  $4^{\circ}\text{C}$  and measured within 24 hours after death. (A) Cornea and lens were removed before OCT scanning and the OCT beam was delivered through the vitreous medium and focused on the retina. The tomographic image corresponds to a section of the retina and optic disk along the papillomacular axis. The retina temporal to the disk is on the left. Identifiable structures are, from top to bottom, vitreous, retina (RNFL, red; subapical retina, yellow to light blue), subretinal fluid (SRF), retinal pigment epithelium (RPE), and choroid and sclera. The RNFL thickness varies between 70 and 90  $\mu\text{m}$ , increasing toward the optic disk. The overall retinal thickness is 220  $\mu\text{m}$ . Blood vessels (BV) in the optic disk appear as characteristic dark spots. The nasal retina appears on the far right. The sampled pixel size is 3.8 (vertical) by 20 (horizontal)  $\mu\text{m}$ . Interpolation between pixels was performed to improve image readability. The color scale spans  $4 \times 10^{-10}$  (black) to  $10^{-6}$  (white) of the incident power. (B) Stevenol's blue-stained plastic section. The RNFL and overall retinal thickness closely match those of the tomograph; the SRF is much smaller than in the tomograph because of dehydration during histologic processing. Vitreous (V), retina (R), sclera (S), blood vessel (B), SRF (F). Bar = 300  $\mu\text{m}$ .

# História do OCT

## *In vivo* retinal imaging by optical coherence tomography

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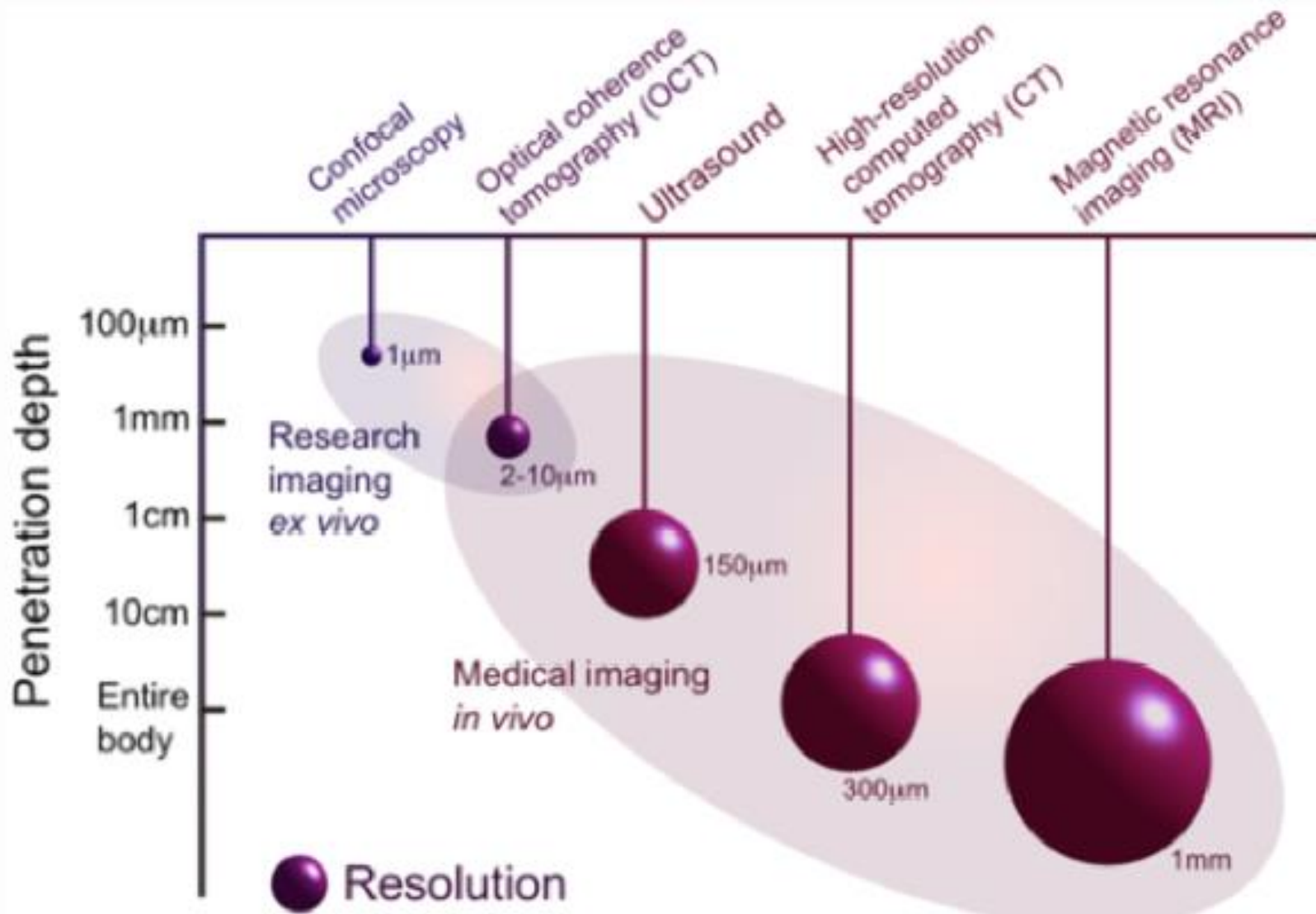
**J. G. Fujimoto**

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Received May 27, 1993

We describe what are to our knowledge the first *in vivo* measurements of human retinal structure with optical coherence tomography. These images represent the highest depth resolution *in vivo* retinal images to date. The tomographic system, image-processing techniques, and examples of high-resolution tomographs and their clinical relevance are discussed.

**November 1, 1993 / Vol. 18, No. 21 / OPTICS LETTERS 1864**



**Figure 3.** Comparison of OCT resolution and imaging depths to those of alternative techniques; the "pendulum" length represents imaging depth, and the "sphere" size represents resolution.

# Optical Coherence Tomography (OCT)

## Imagem usando “ecos” de luz

Método de diagnóstico por imagem, capaz de observar a microestrutura interna dos tecidos biológicos.

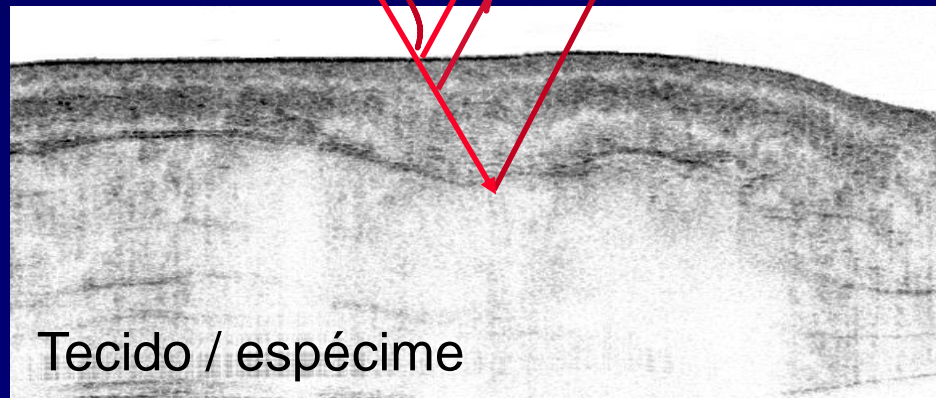
Baseado na interferometria de baixa coerência para medir o atraso entre os “ecos” (pulsos) de luz.

A capacidade da OCT de gerar imagem de tecidos moles e duros sem haver dano ao paciente, a torna de grande interesse para essa área.

Luz incidente

Intervalo de tempo entre os pulsos

Intervalo de tempo =  
Distância x Velocidade

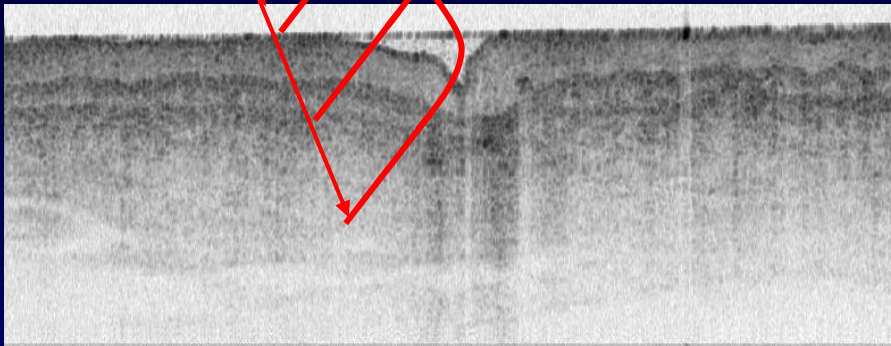


A tomografia óptica é similar ao ultra-som do modo B, utilizando ondas de luz ao invés de ondas sonoras.



# OCT: Princípio de operação

OCT é análoga à imagem em ultrassom  
Utiliza luz infravermelho ao invés de som



Vel. do som  $\sim 1,48 \times 10^3$  m/seg (na água)  
Vel. da luz  $\sim 3 \times 10^8$  m/seg

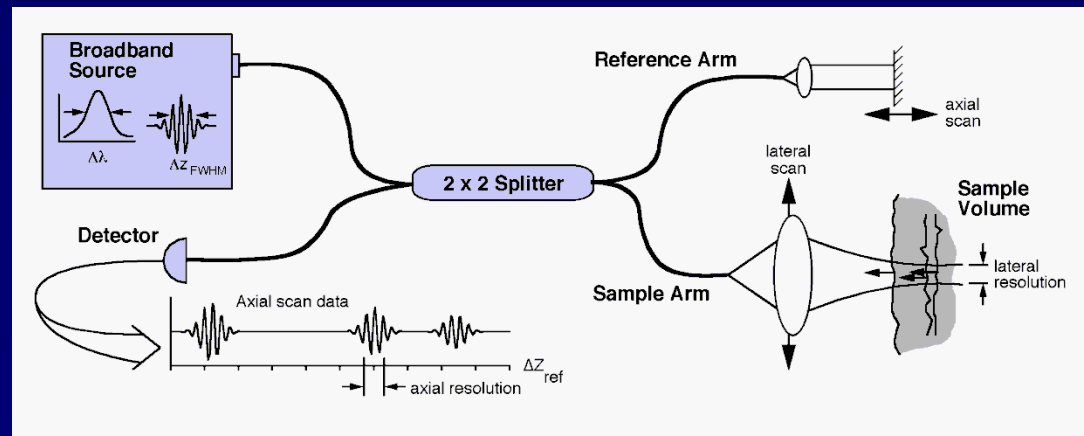
Pele humana

*5 mm wide x 1.6 mm deep*

Resolução espacial: 10-30  $\mu\text{m}$   
( $\sim 100$  pixels/mm)

Resolução temporal: 30fs!!!

Interferometria é utilizada para medir pequenos atrasos devido ao espalhamento de fótons

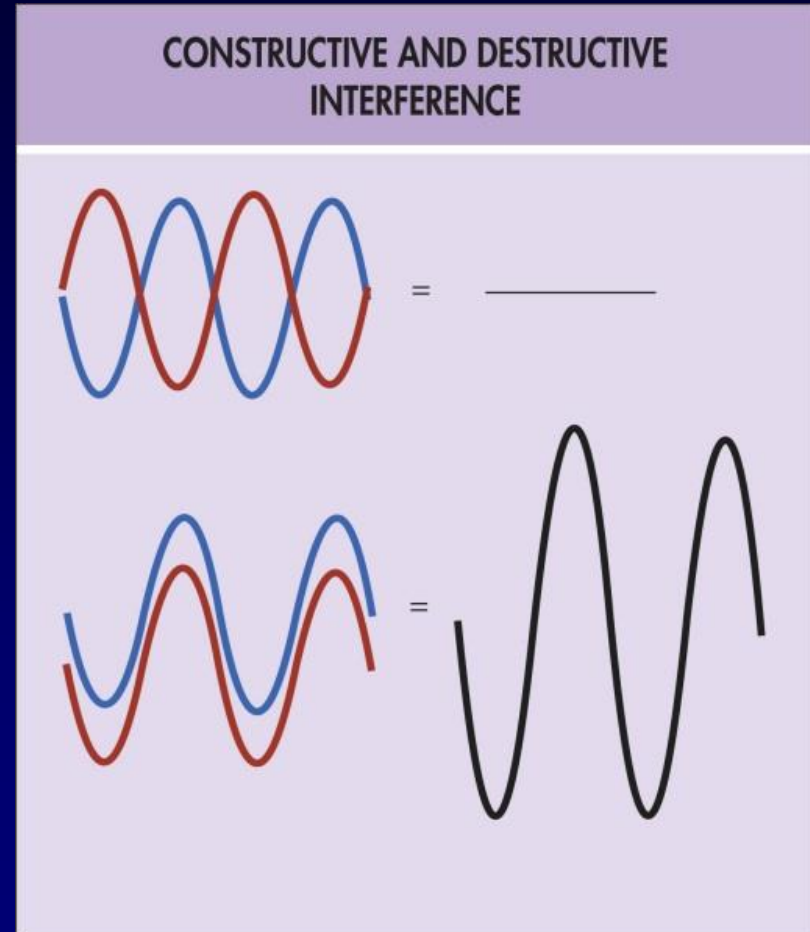


# Interferometria

- Um interferômetro funciona pelo princípio no qual duas ondas que coincidem com a mesma fase irão ser amplificadas e se elas estiverem com fases opostas ( $90^\circ$  de diferença) irão ser canceladas.
- Fontes de luz:
  - Monocromáticas: “único” comprimento de onda.
  - Policromáticas: vários comprimentos de onda (espectro largo ou várias linhas).
  - Luz branca: fonte com todo espectro de luz visível ou combinação de vermelho, verde e azul dando a impressão visual de branco. A luz branca de espectro largo tem comprimento de coerência muito pequeno (alguns micrometros).
  - Coerência: propriedade das ondas que as permite exibir interferência. O grau de coerência mede a qualidade da interferência.
    - Coerência temporal, mede quão bem uma onda pode interferir com ela mesma em tempos diferentes, O comprimento de coerência é definido pela distância que a onda percorre durante o tempo de coerência.
- Alguns tipos de interferômetros: Michelson, Mach-Zehnder, Fabry-Perrót, ...

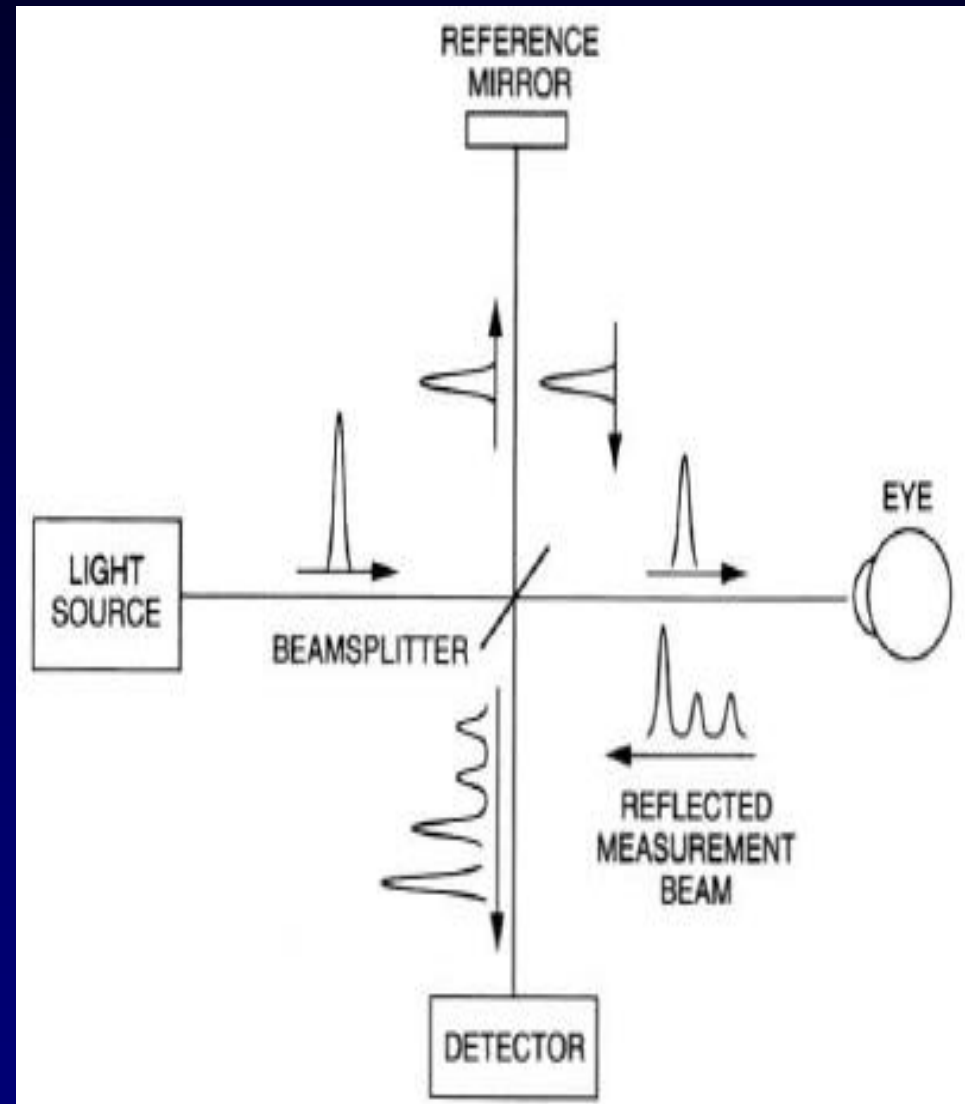
# Princípio da Interferometria

- Interferometria é a técnica de sobrepor 2 ou mais formas de onda para detectar diferenças entre elas.
- Duas ondas com a mesma frequência e mesma fase serão somadas (construtivas), enquanto duas ondas com fases diferentes serão subtraídas (destrutivas).



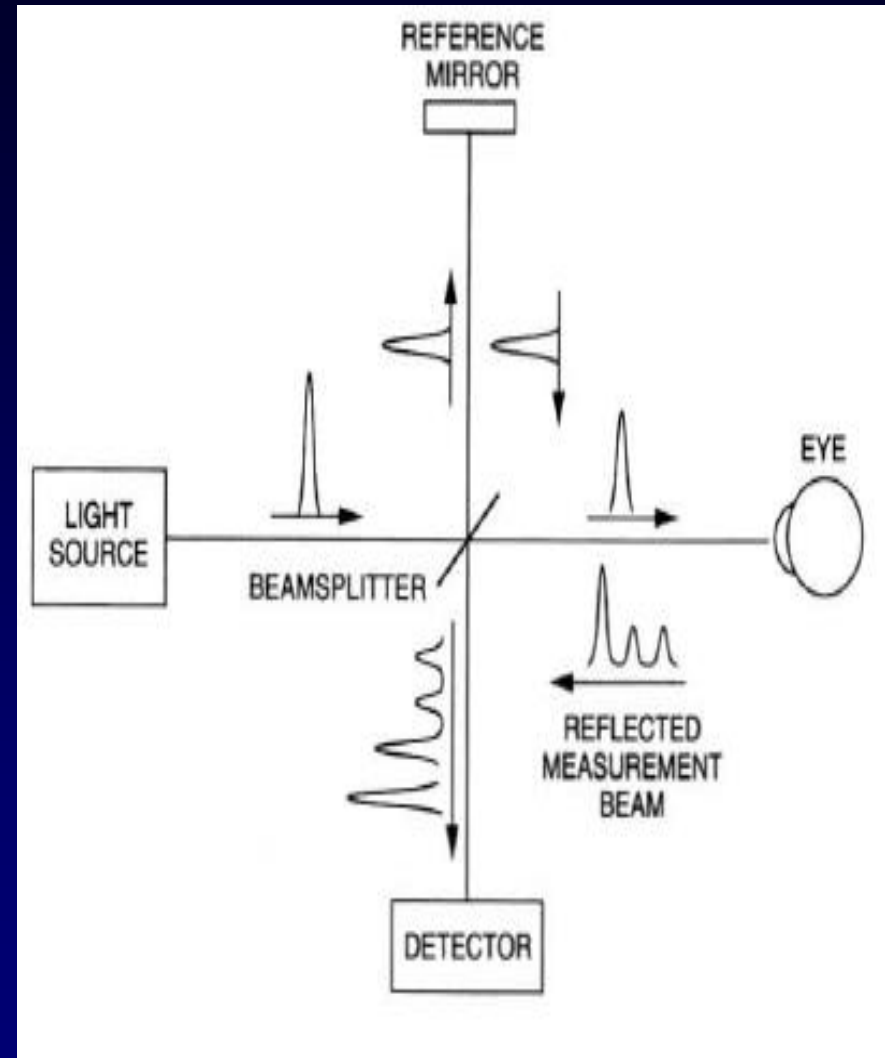
# Princípio da Interferometria

- Luz de uma fonte é direcionada para um espelho parcialmente reflexivo e é dividida em um feixe de referência e um feixe de medida.
- A luz é refletida da amostra com diferentes atrasos devido à microestrutura interna da amostra.

