Coherent Endoscopic Metrology

Medical Centre, University of Münster
Laboratory of Biophysics

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Proximal endoscopic ESPI

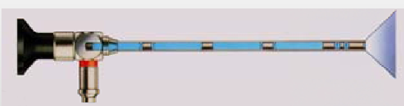
Motivation

ESPI system outside the cavity
(proximal arrangement):

- Standard CCD cameras and standard endoscopes can be used
- Modular concept

Proximal endoscopic ESPI

Rigid endoscopes



- illumination and inspection of cavities and organs
- minimal invasive operations by visual control
- special optics (e. g. rod lens optics)
- distal und proximal systems

Proximal endoscopic ESPI

Flexible endoscopes

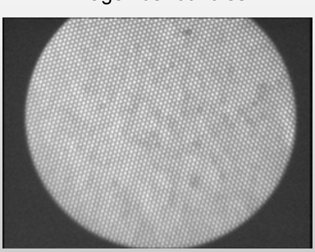
Storz bronchoscope
diameter ≈ 6 mm

Storz endoscope 1180 A 0°,
diameter ≈ 3 mm:

Proximal endoscopic ESPI

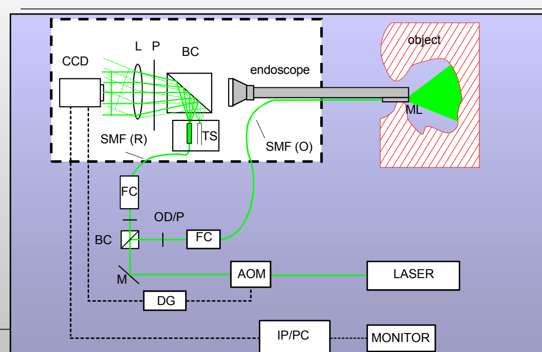
Flexible endoscopes

“image fiber bundles”



Prox. SPS endoscopic ESPI

Endoscope-ESPI-camera-system



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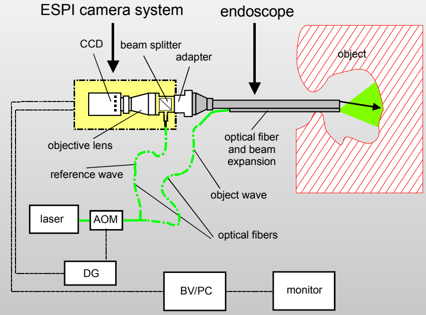
Prox. endoscope ESPI camera system



SPS endoscopic ESPI

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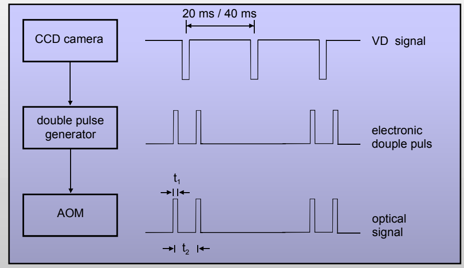
Exposure scheme



exposure time t_1 and time delay t_2 between two exposure
repetition rate : 12,5 / 25 Hz

SPS endoscopic ESPI

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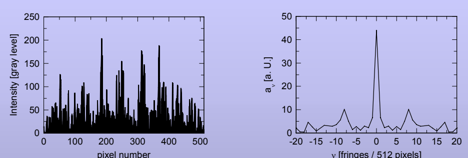
Automatic determination of the correlation fringe contrast *V* by Fourier transformation



$$V = \frac{2|a_\nu|}{a_0}$$

a_ν : frequency part of fringes

a_0 : zero order

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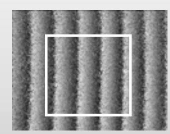
Quantification of the phase difference noise

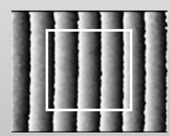
Standard deviation $\sigma_{\Delta\phi}$

$$\sigma_{\Delta\phi} = \sqrt{\frac{1}{(N \cdot M) - 1} \sum_{i=1}^{N} \sum_{j=1}^{M} \left(\Delta\phi_{i,j} - \overline{\Delta\phi_{i,j}}\right)^2}$$

$\Delta\phi_{i,j}$ phase difference

$\overline{\Delta\phi_{i,j}}$ phase difference filtered twice by a 9 x 9 pixel (sin-, cos-) average filter