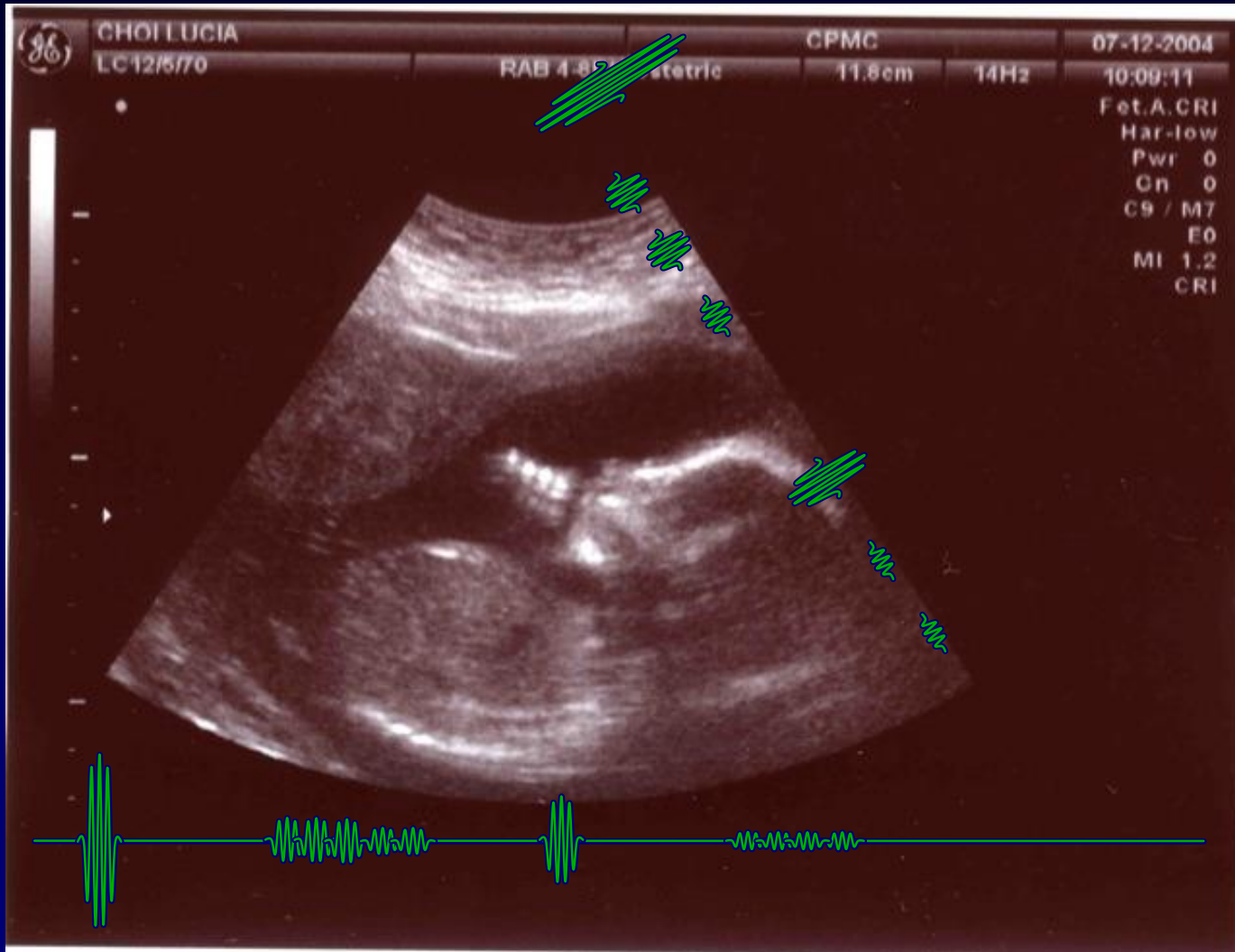


# Princípio da Interferometria

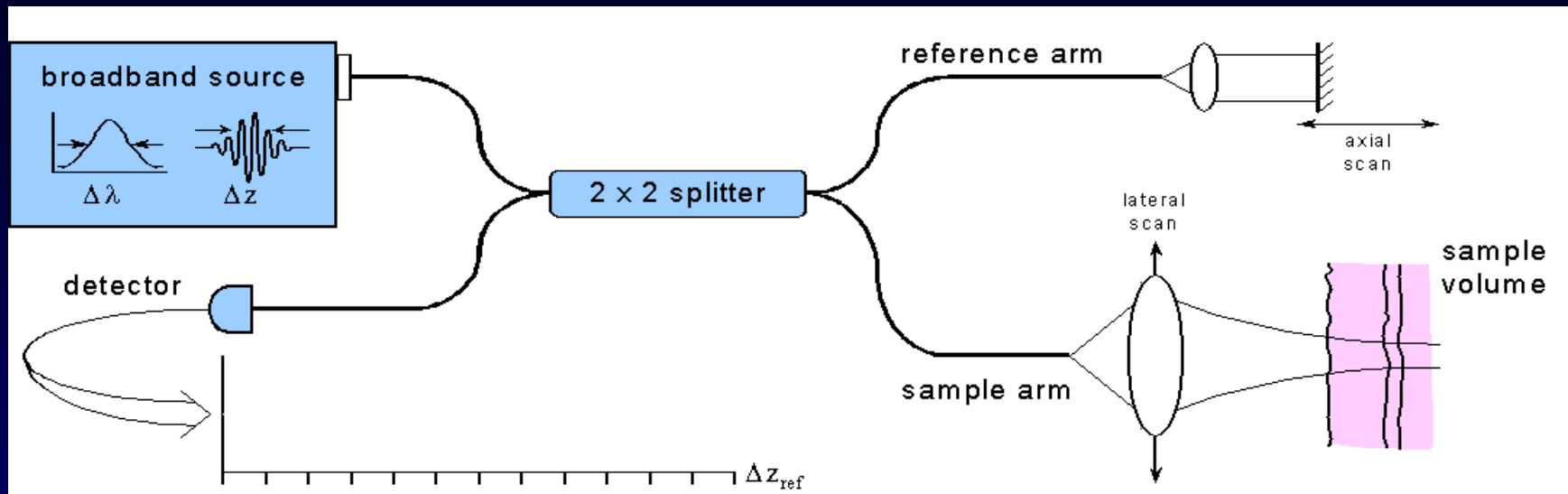
- A luz no feixe de referência é refletida a partir do espelho de referência, que tem a sua posição variável, produzindo atrasos variáveis no tempo.
- A luz refletida da amostra, consistindo de múltiplos “ecos” e a luz do espelho de referência, consistindo de um único “eco” com atraso conhecido são combinadas.



# Ultrasound

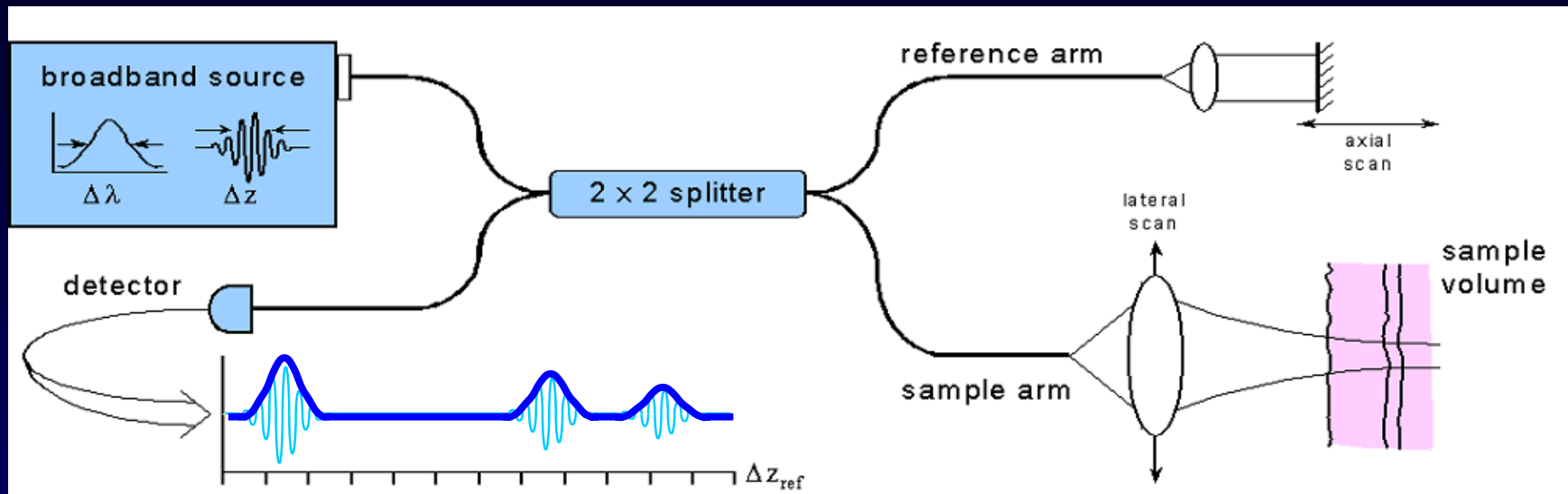


# Interferometria e OCT

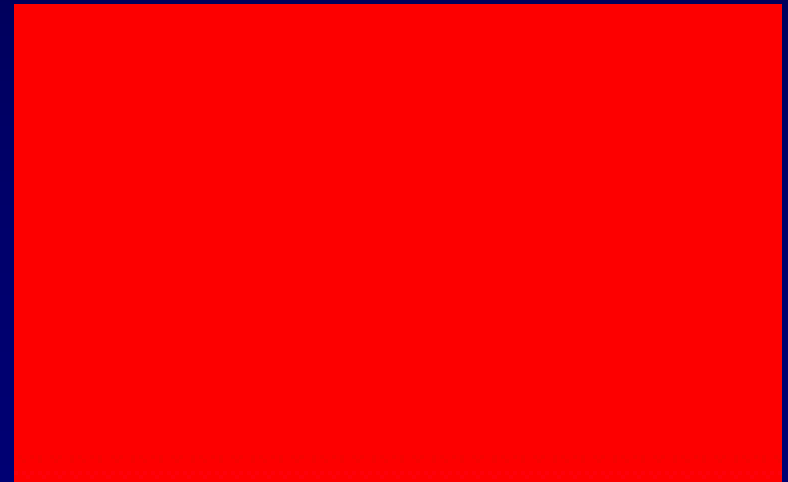


© OCT utiliza um interferômetro para detectar os atrasos entre sinais de luz

# Interferometria e OCT

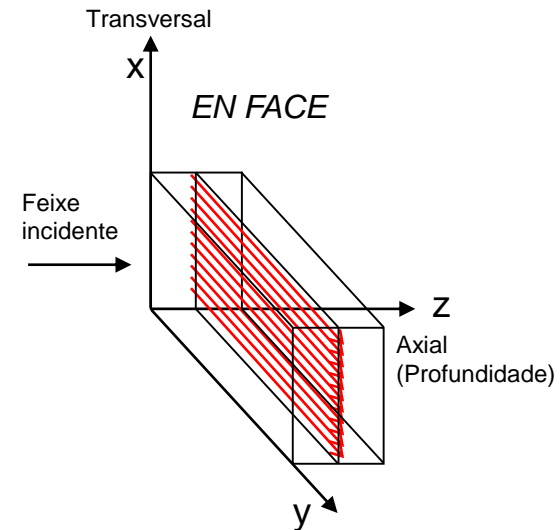
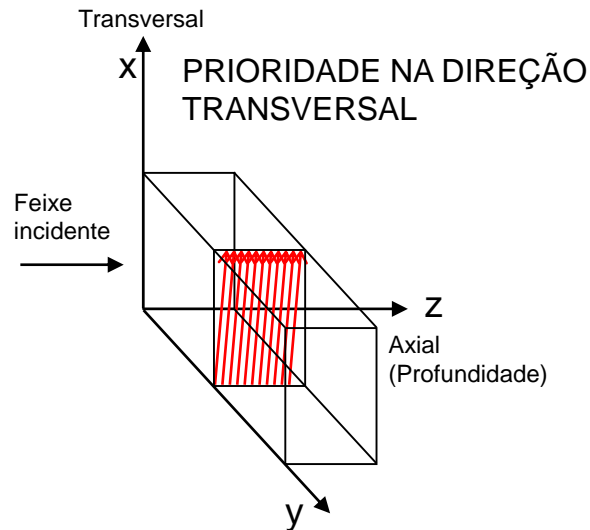
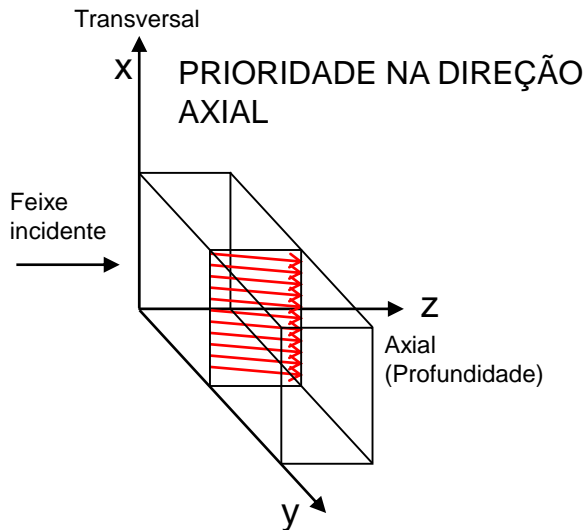
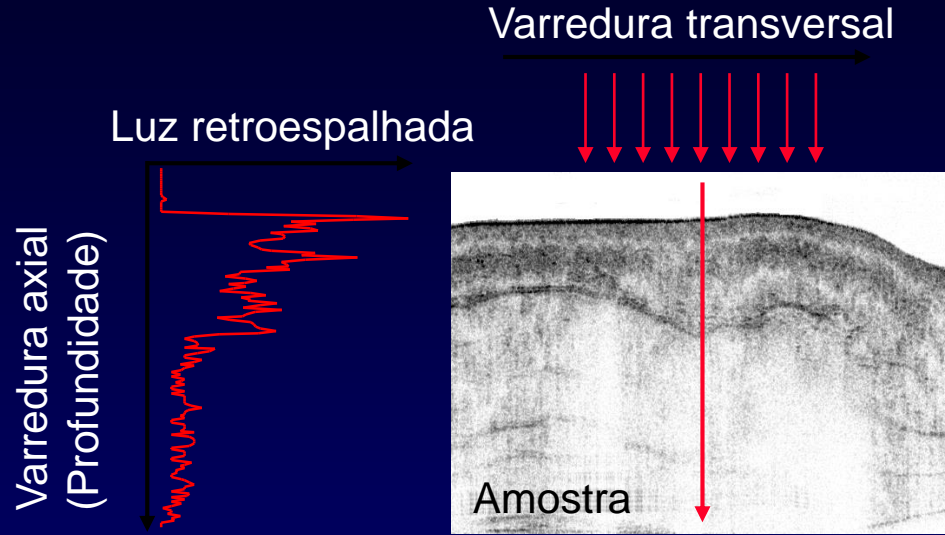


- ◎ A intensidade dos padrões de interferência mede a refletividade através do tecido.

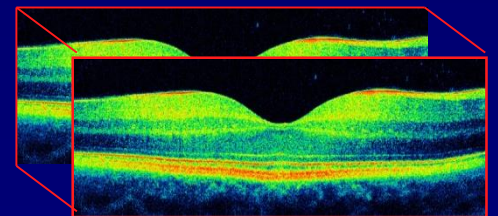
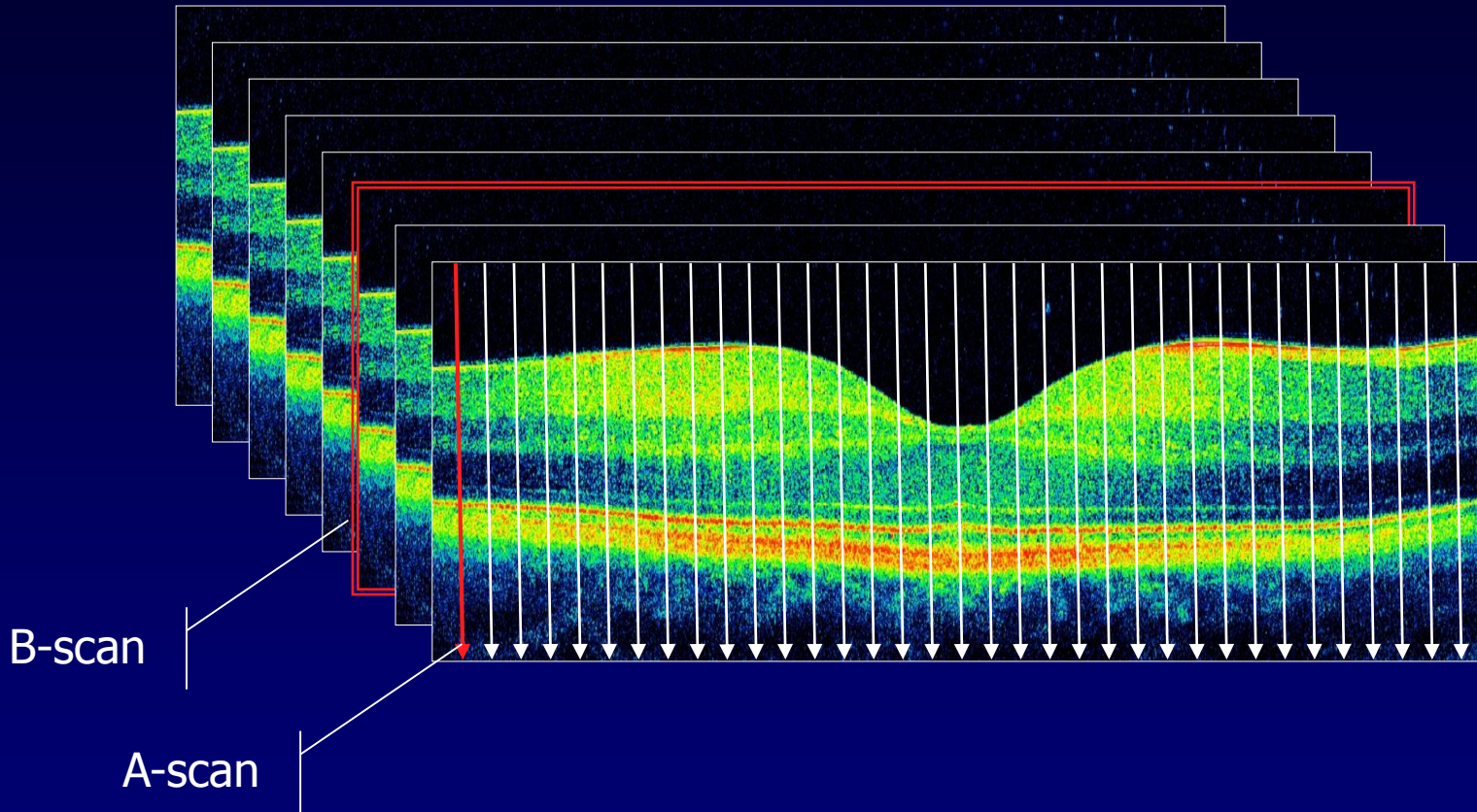




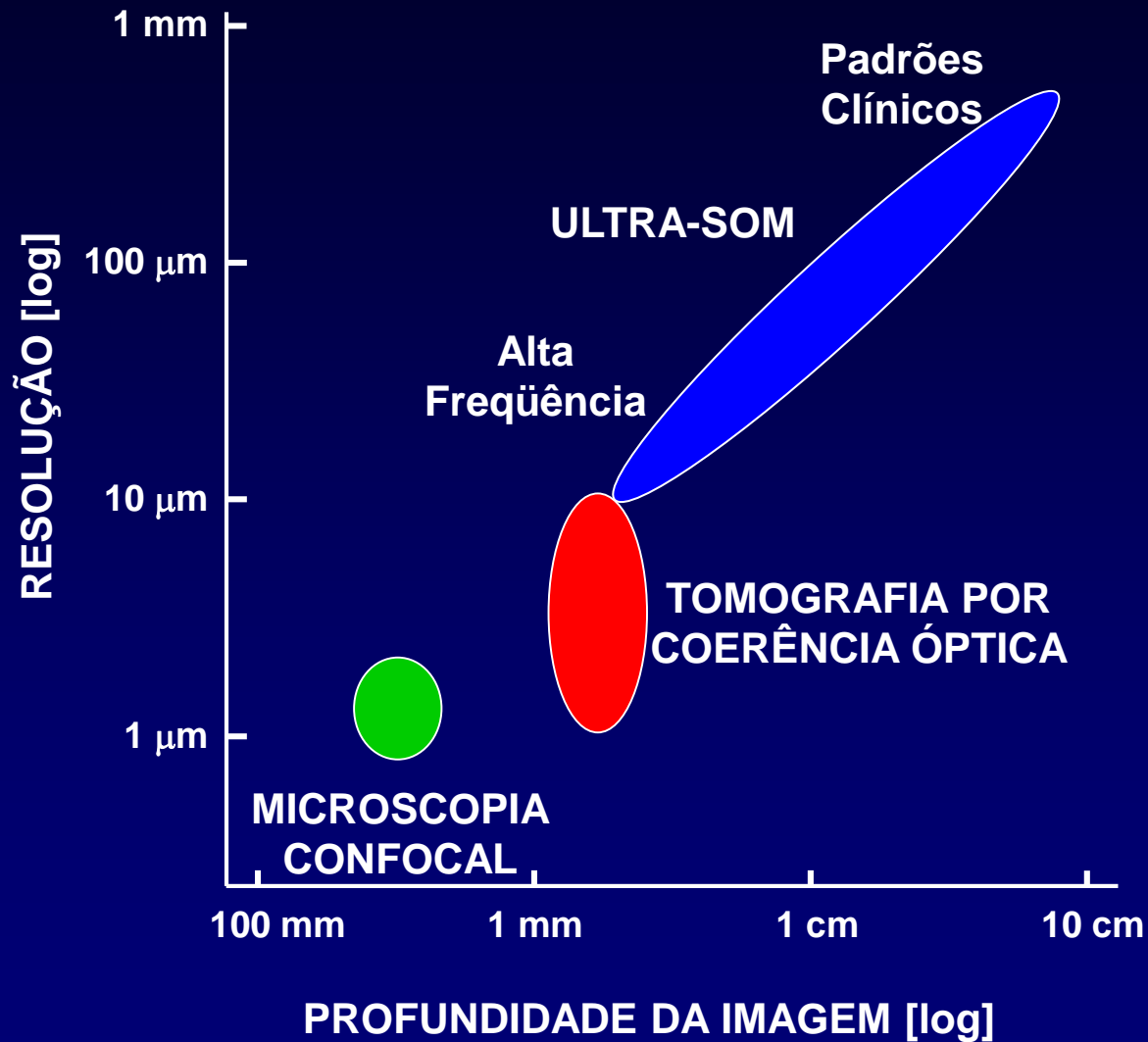
# Geração da imagem



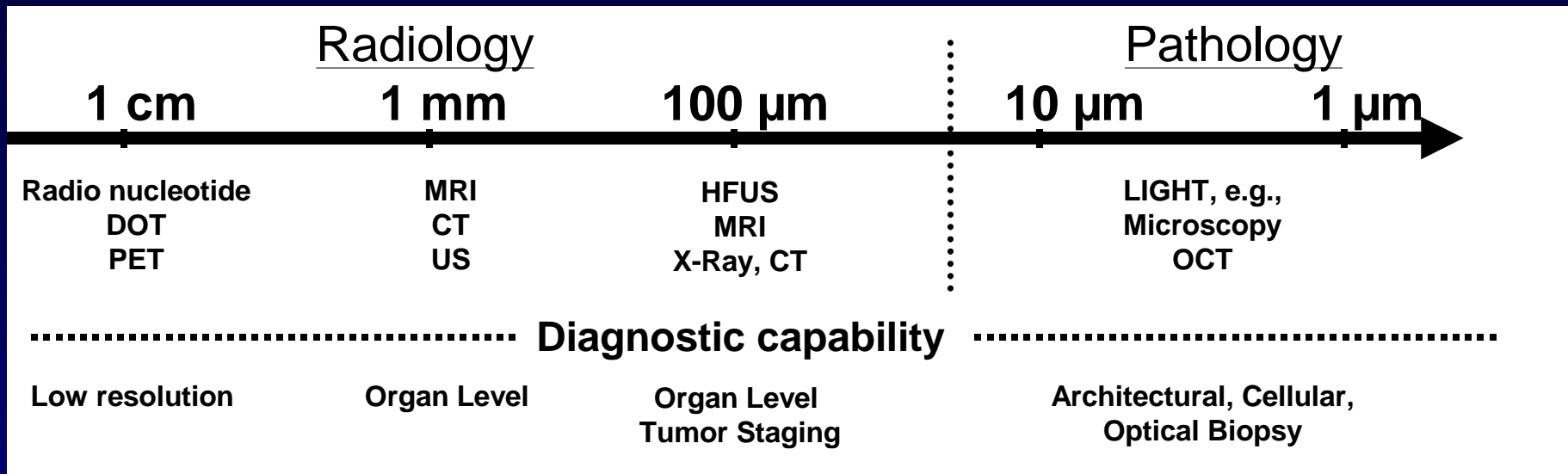
# A-SCAN, B-SCAN, 3D-SCAN



# Comparada a outras técnicas para a geração de imagens na medicina



# Óptica em Medicina



Academia

Start-up

Carl Zeiss

Outlook

1990  
Pre-Basic  
research

1991  
Patent  
application

1995  
Early  
prototype

1996  
OCT1  
(Lab tool)

1997  
OCT1

2000  
OCT2  
(Upgraded)

2002  
Stratus  
OCT

2007  
Cirrus  
HD-OCT

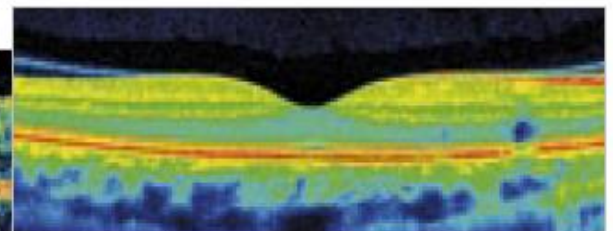
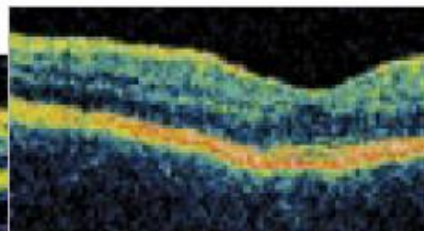
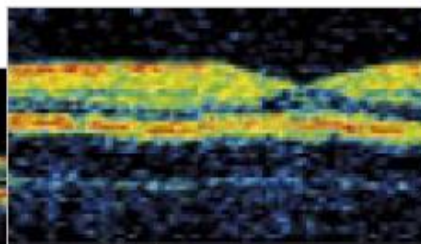
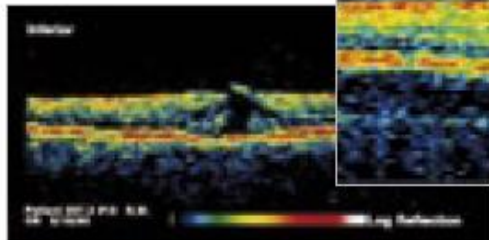
1st generation



2nd generation



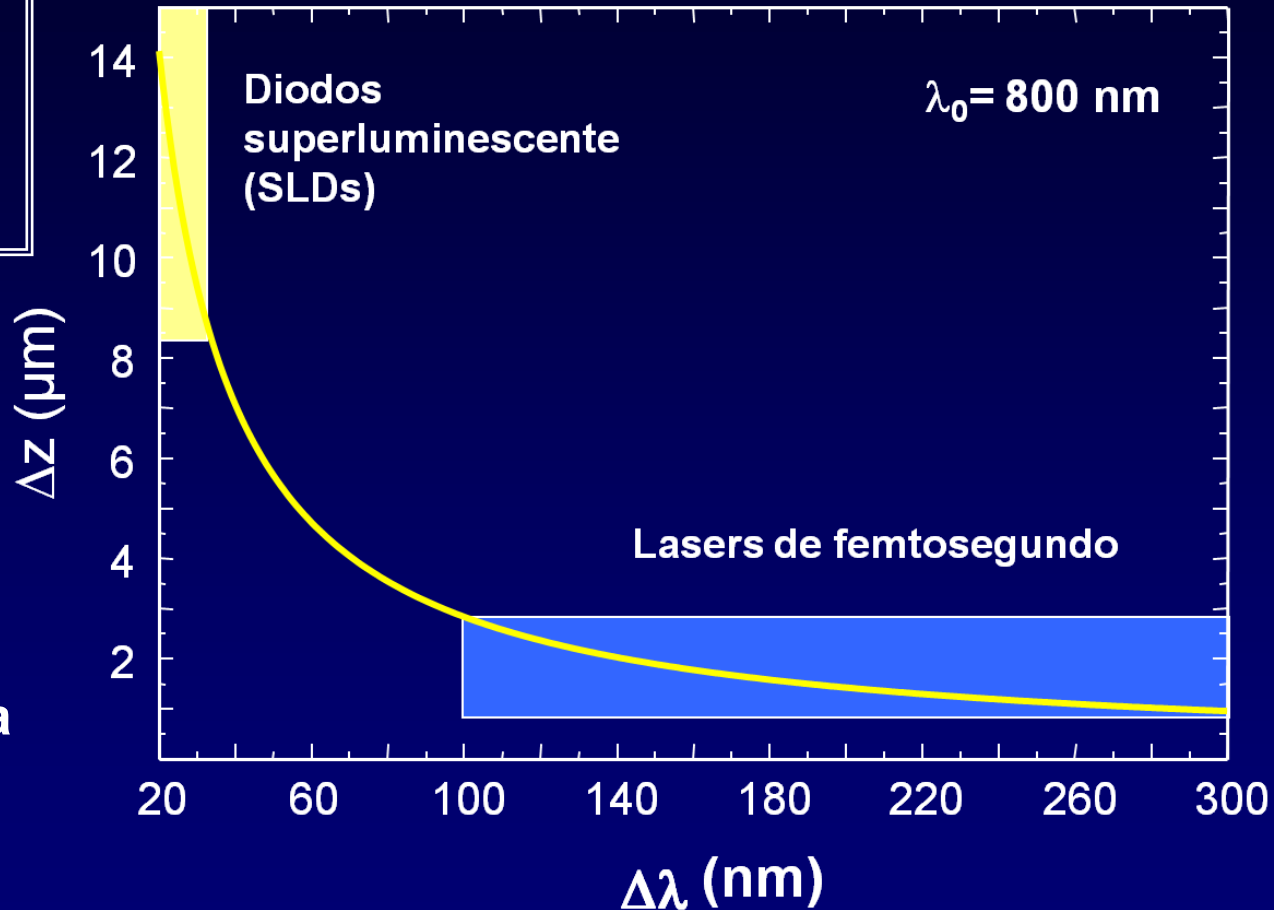
3rd generation



# Largura de Banda – Resolução Axial

$$\Delta z = \frac{2 \ln(2)}{\pi} \frac{\lambda_0^2}{\Delta \lambda}$$

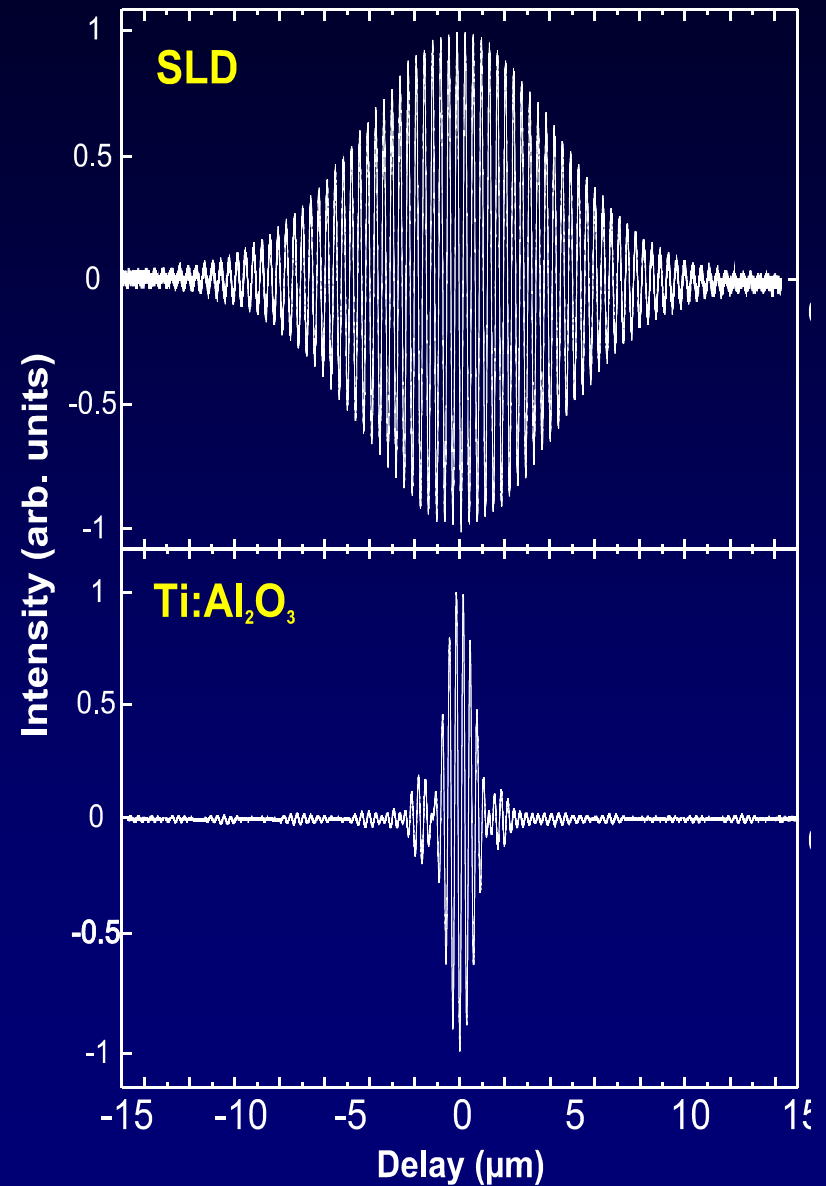
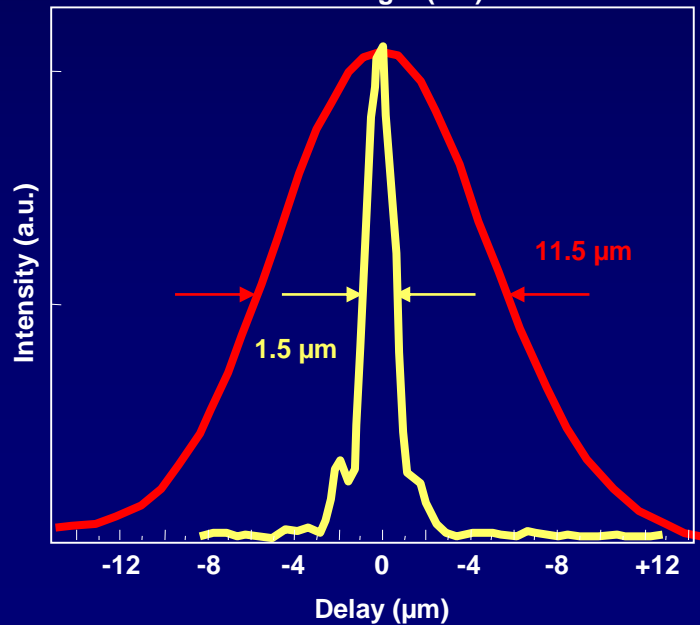
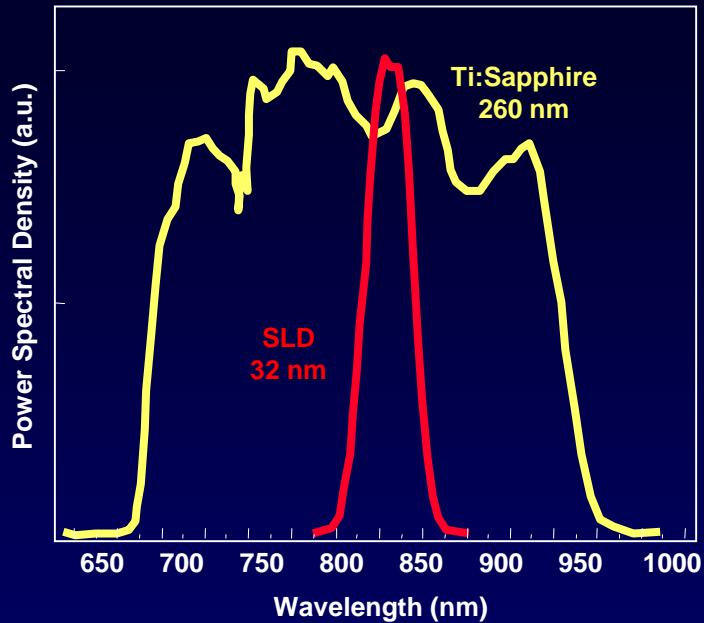
$\Delta z$ ... Comprimento de coerência  
 $\lambda_0$ ... Comprimento de onda central  
 $\Delta \lambda$ ... Largura de banda à meia altura (FWHM)



**Assumindo:**

Espectro Gaussiano, meio não dispesivo

# Fonte de luz x Resolução do OCT



# Como funciona?

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(2\pi \tau \nu)$$

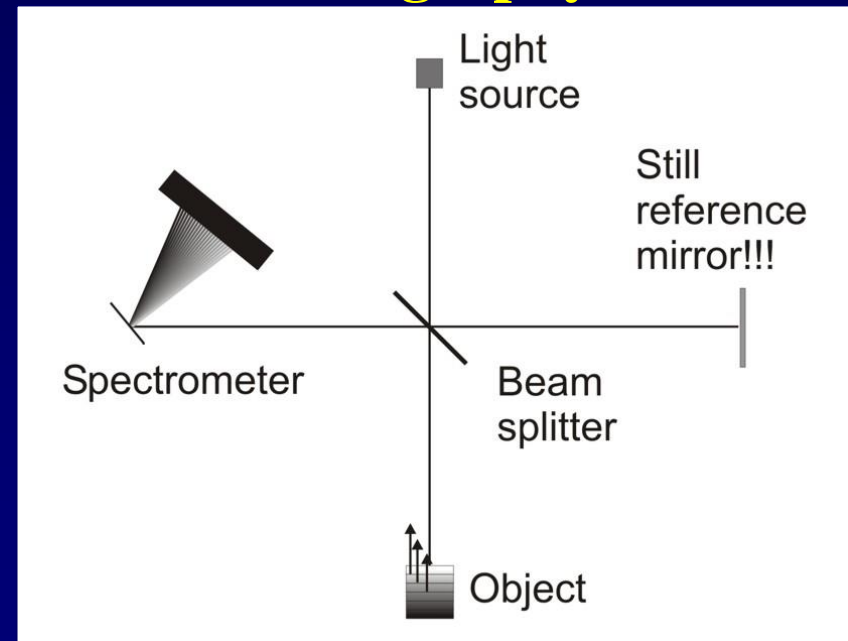
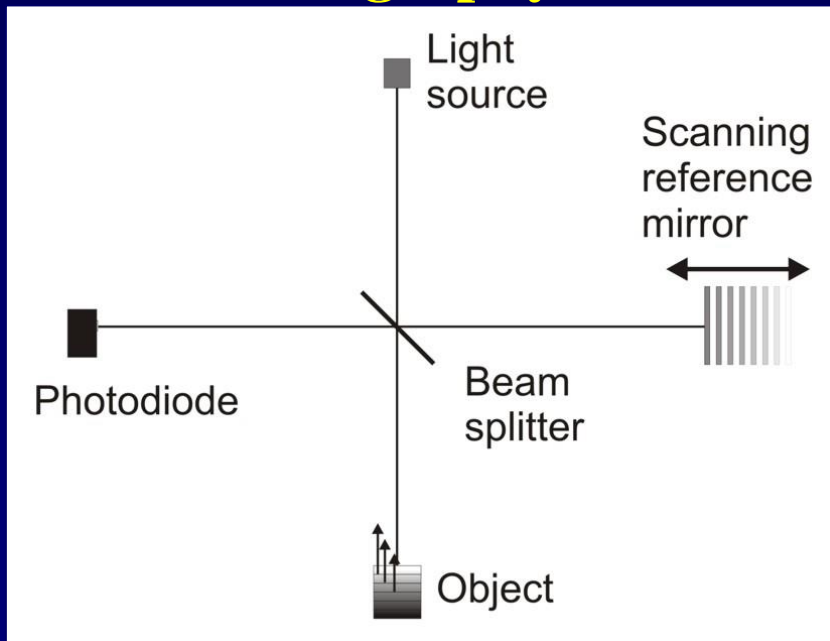
variando  $\tau$

variando  $\nu$

$\tau$  – atraso no caminho óptico  
 $\nu$  – frequência óptica

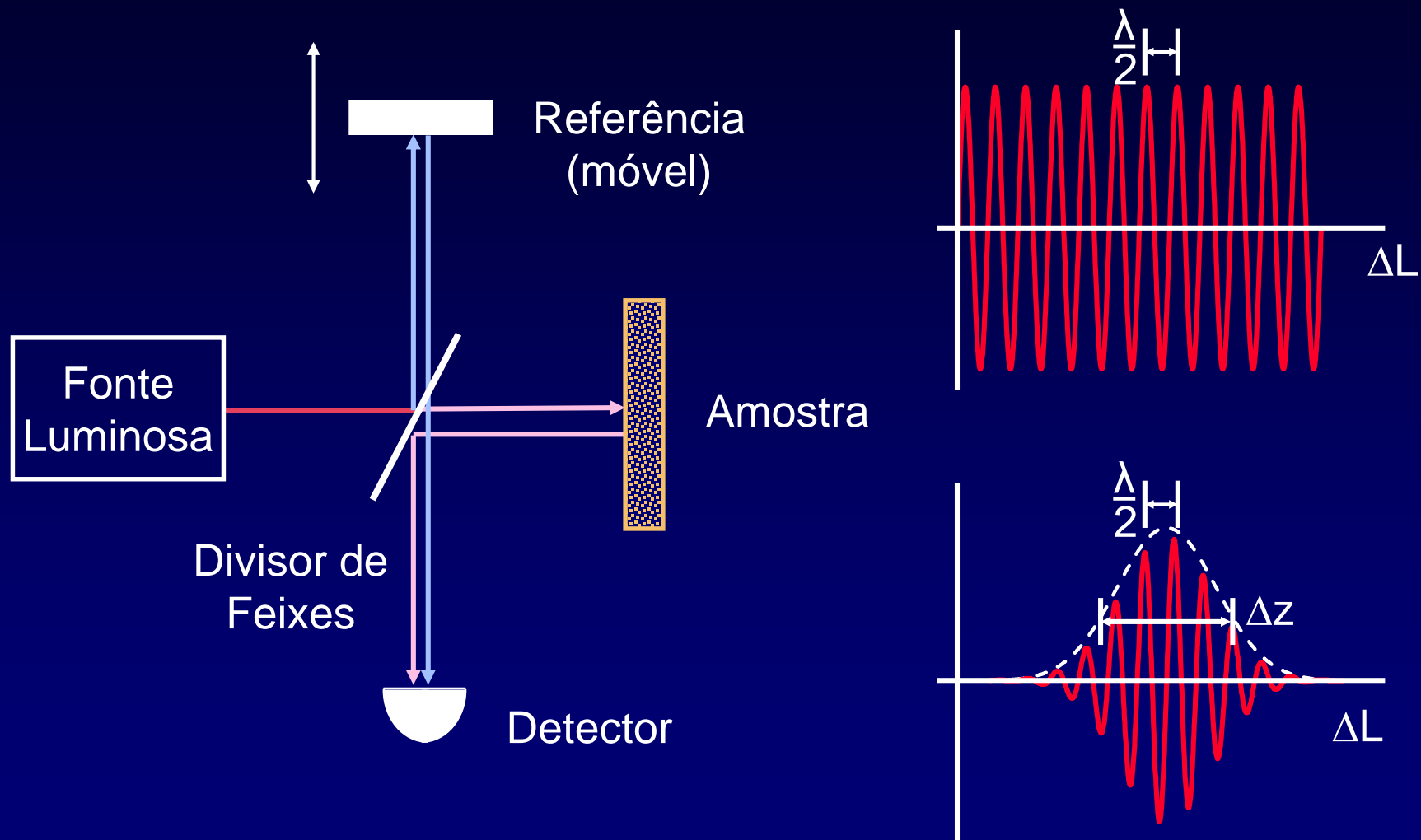
**Time domain  
Optical Coherence  
Tomography:**