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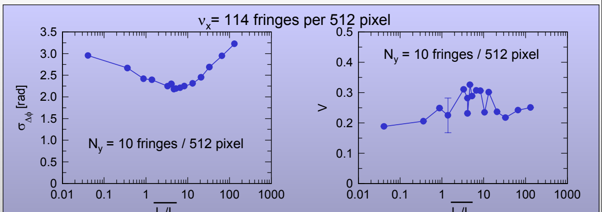
Intensity ratio between reference wave and object wave (tilted metal plate)



standard deviation contrast

=> Optimum intensity ratio: $\overline{I_R/I_O} \approx 5 - 10$

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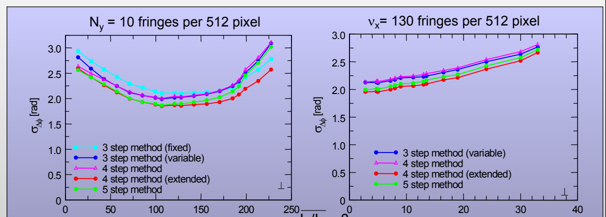
Comparison of different algorithms for phase difference evaluation (metal plate)



=> Optimum carrier frequency:
$\nu_x \approx 100 - 150$ fringes per 512 pixel $\sigma_{\Delta\phi,min} \approx 2{,}0$ rad

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Exposure time t_B and frequency f of object motion (loudspeaker)

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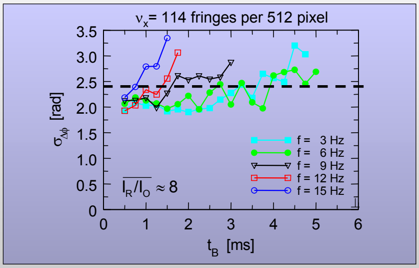

=> For t_B ≈ 0.5 ms $\sigma_{\Delta\phi}$ is found in the range of the values for static objects

=> It is necessary to reduce the exposure time further

Prox. SPS endoscopic ESPI

Influence of wet surface (drying process of a wet tilted metal plate)

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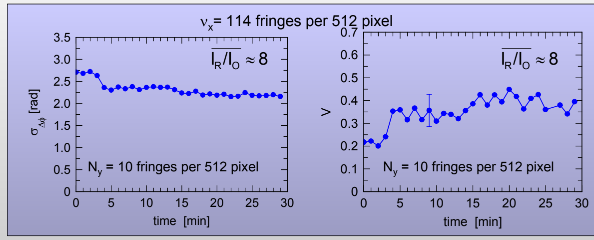

standard deviation contrast

=> Increase of $\sigma_{\Delta\phi}$ and decrease of V

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Displacement detection

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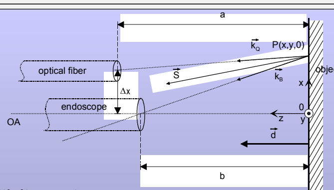

$\vec{S}$: sensitivity vector

$\vec{d}$: displacement vector

$$\Delta\phi = \frac{2\pi}{\lambda}\vec{S}\cdot\vec{d}$$

$$d_z(x,y) = \Delta\phi(x,y)\cdot\frac{\lambda}{2\pi\left(\frac{a}{\sqrt{(\Delta x - x)^2+y^2+a^2}}+\frac{b}{\sqrt{x^2+y^2+b^2}}\right)}$$

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Correction of radial distortions

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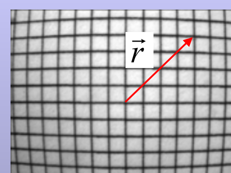
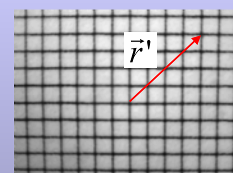
Distortion δ_r



prox. endoscope optics

$$\delta_r = K_1 r^3 + K_2 r^5 + \ldots$$

Correction



after correction

$$\vec{r}\,' = \vec{r} + \vec{\delta}_r$$

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Displacement detection (tilted metal plate)

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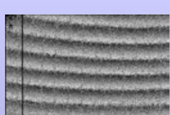