**Spectral/Fourier domain  
Optical Coherence  
Tomography:**



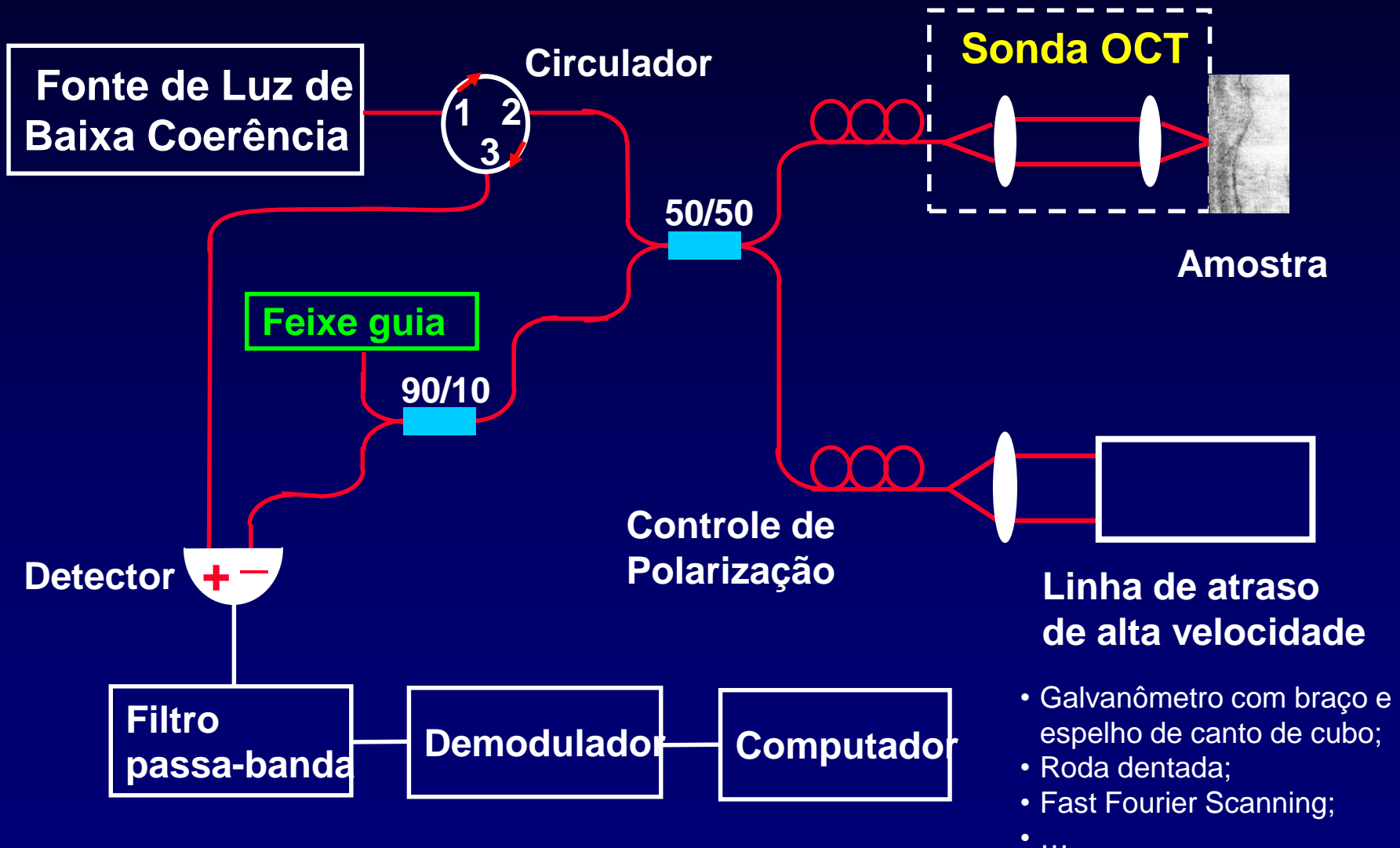


# Interferometria de baixa coerência OCT – domínio do tempo

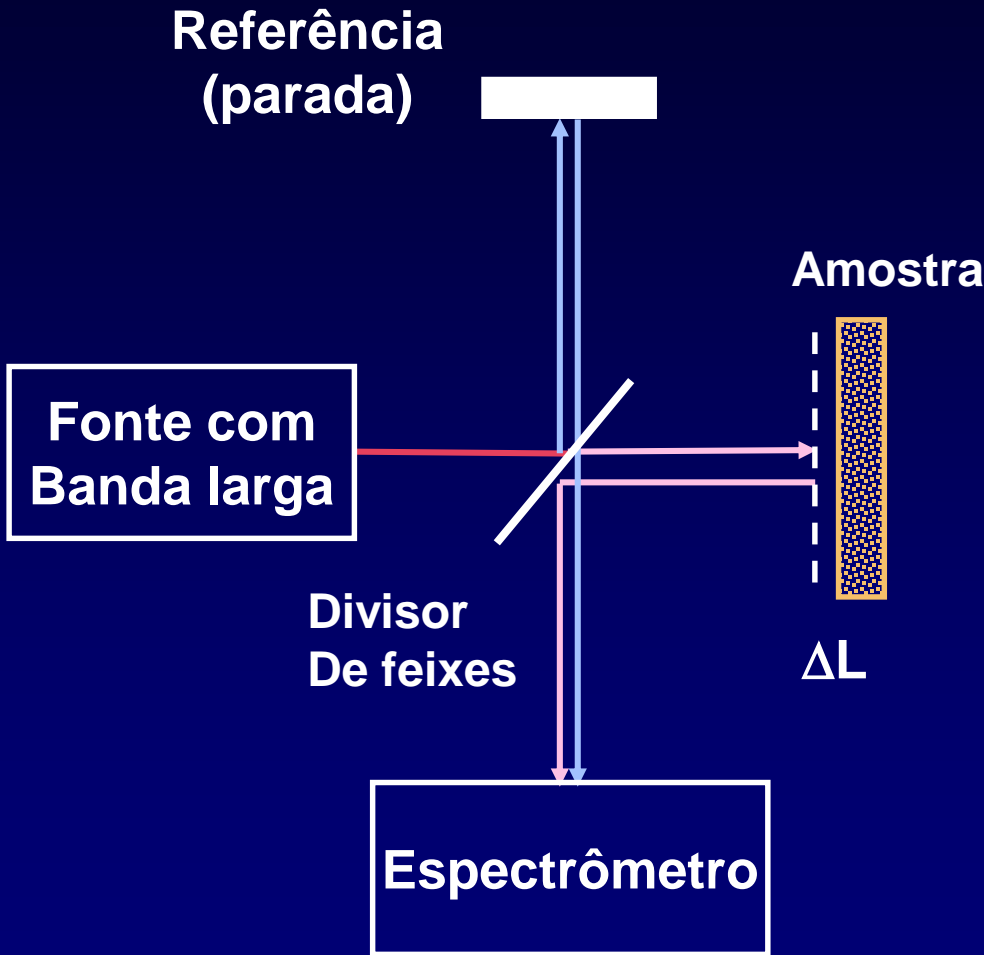


Intervalos de tempo entre os ecos da luz refletida são medidos por correlação

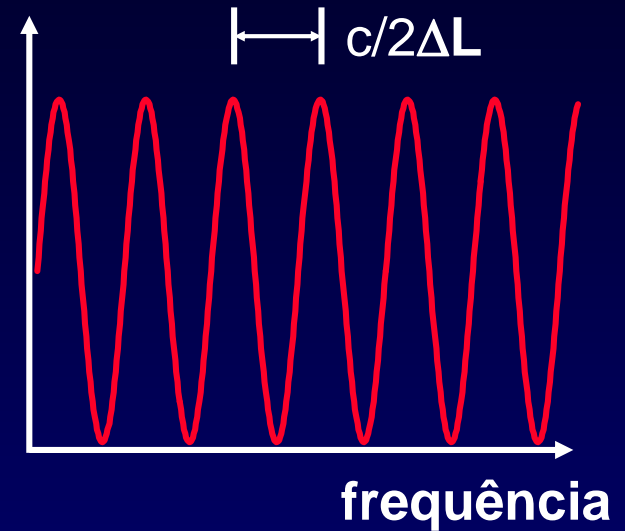
# Sistema para fazer imagens com OCT



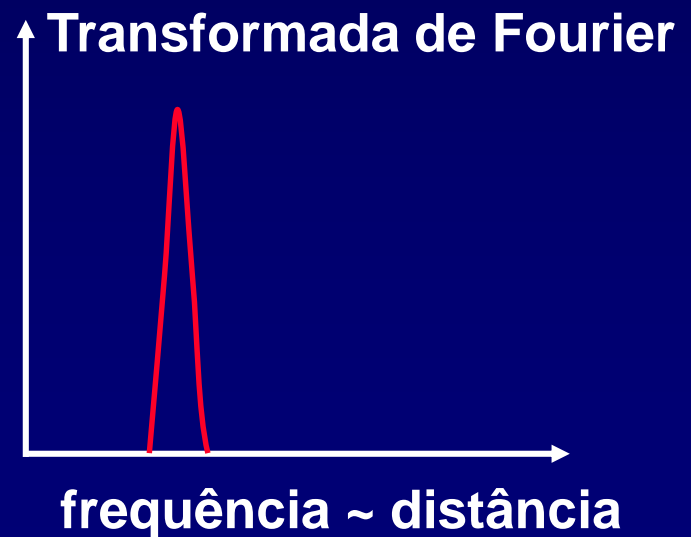
# Interferometria no domínio Fourier/Espectral



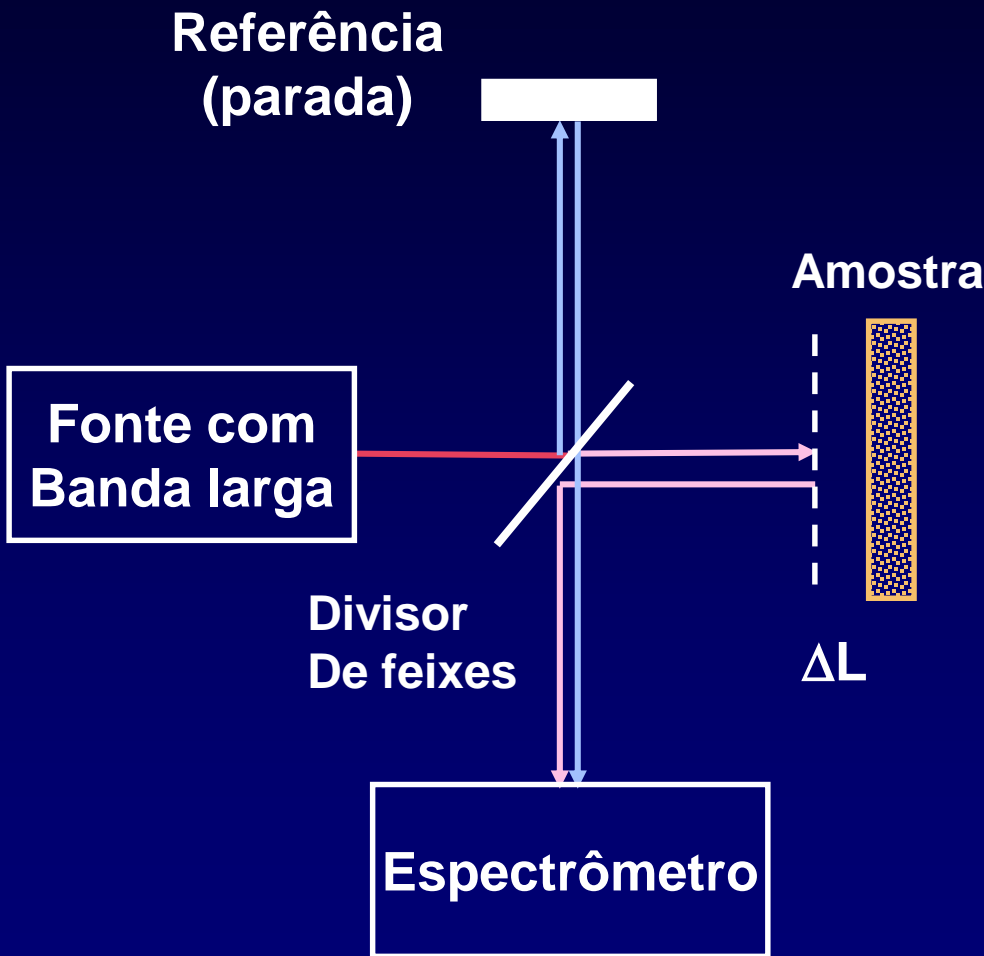
Espectro da Interferência



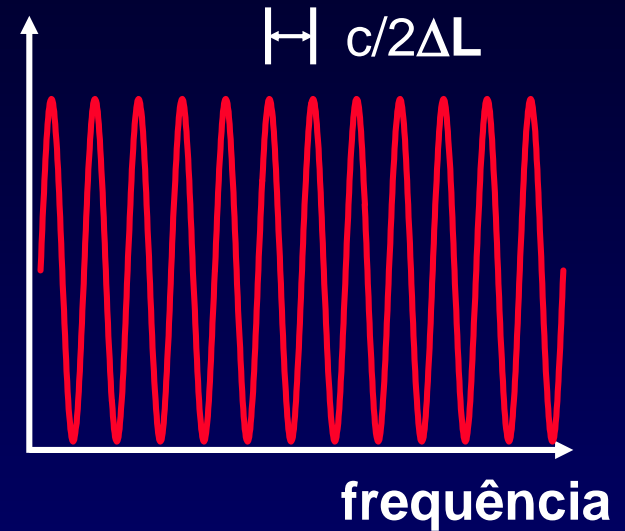
Transformada de Fourier



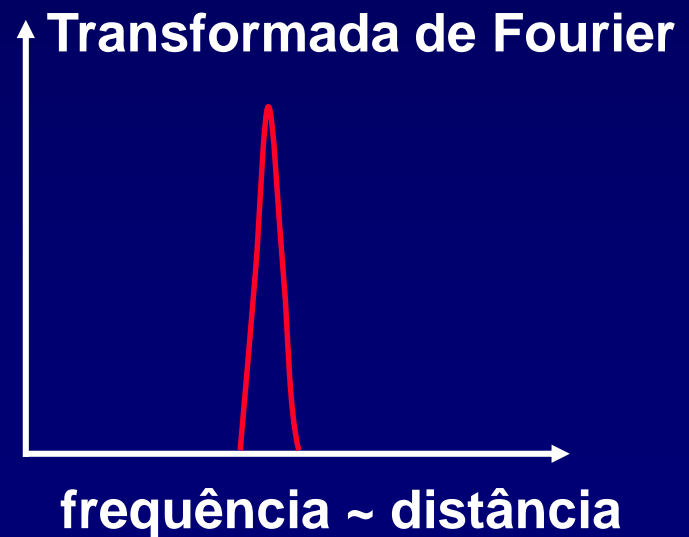
# Interferometria no domínio Fourier/Espectral



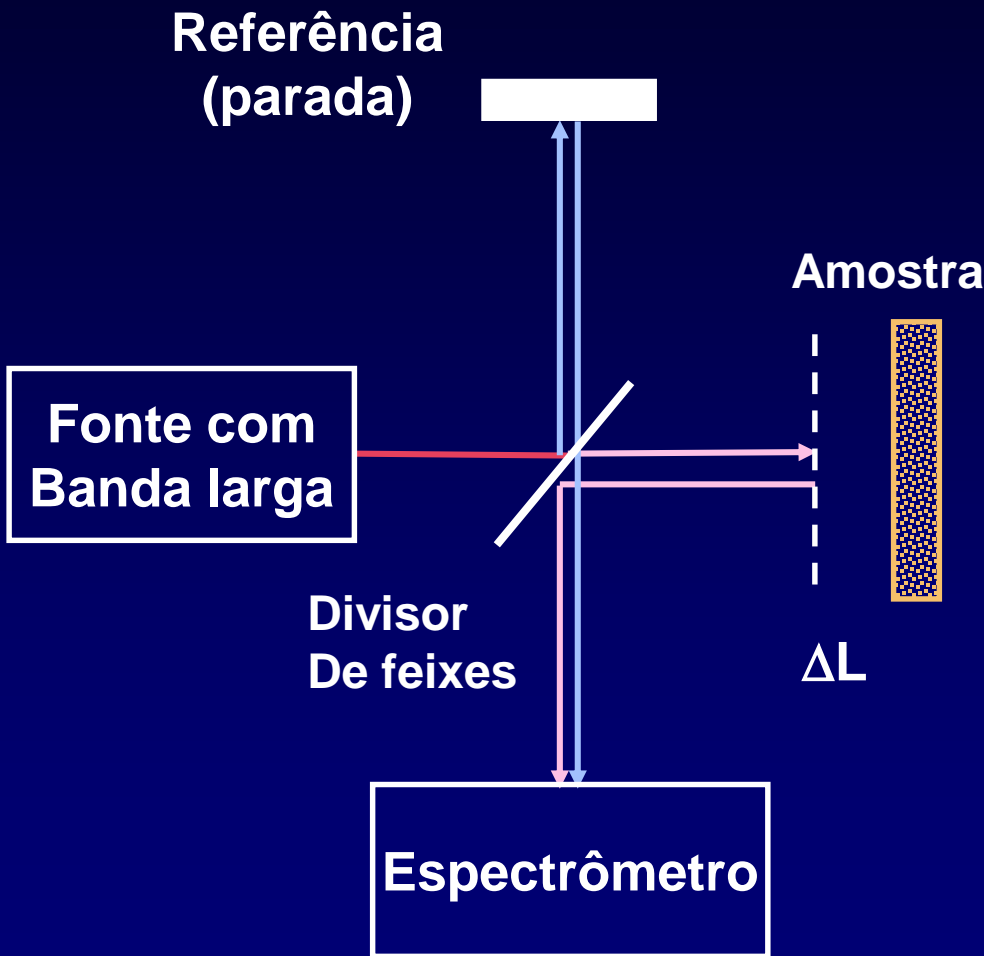
Espectro da Interferência



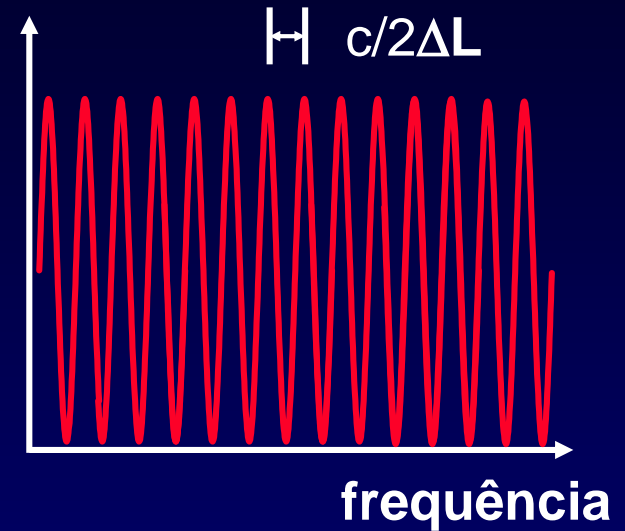
Transformada de Fourier



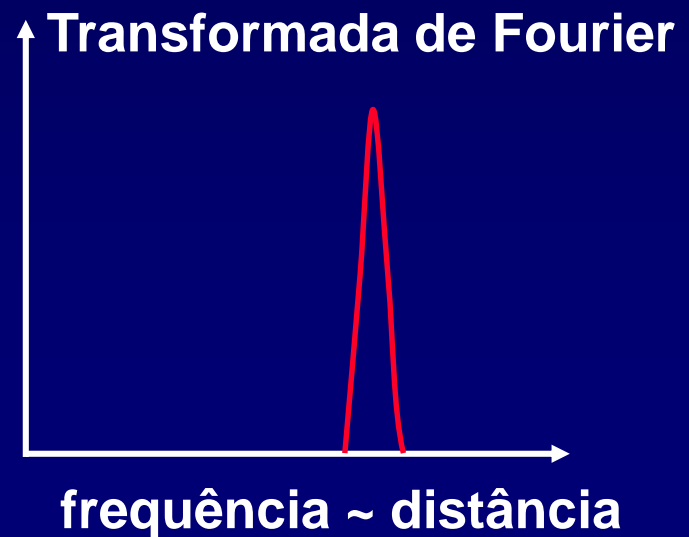
# Interferometria no domínio Fourier/Espectral



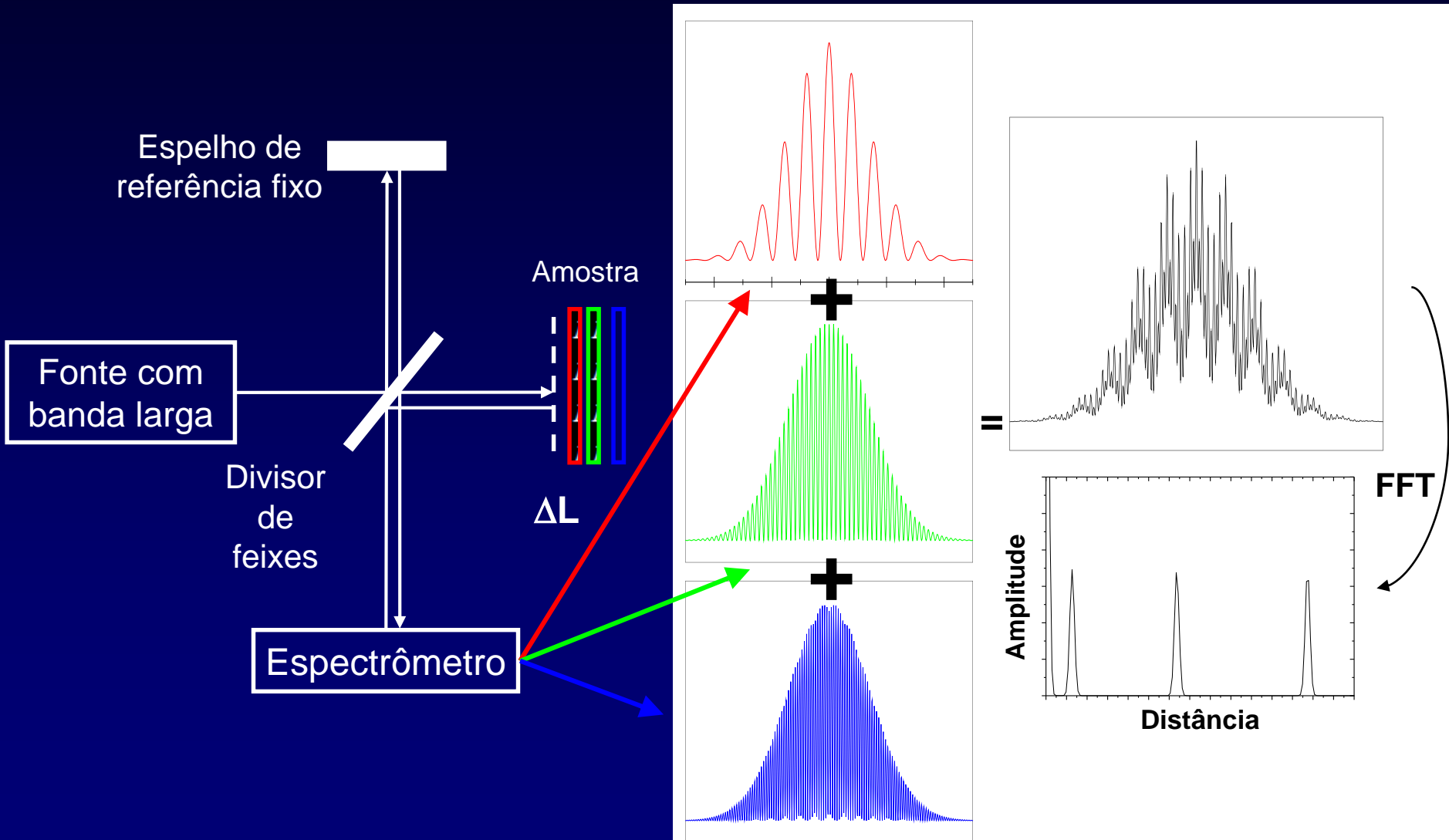
Espectro da Interferência



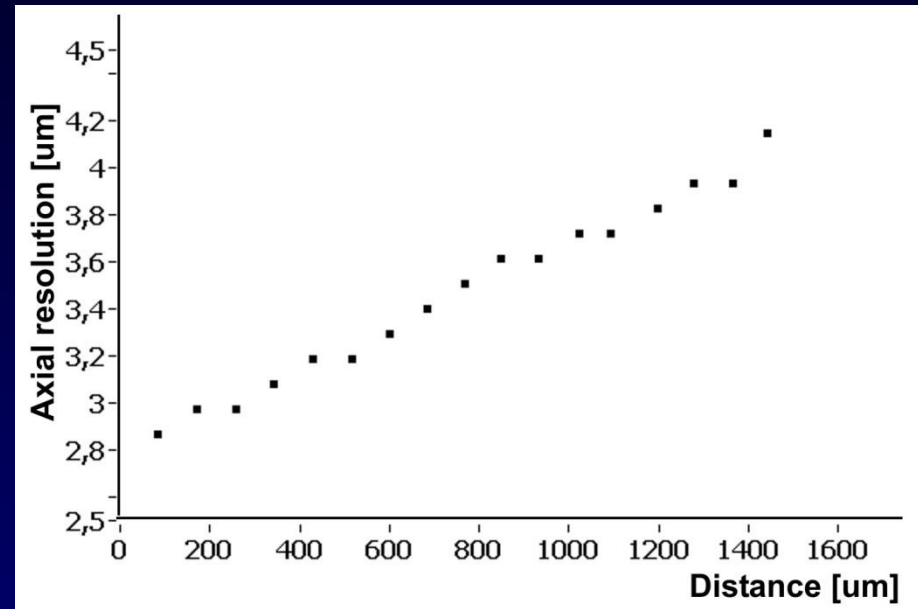
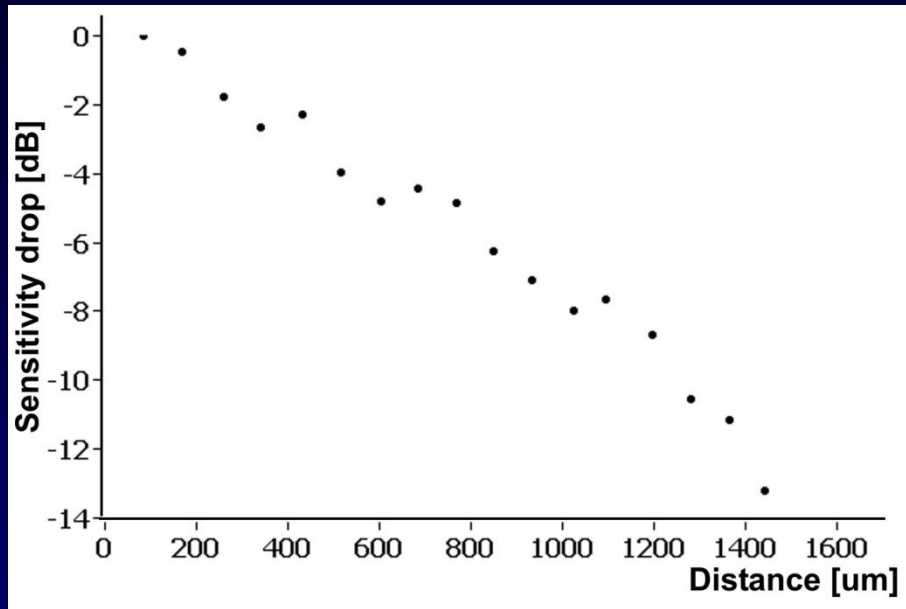
Transformada de Fourier



# Princípio básico de funcionamento da tomografia por coerência óptica espectral



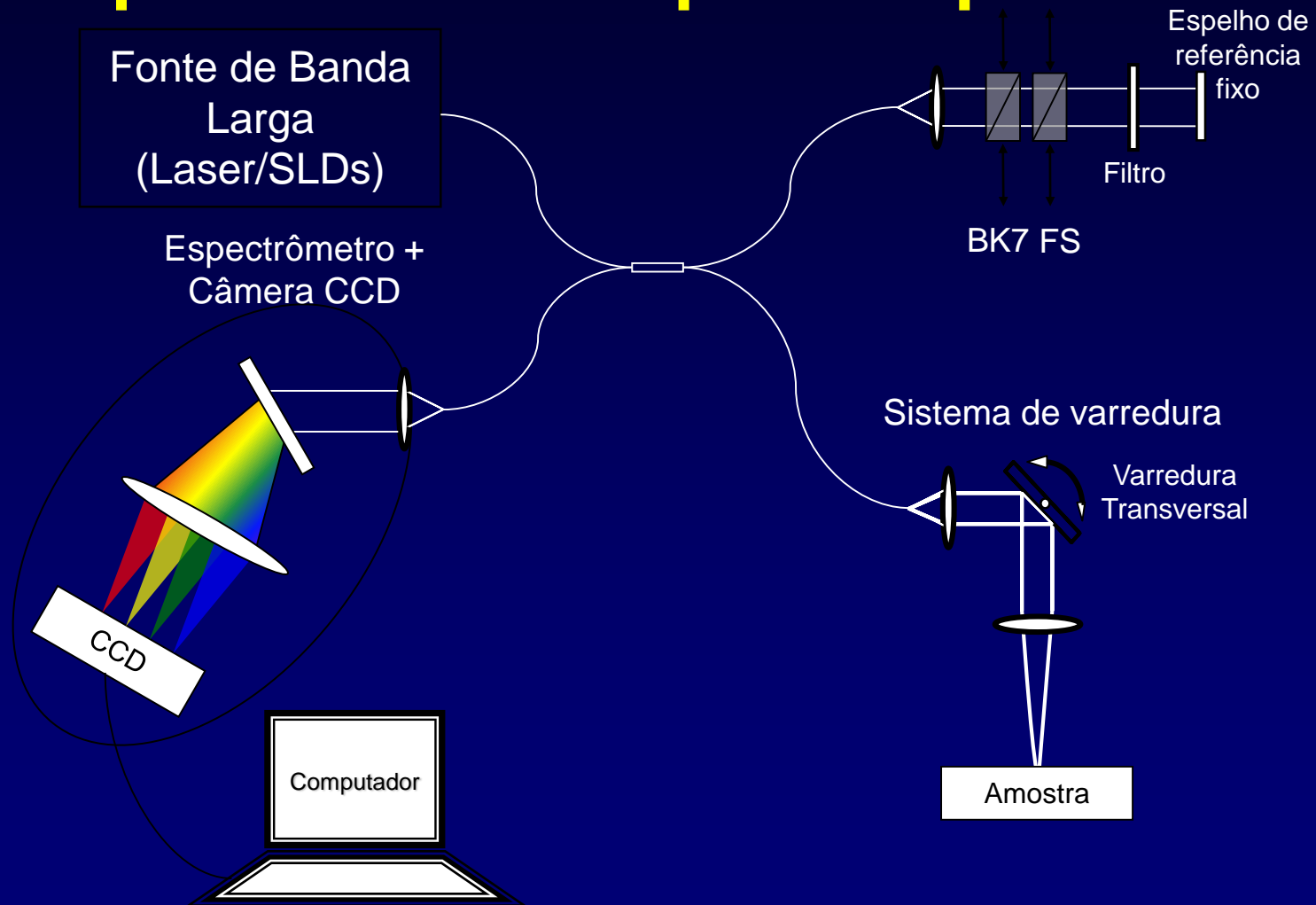
# Limitações da técnica – Sensitividade e resolução variando com a profundidade



Limite de profundidade de 1.5 mm  
Variação de 14 dB em sensibilidade  
Resolução degrada-se de 3  $\mu\text{m}$  para 4  $\mu\text{m}$

Resolução do espectrômetro  
Mapeamento não linear de comprimento de onda para frequência  
Tamanho dos pixels  
Cross talk entre os pixels

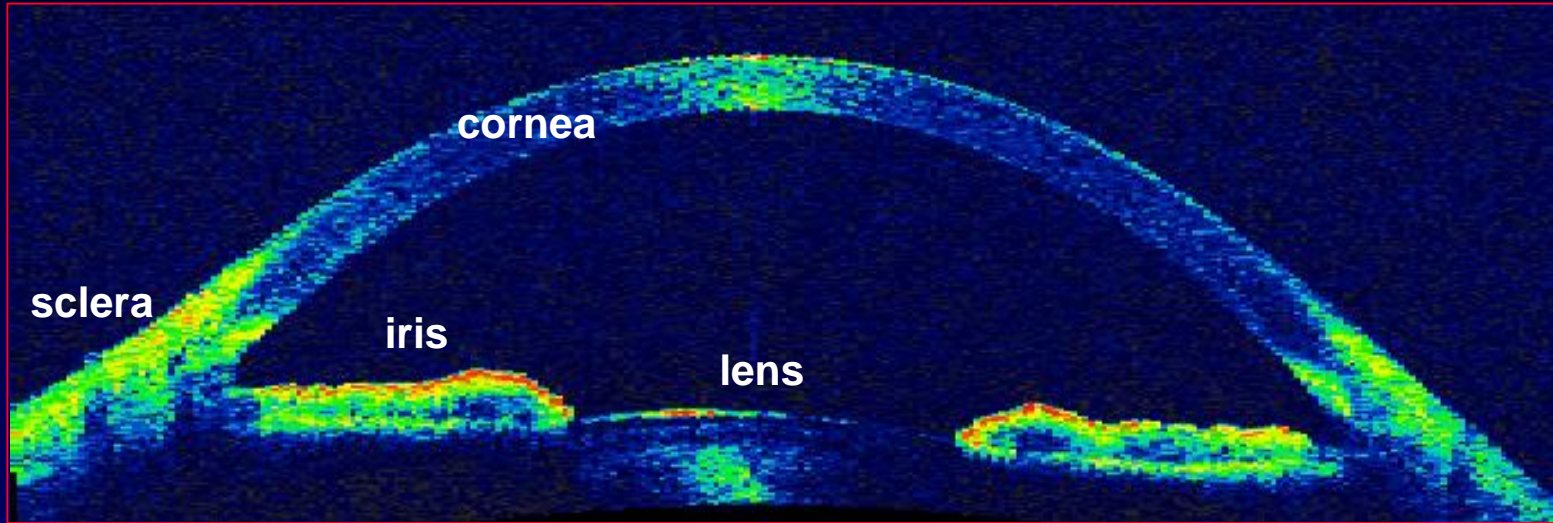
# Geração de imagens por tomografia por coerência óptica espectral



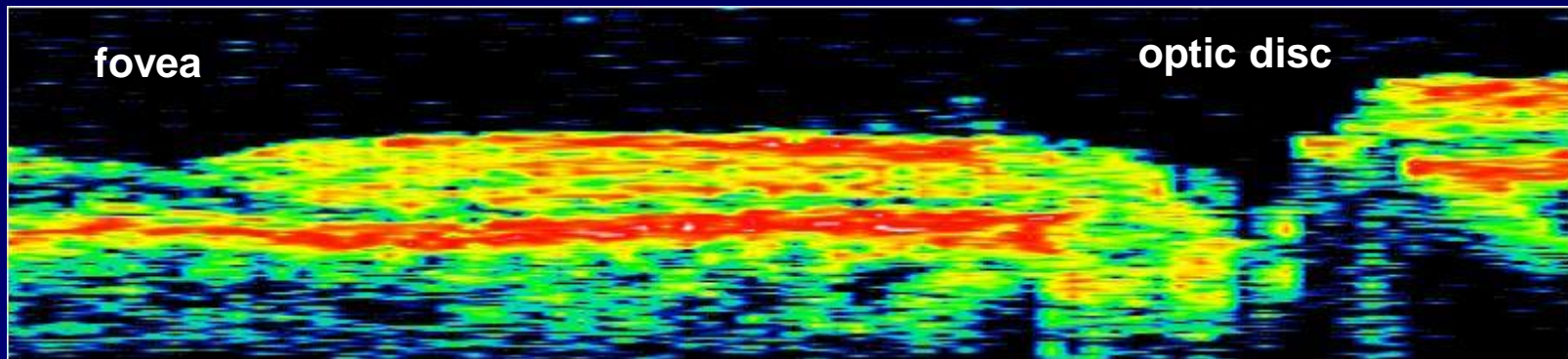


# OCT: Imagem Oftalmológica

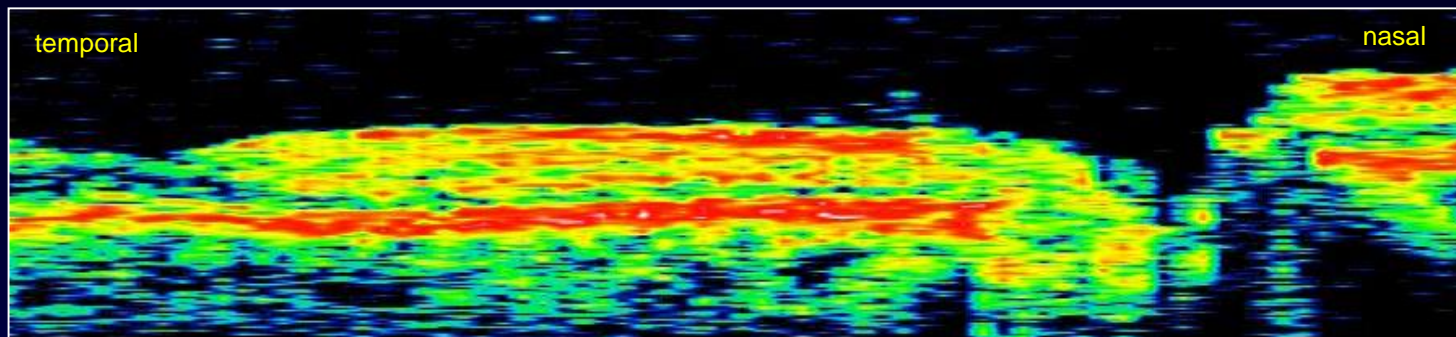
## Câmara Anterior



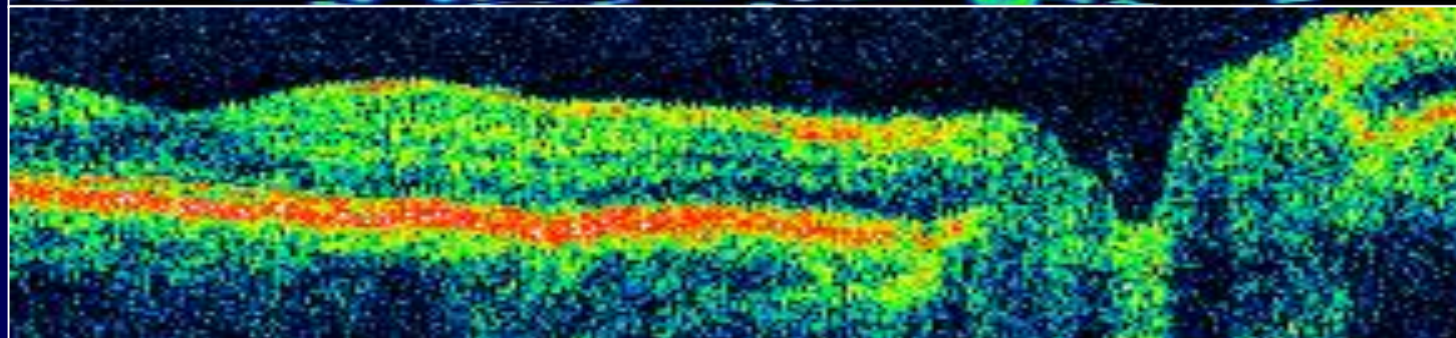
## Retina



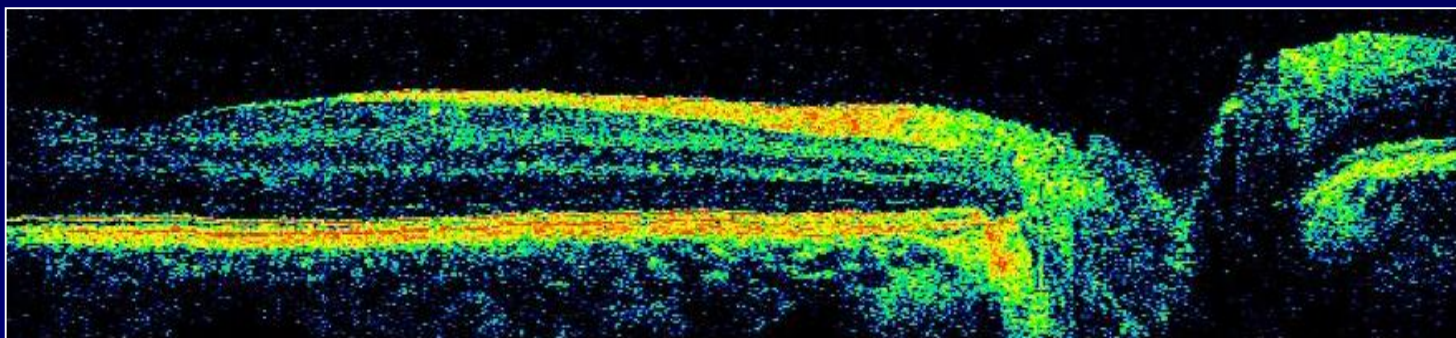
250  $\mu\text{m}$



250  $\mu\text{m}$



10  $\mu\text{m}$  resolução axial



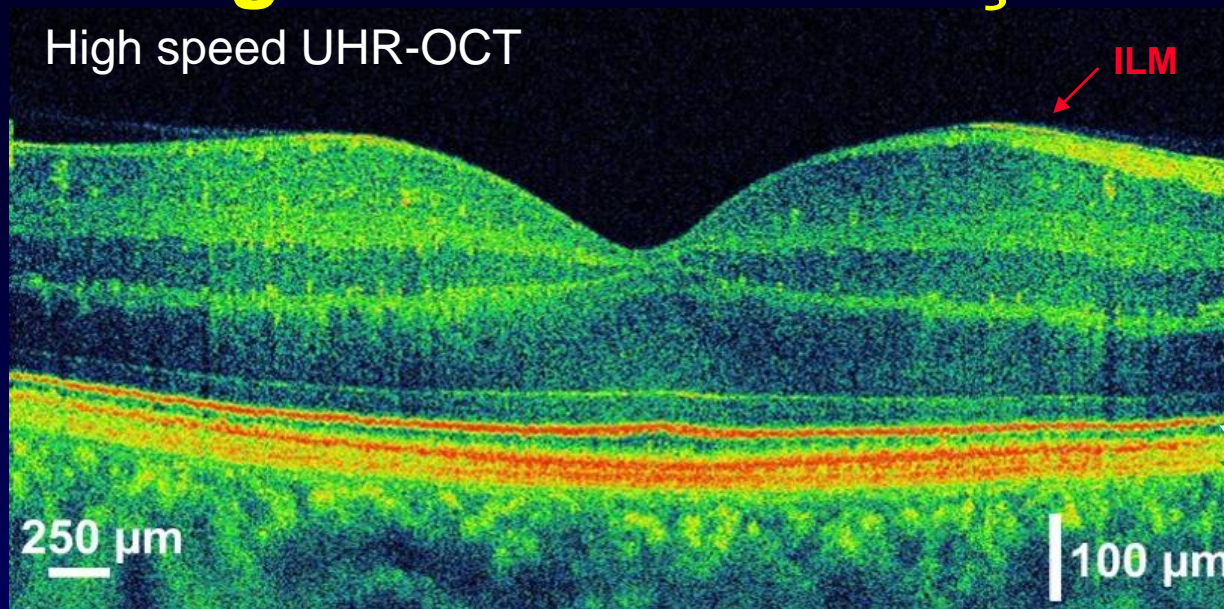
3  $\mu\text{m}$  resolução axial

# Imagens de alta definição

High speed UHR-OCT

2048 x 1024 pixel

0.13 sec

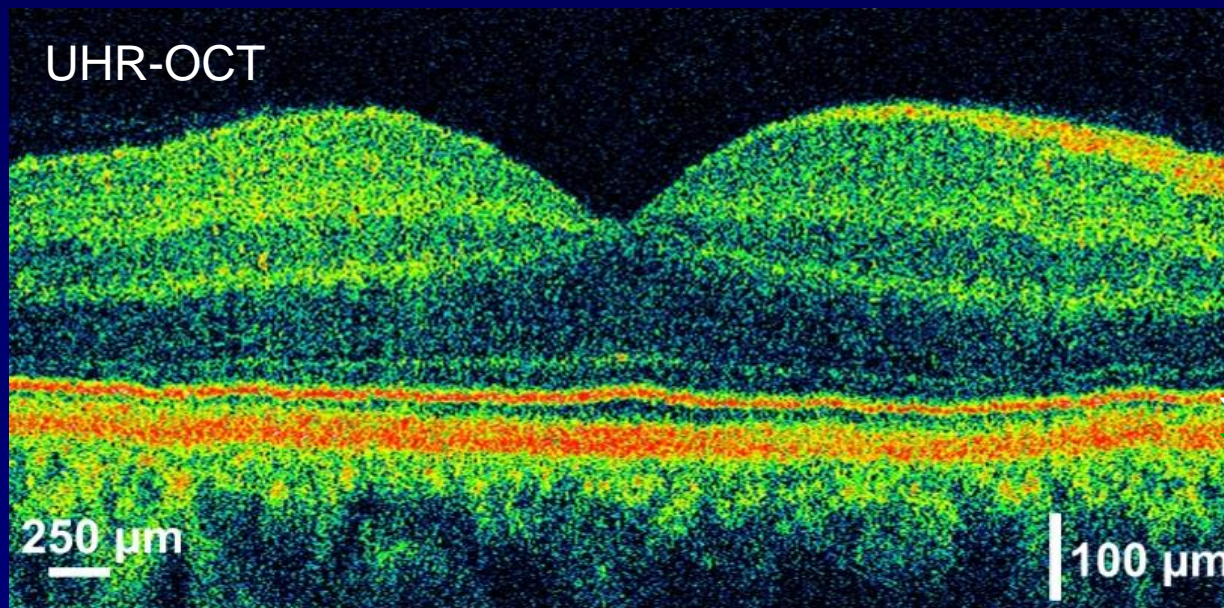


NFL  
GCL  
IPL  
INL  
OPL  
ONL  
ELM  
IS/OS  
RPE/Choroid

UHR-OCT

600 x 1024 pixel

4 sec

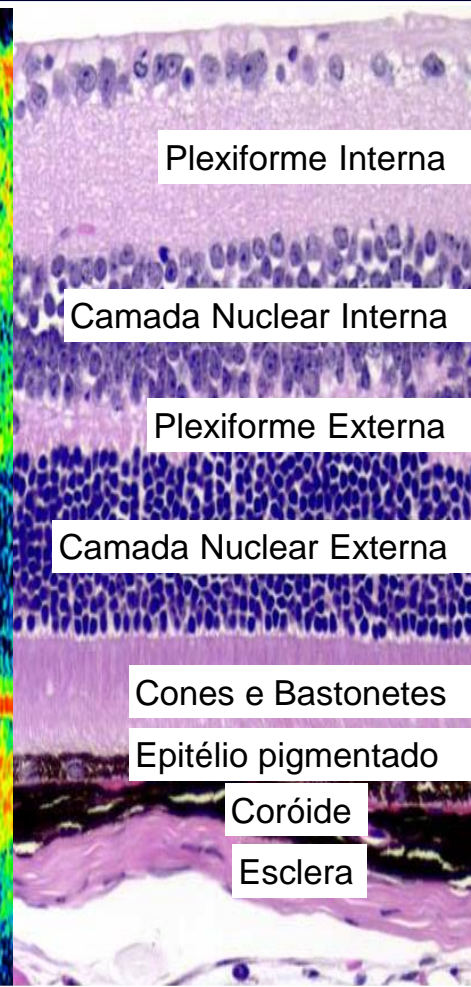
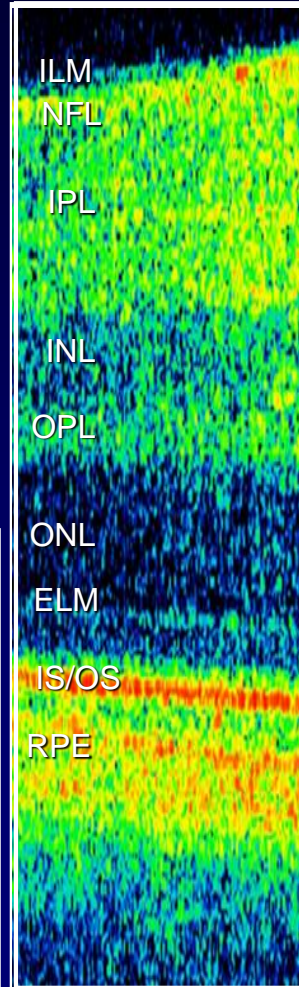
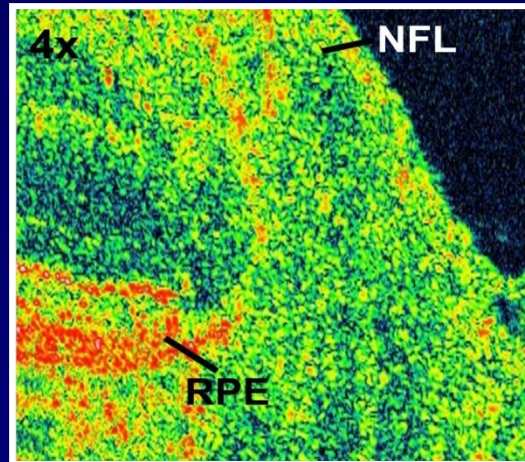
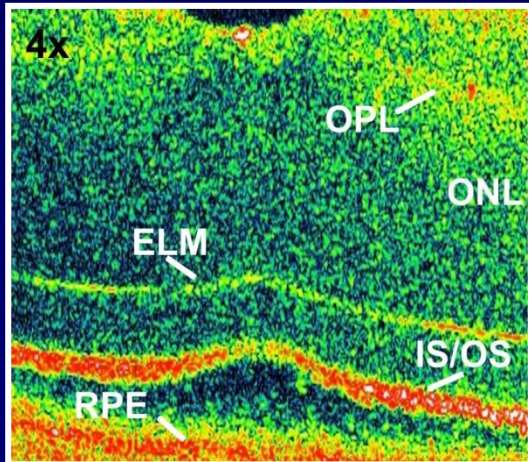
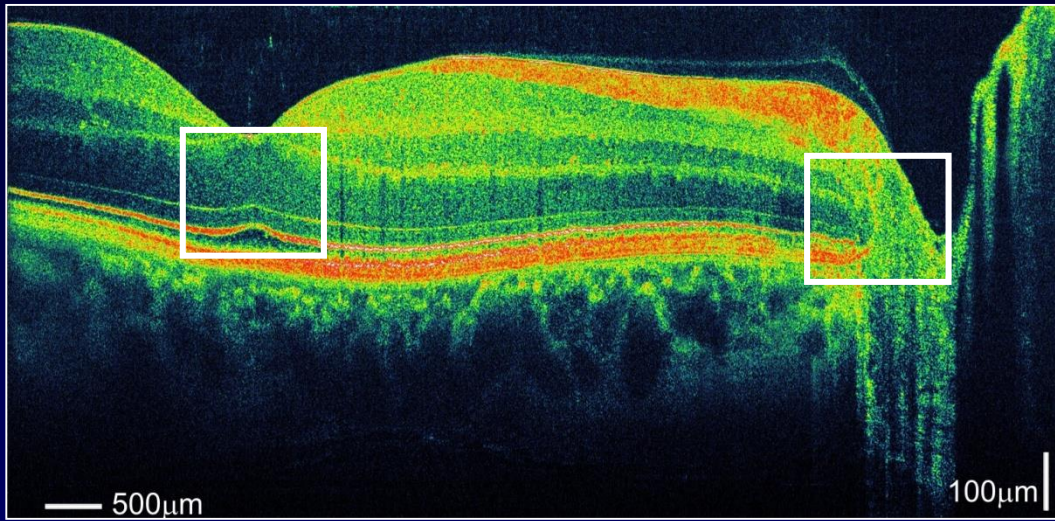


NFL  
GCL  
IPL  
INL  
OPL  
ONL  
ELM  
IS/OS  
RPE/Choroid

Temporal

Nasal

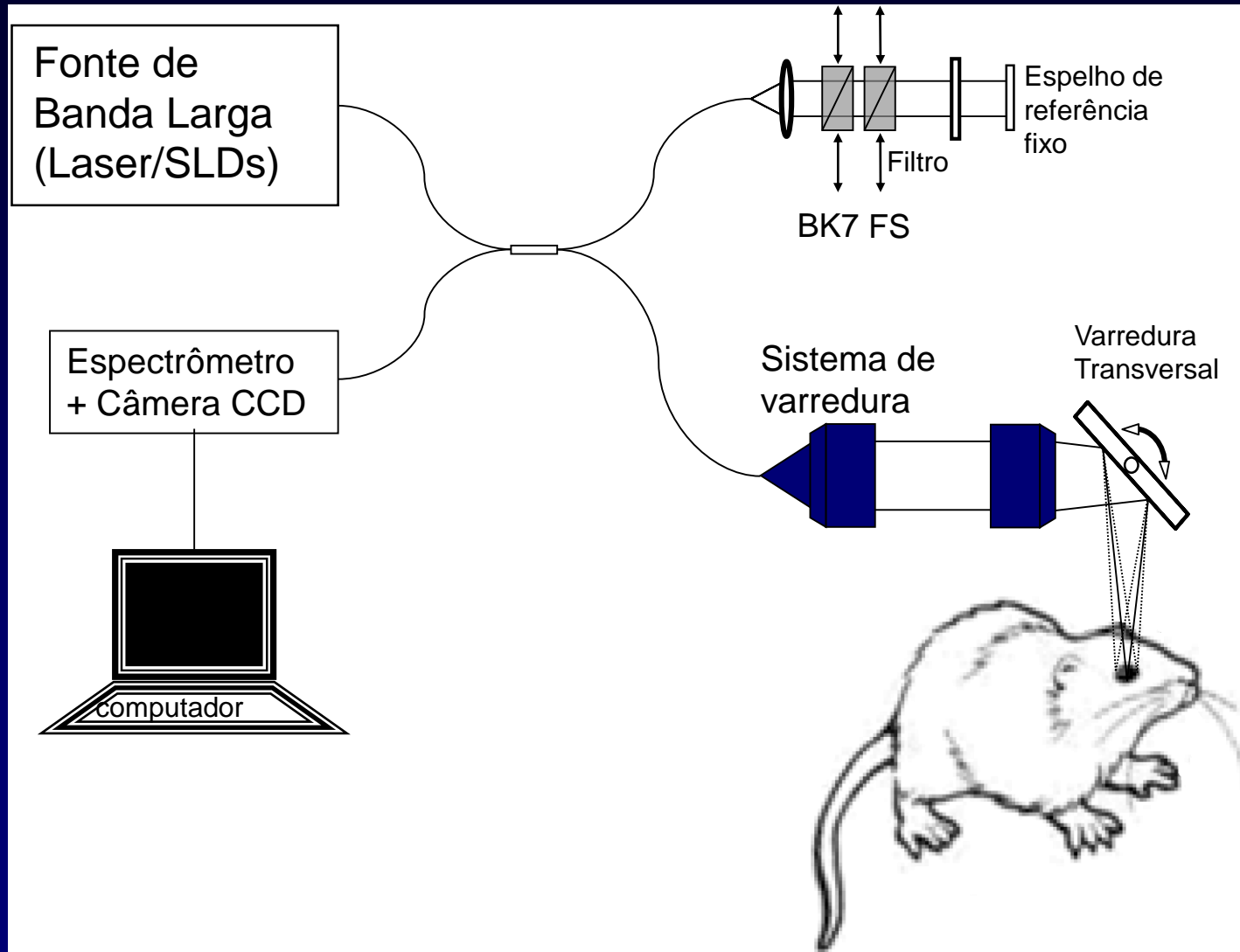
# Qualidade da imagem



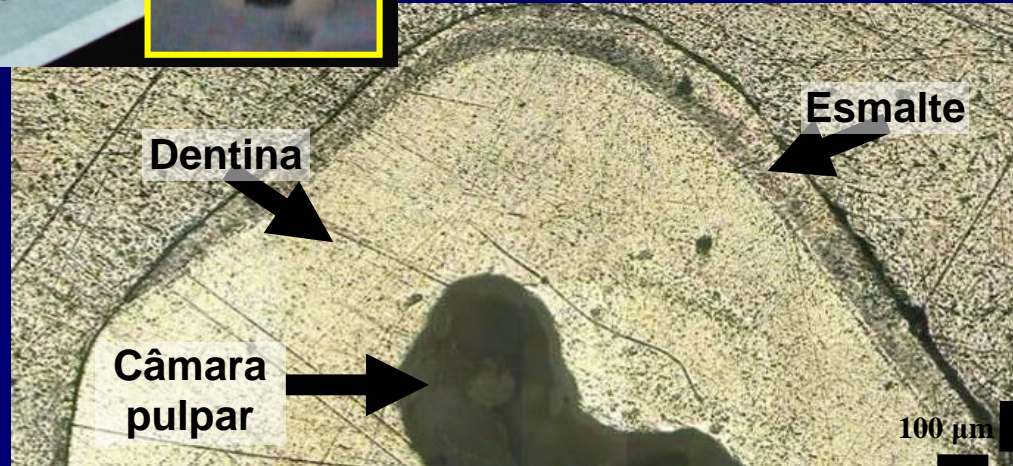
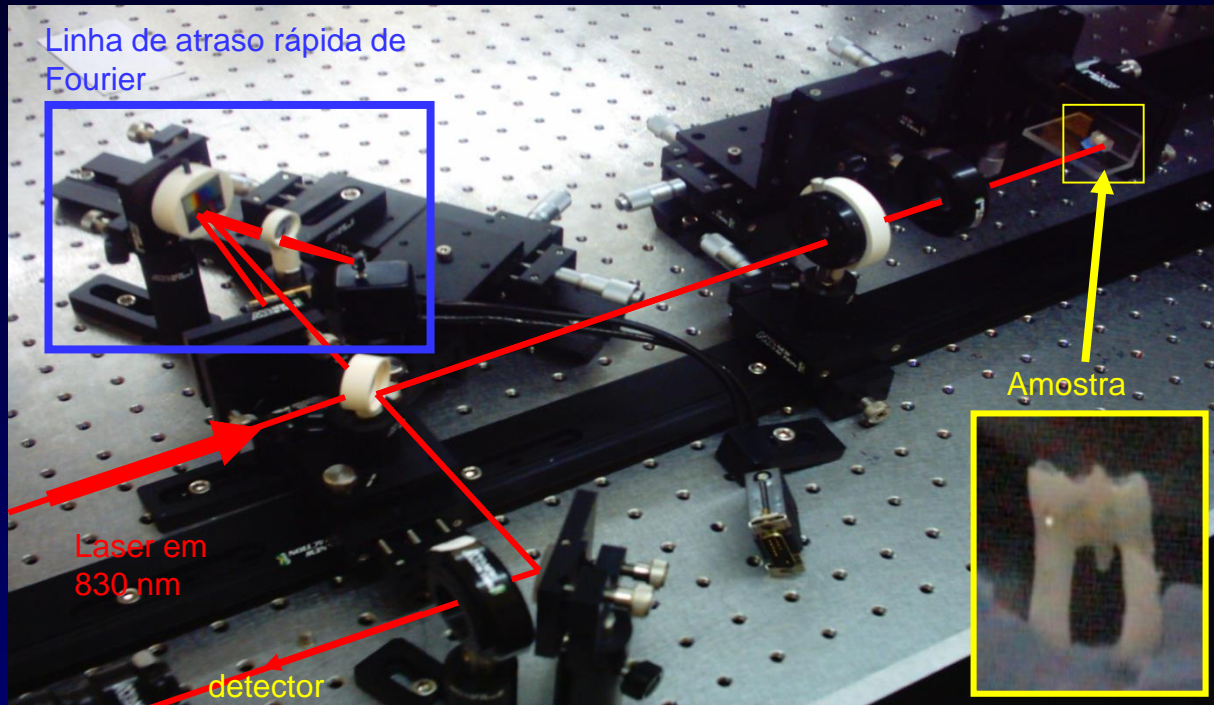
# Aplicações diversas

- TCO em oftalmologia
- TCO em dermatologia
- Outras aplicações médicas
- Biópsia óptica
- TCO em odontologia
- Outras aplicações

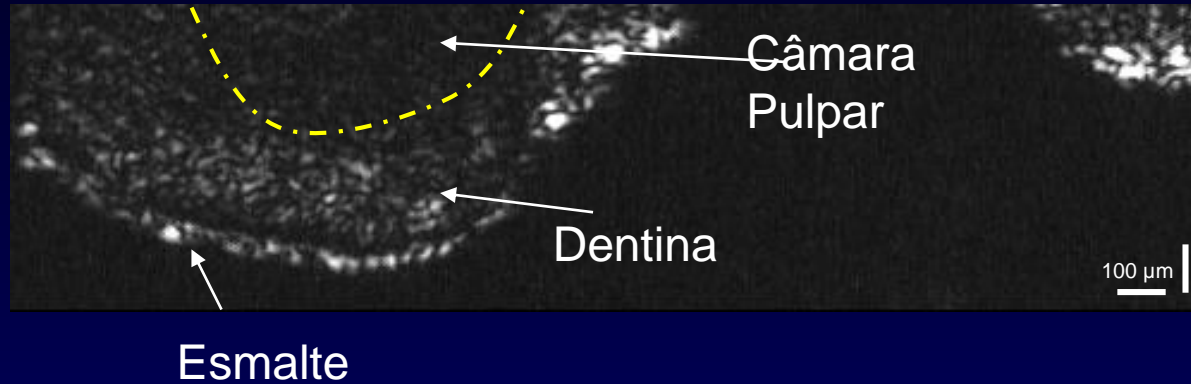
# Imagens de tomografia por coerência óptica espectral em pequenos animais



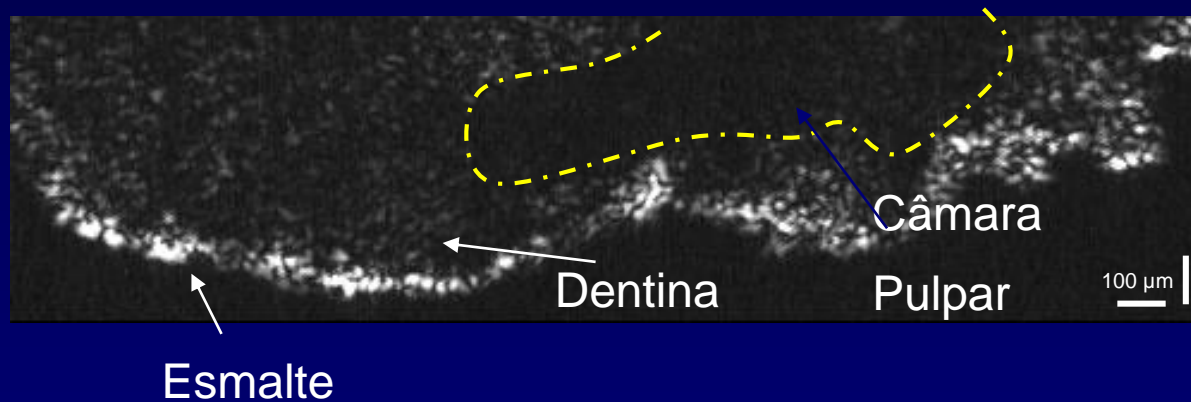
# Odontologia



# Resultados



canal radicular



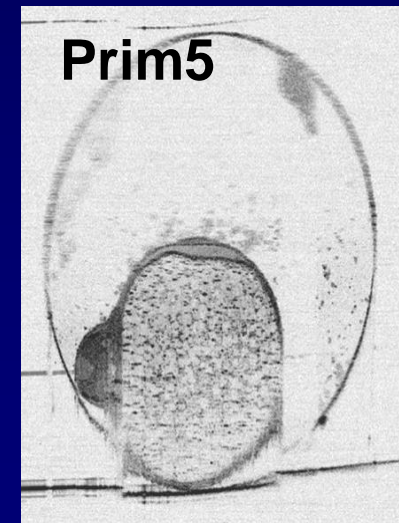
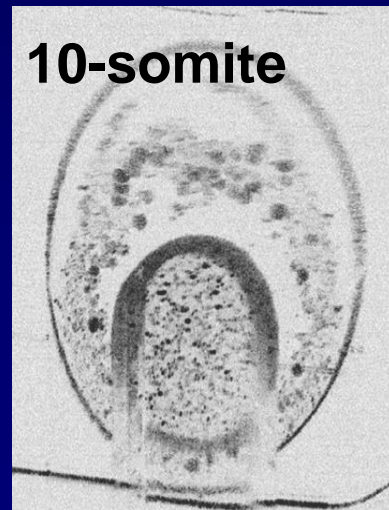
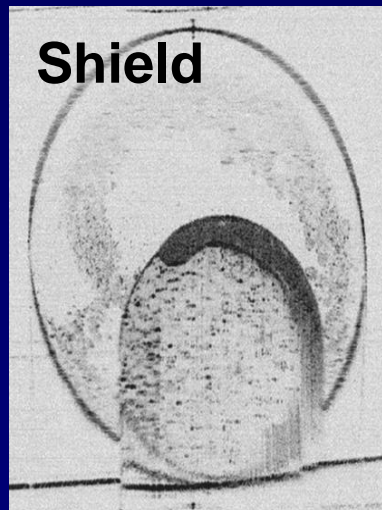
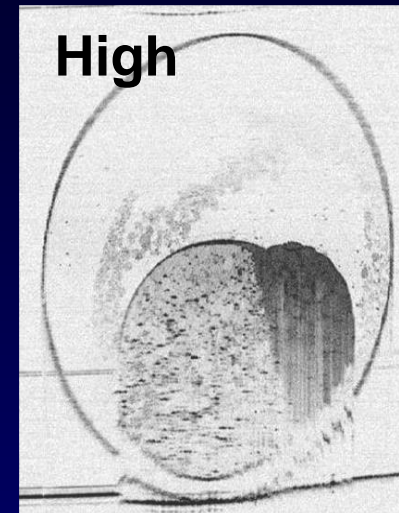
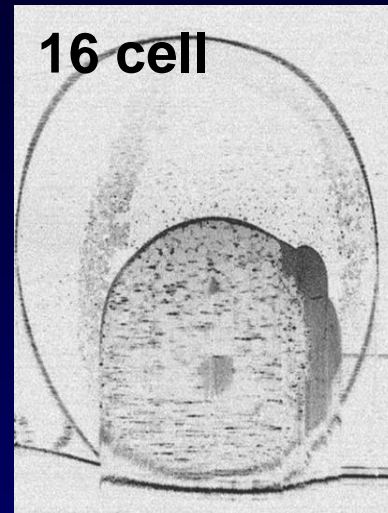
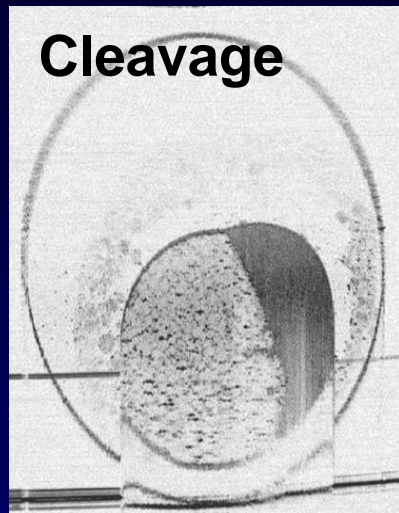
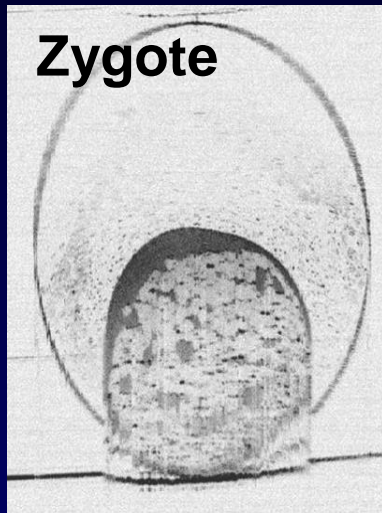
400  $\mu\text{m}$  acima do canal radicular



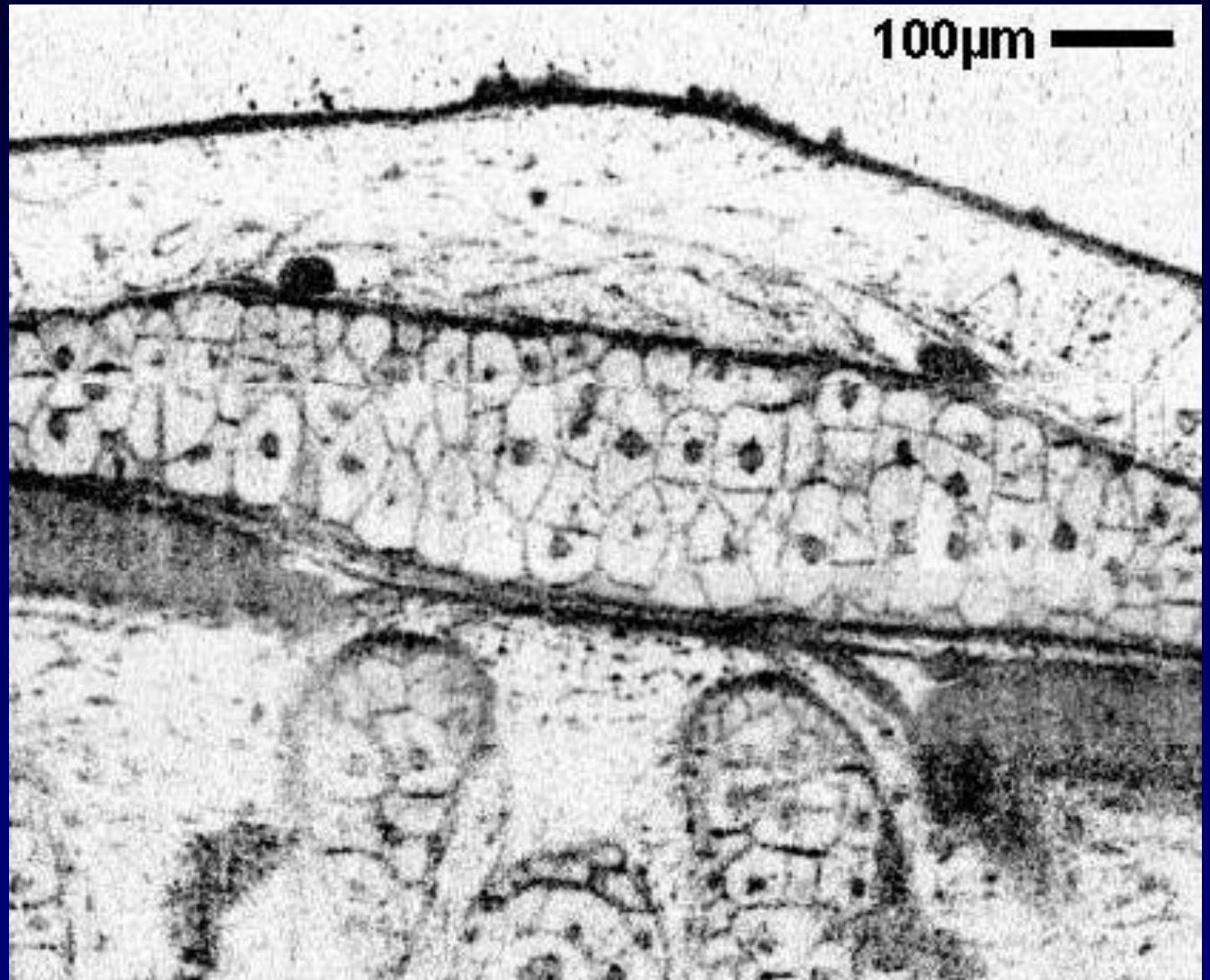
Coroa



# Imagem longitudinal do embrião do peixe zebra em desenvolvimento



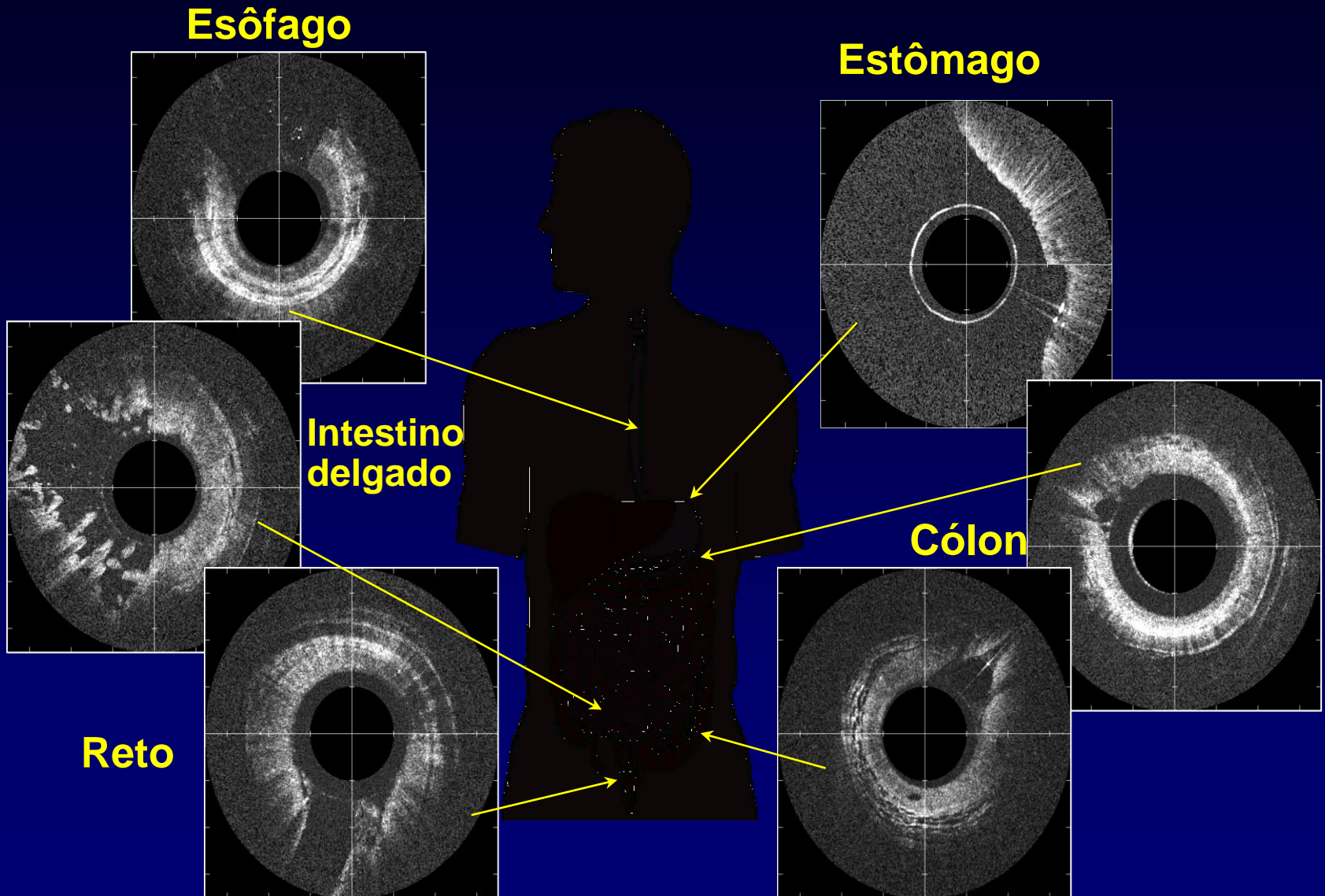
# Resolução sub-celular do OCT *In vivo*



Girino do  
*Xenopus laevis*  
(Rã Africana)

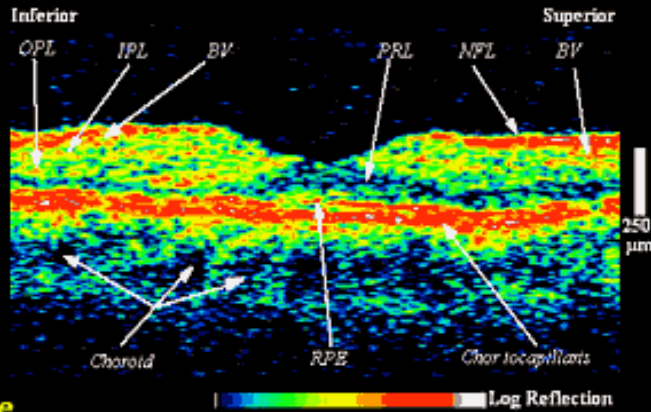
W. Drexler, et al.  
Opt. Lett. (1999)

# OCT Endoscópico

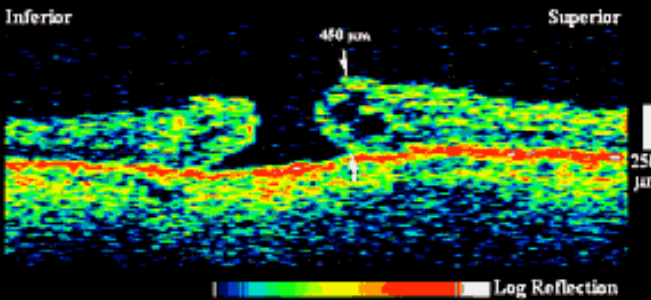


# Oftalmologia

## Normal retina



## Macular hole



## Impending macular hole

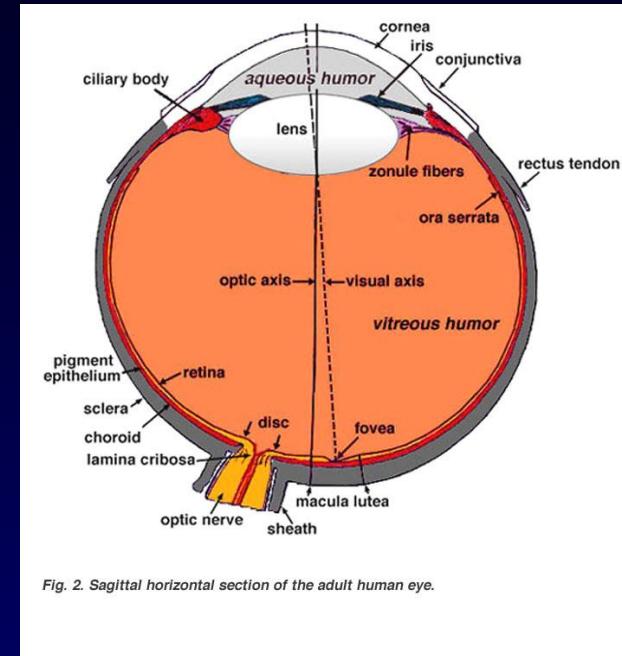
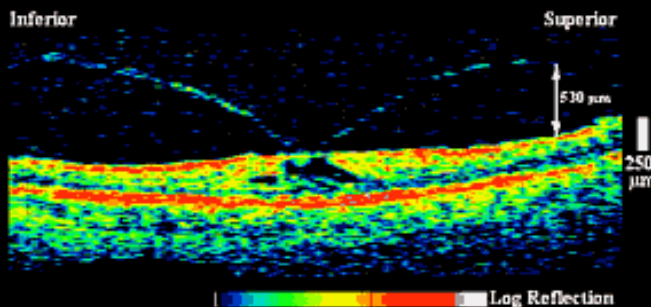


Fig. 2. Sagittal horizontal section of the adult human eye.

Normal patient

Patient with impaired vision (20/80):  
The cause is a macular hole

Patient's other eye (vision 20/25):  
Impending macular hole, which can  
be treated

# Ultra-high resolution OCT

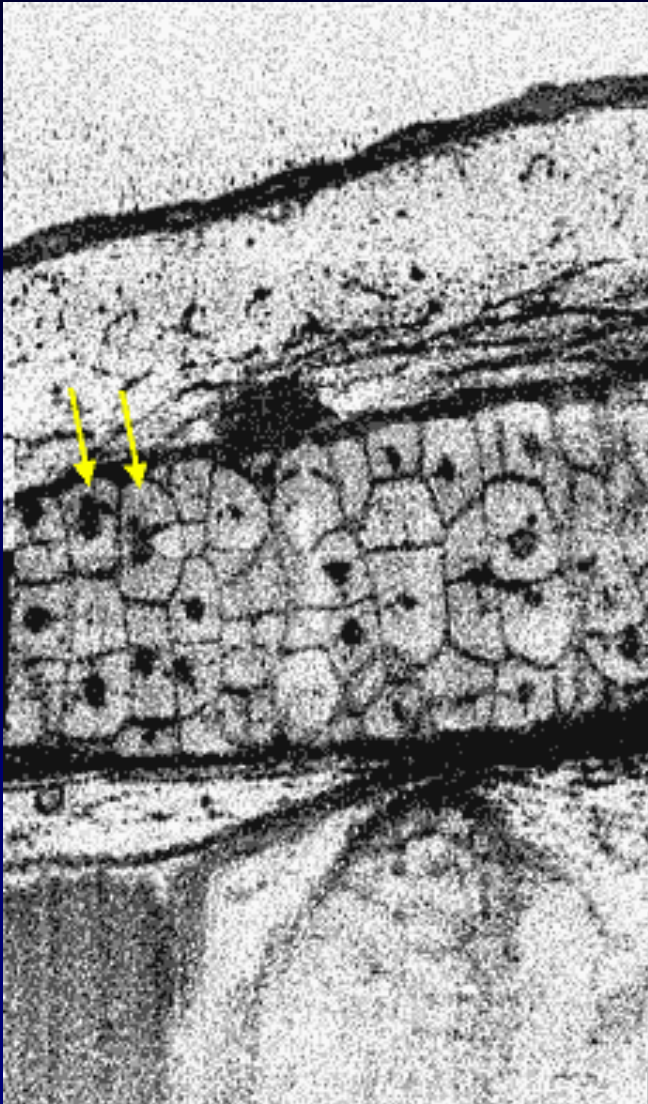
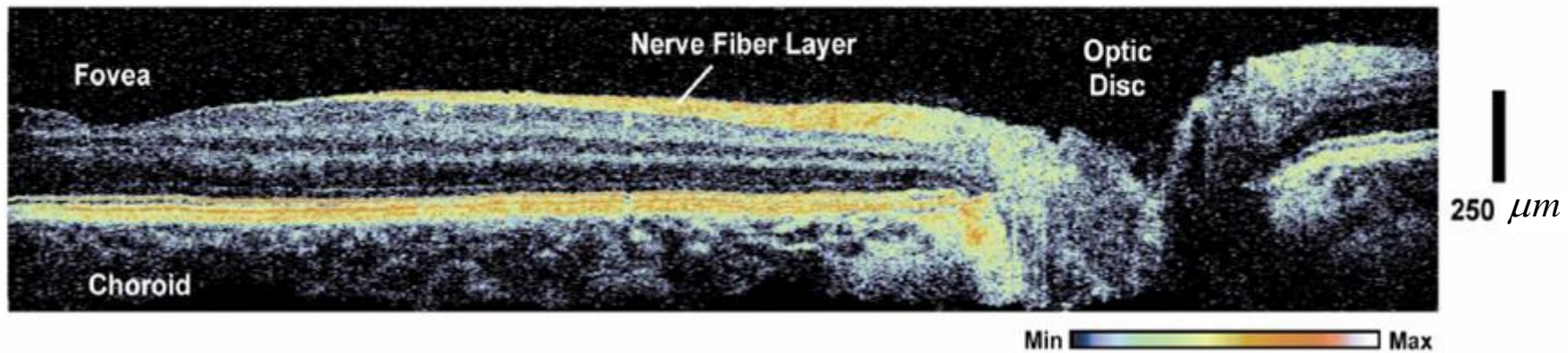
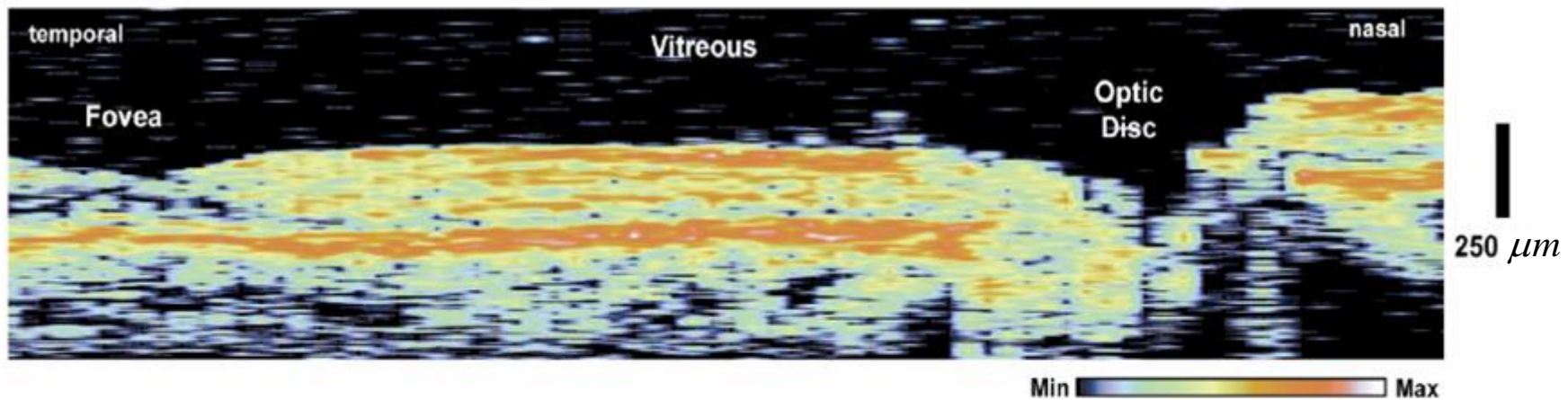


Image through the skin of a living frog tadpole  
Resolution: 3  $\mu\text{m}$

# Ultra-high-resolution-OCT versus commercial OCT



W. Drexler *et al.*, "Ultra-high-resolution ophthalmic optical coherence tomography", *Nature Medicine* 7, 502-507 (2001)

# OCT endoscópico comercial

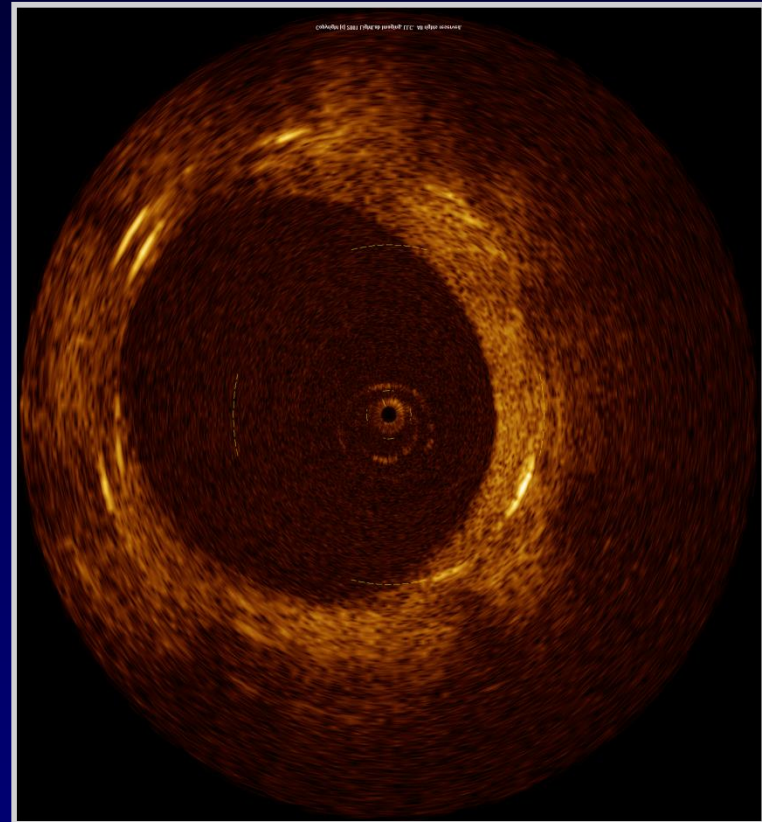
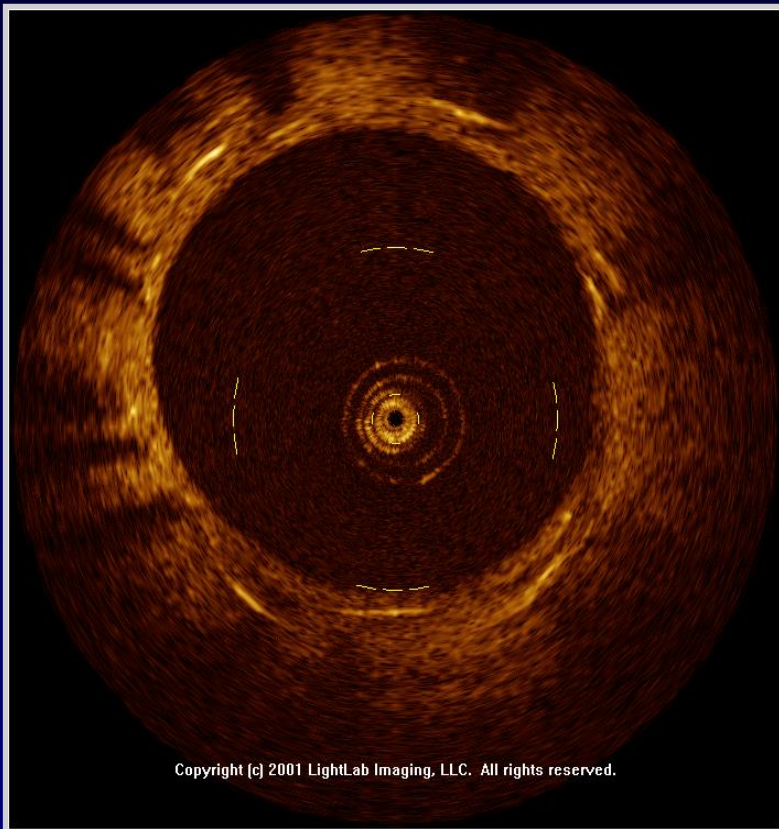


**Imagens endoscópicas e  
broncoscópicas – parceria com  
Pentax**

**Imagem intravascular**

**Empresa adquirida pela  
Goodman, Ltd.**

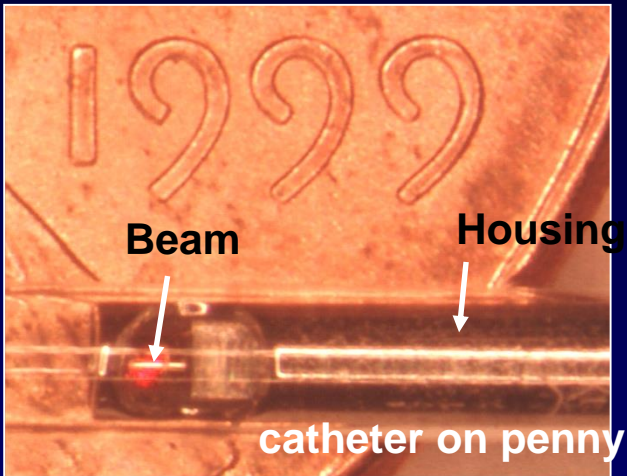
# Artéria humana *In vivo*



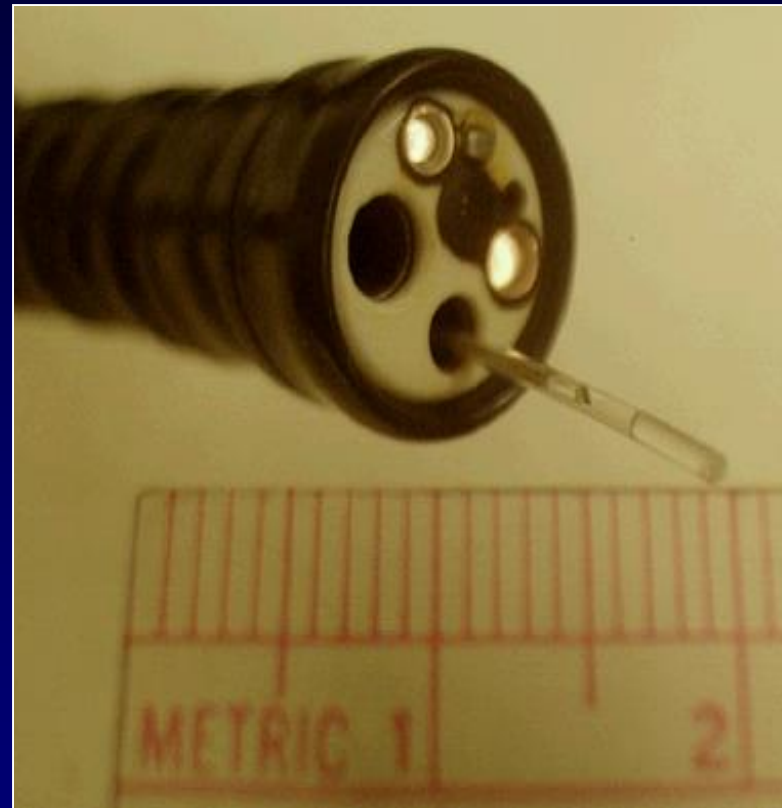
Prof. E. Grube - Siegburg Heart Center  
LightLab Imaging 0.014" ImageWire



# Imagem de OCT Endoscópica



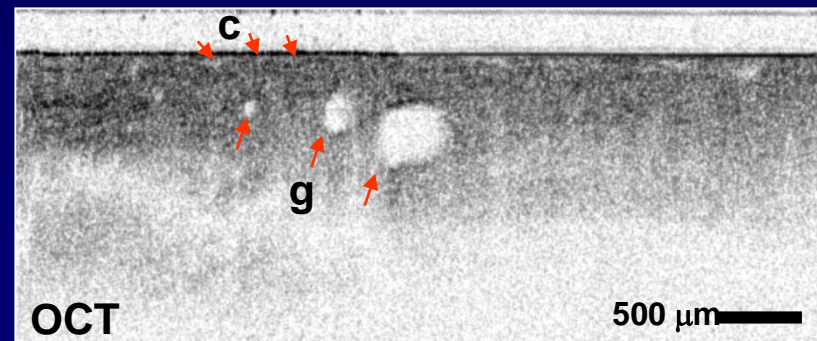
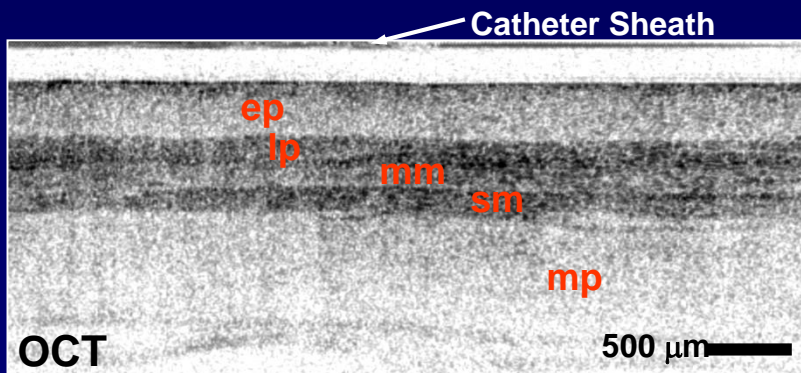
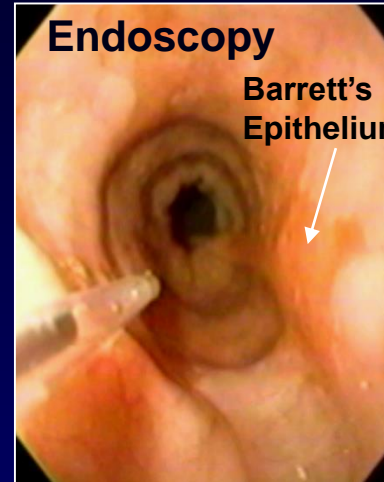
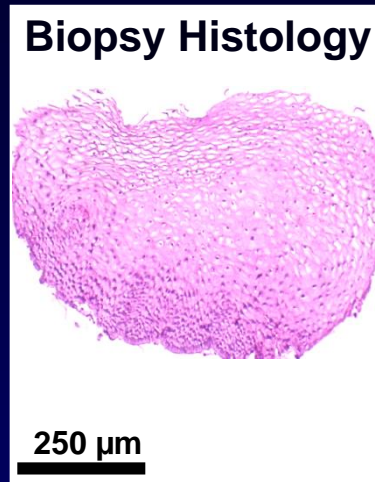
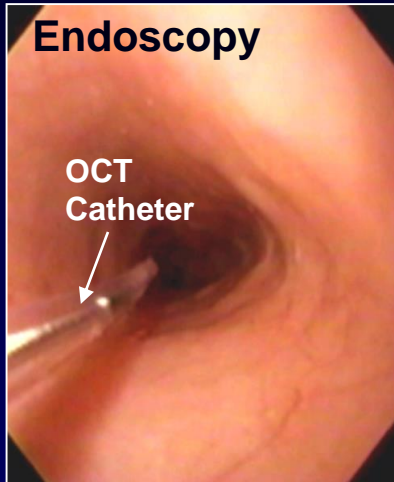
A sonda é introduzida pela porta de biópsia através de um endoscópio padrão.



# Esôfago normal e pré-cancerígeno

## Normal

## Barrett's



ep: epithelium  
mm: muscularis mucosa  
mp: muscularis propria

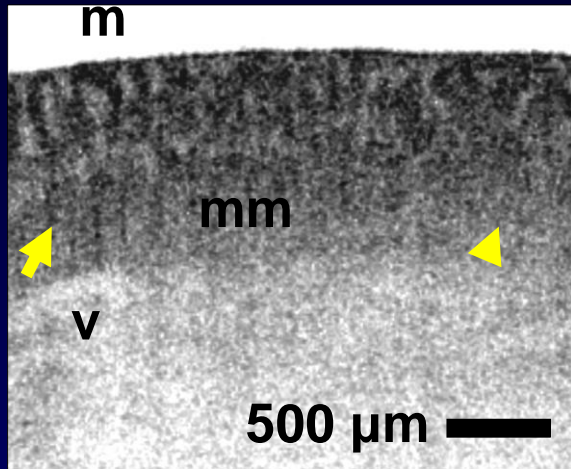
lp: lamina propria  
sm: submucosa

c: crypts

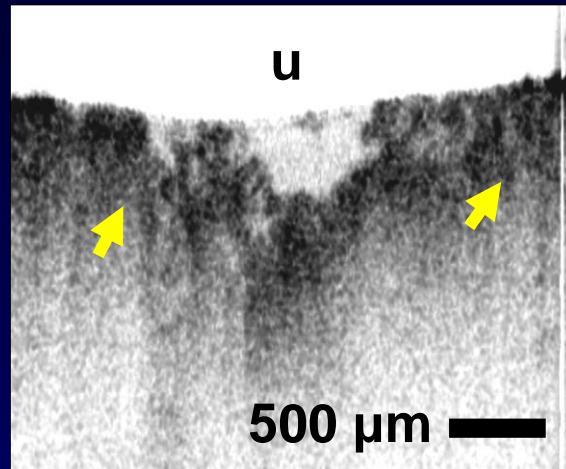
g: glands

# Câncer de cólon *Ex vivo*

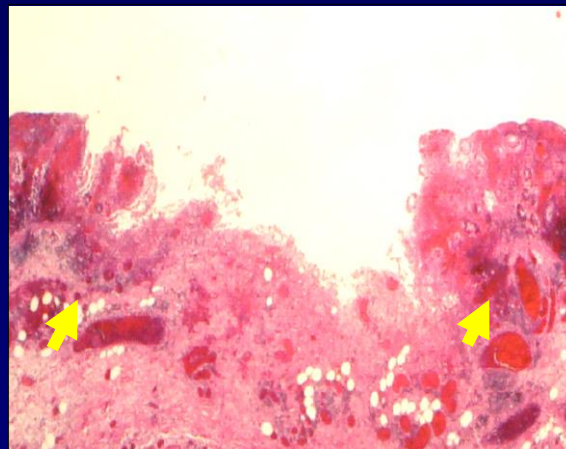
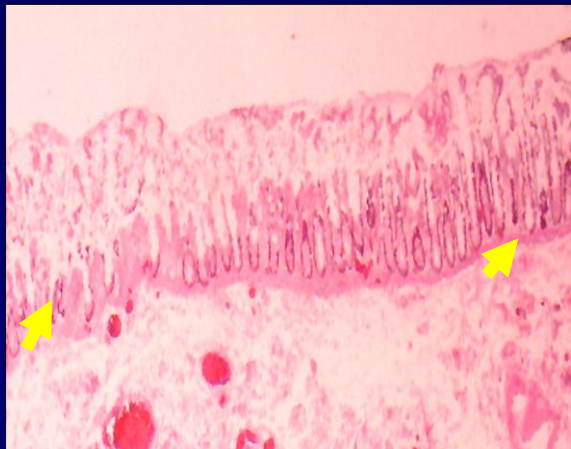
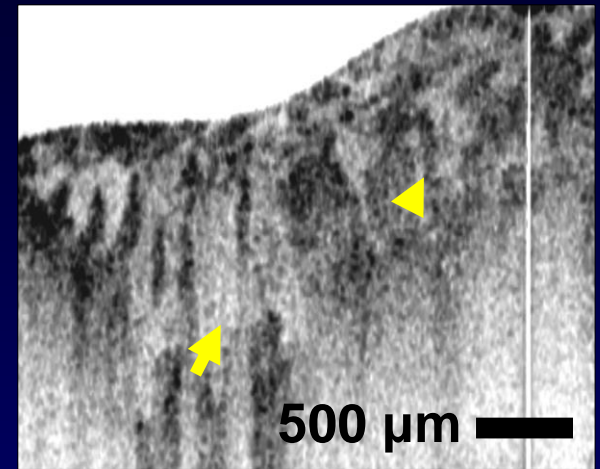
Normal Colon



Ulcerative Colitis

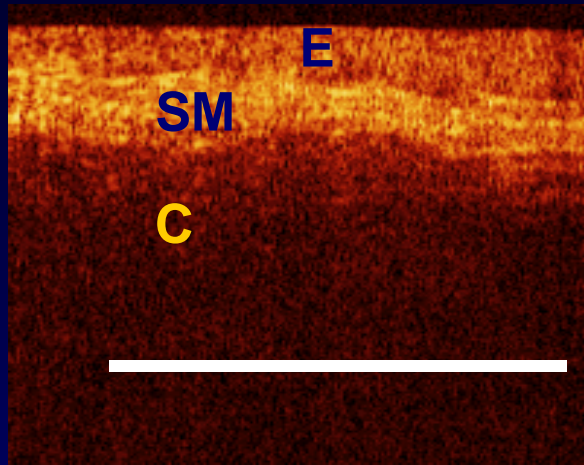


Adenocarcinoma

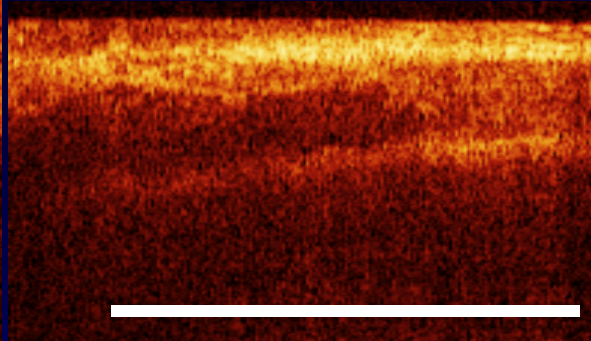


# OCT em Broncoscopia

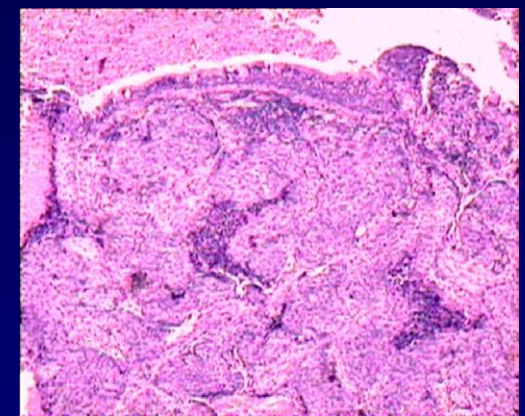
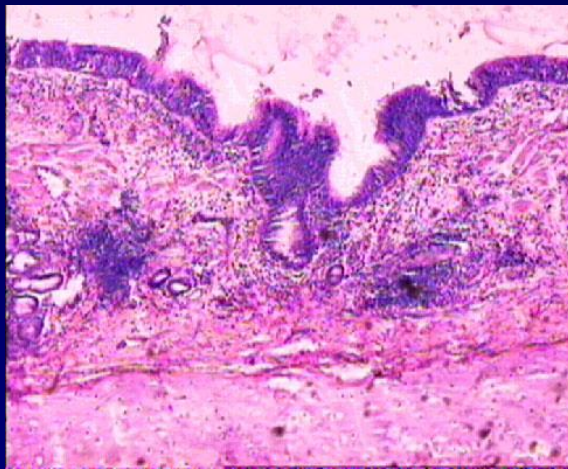
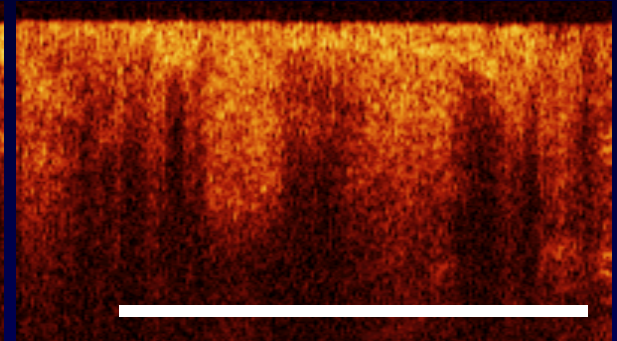
Normal bronchus



Edema



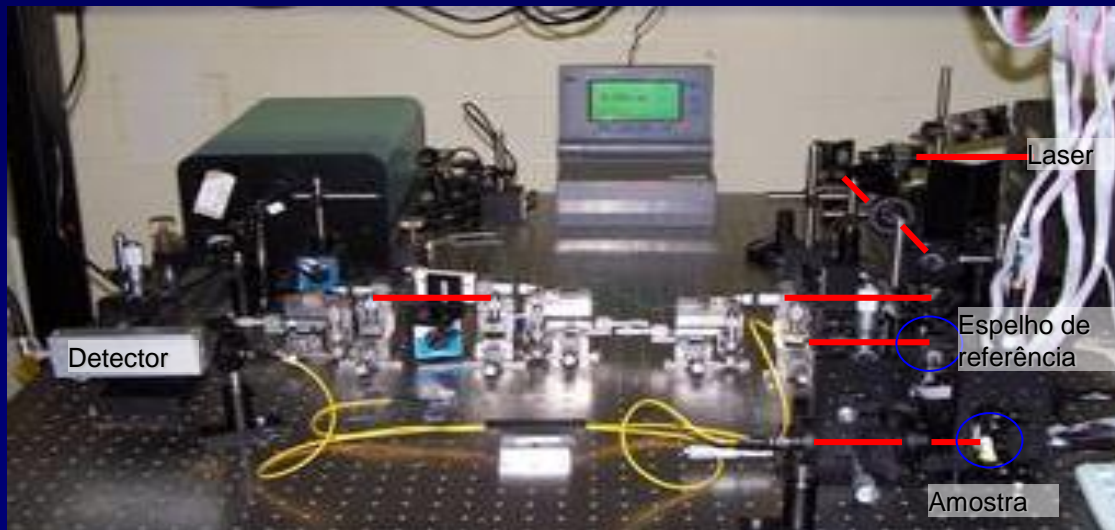
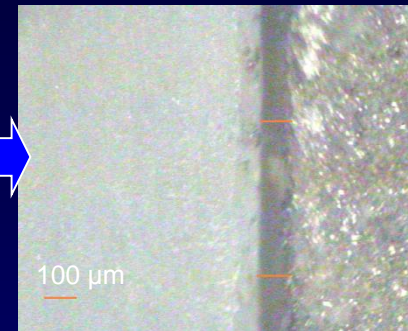
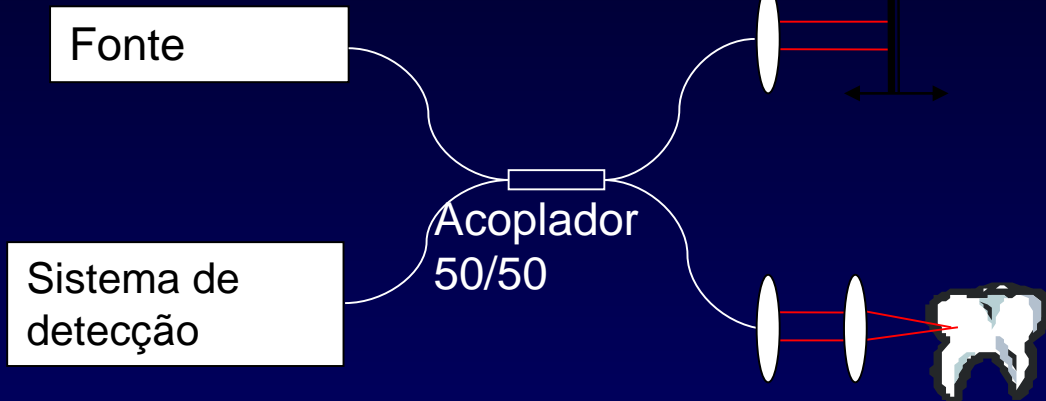
Carcinoma



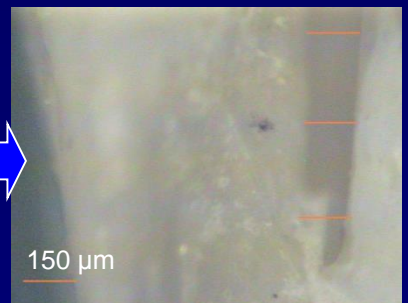
(epithelium E, submucosa SM, cartilage C)

# Análise de restaurações dentárias

Espelho móvel de referência



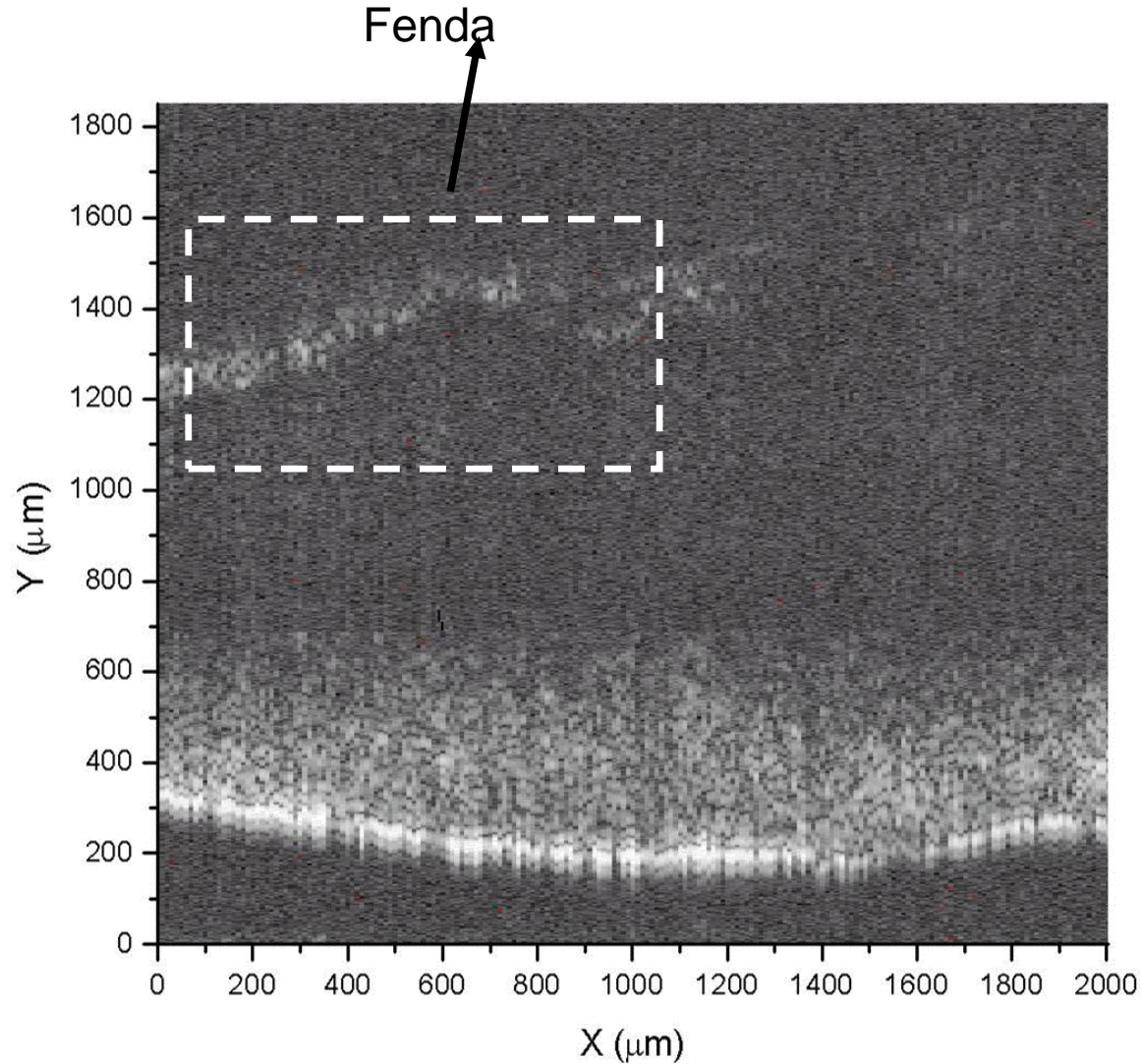
Fenda



# Análise de restaurações dentárias

Superfície  
Ar / Esmalte

Fenda  
120 $\mu\text{m}$



# Pontos importantes

- Técnica não invasiva de diagnóstico
- OCT consegue visualizar patologias com resolução inédita
- Melhoria no entendimento de patogêneses
- Promessa de melhoria para medidas quantitativas
- Pode acompanhar a progressão de doenças

<https://www.youtube.com/watch?v=J014Q5z7rJg>

<https://www.youtube.com/watch?v=HJnNJIUPm4s>

<https://www.youtube.com/watch?v=VyePASErr5Q>