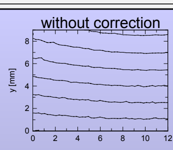

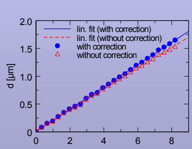

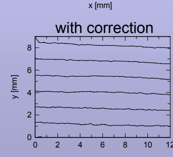

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Manually stimulated membrane

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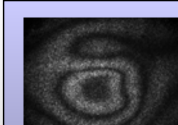
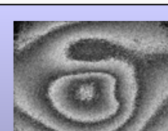
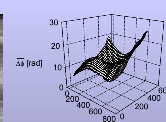
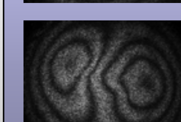
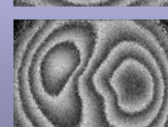
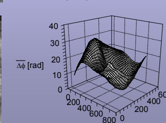












t_B = 0,5 ms distance between two records: 5 ms

Prox. endoscopic ESPI

Applications

Investigation of biological artificial heart valve prostheses:
Motivation

- implants for the human heart;
- particular compatible toward patients;
- shorter lifespan;
- individuality of each prostheses.

=> Requirement of careful selection through methods of non-destructive quality control.

Prox. endoscopic ESPI

Biological heart valve prostheses (in vitro)

front

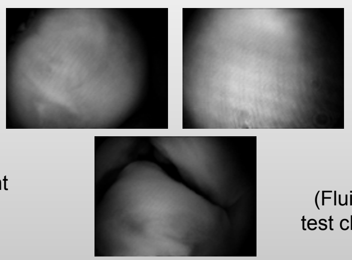
back

„Bioimplant“, St. Jude Medical, Inc.

Prox. endoscopic ESPI

Biological heart valve prostheses (in vitro)

Flexible endoscope optics: bronchoscope



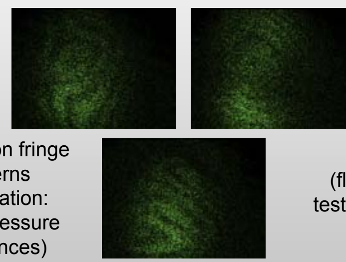
White light images

(Fluid filled test chamber)

Prox. endoscopic ESPI

Biological heart valve prostheses (in vitro)

Flexible endoscope optics: bronchoscope



correlation fringe patterns (stimulation: liquid pressure differences)

(fluid filled test chamber)

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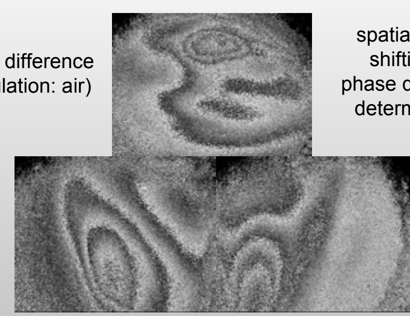
Biological heart valve prostheses (in vitro)

phase difference (stimulation: air)

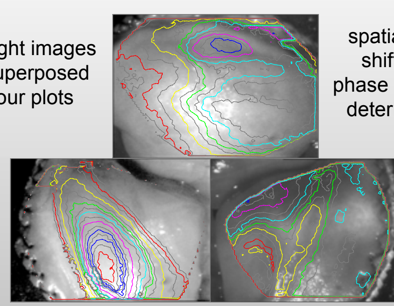


spatial phase shifting for phase difference determination

Prox. endoscopic ESPI

Biological heart valve prostheses (in vitro)

white light images with superposed contour plots



spatial phase shifting for phase difference determination

Prox. endoscopic ESPI

Biological heart valve prostheses (in vitro)

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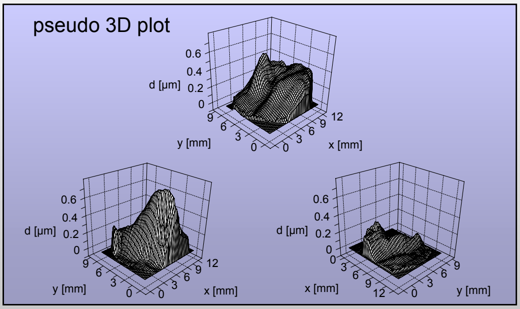
pseudo 3D plot



Prox. endoscopic ESPI

Applications

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Investigation of porcine stomach and human gastric wall:

Motivation

- early recognition of cancers in the gastrointestinal tract;
- minimally invasive detection of changes in tissue elasticity (even underneath the visible surface);
- “endoscopic taction”

Prox. endoscopic ESPI

Porcine gastric wall (in vitro)

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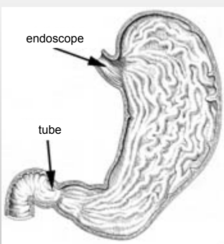

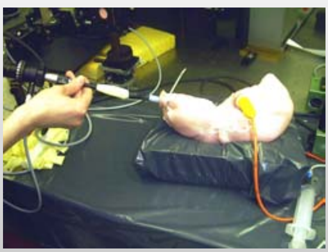

inflation of air
stimulation: test needle

Prox. endoscopic ESPI

Porcine gastric wall (in vitro)

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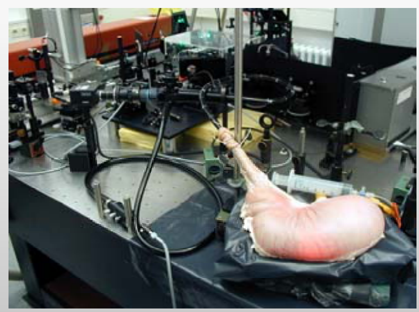

Prox. endoscopic ESPI

Porcine gastric wall (in vitro)

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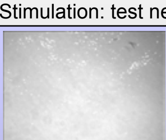
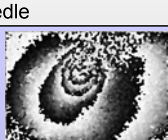
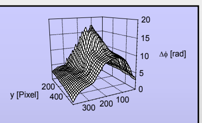
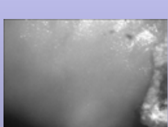
Stimulation: test needle

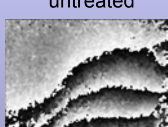


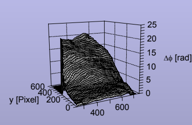




untreated







treated with Histoacryl

Prox. endoscopic ESPI

Human stomach gastric wall (in vitro)

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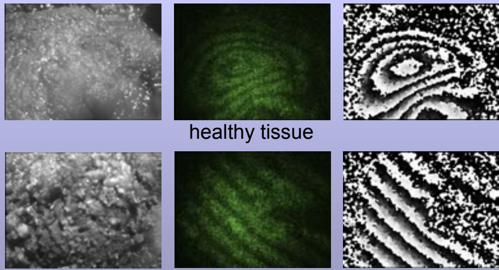
human gastric wall with cancer (lymphoma)

Prox. endoscopic ESPI

Human stomach gastric wall (in vitro)



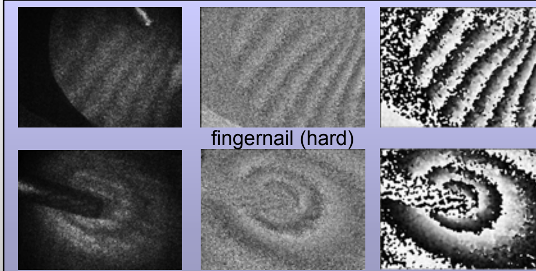
healthy tissue

cancer

Prox. endoscopic ESPI

Human hand (in vivo)

Stimulation: test needle



fingernail (hard)

fingertip (soft)

Distal endoscopic ESPI

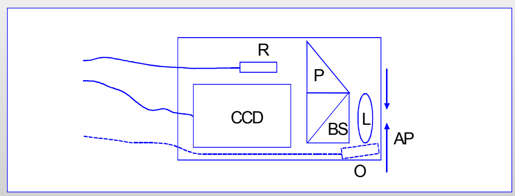
Motivation

ESPI system in the endoscope tip, miniaturization (distal arragement):

- Smaller speckle size against proximal endoscope imaging systems
  ==> Increase in resolution to microscopic dimensions
- Avoidance of phase unstable image fiber bundles
- Avoidance of aberrations and distortions of proximal endoscope imaging systems

Distal endoscopic ESPI

Principle

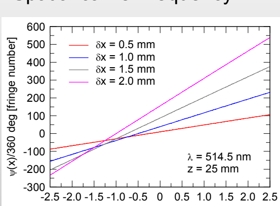


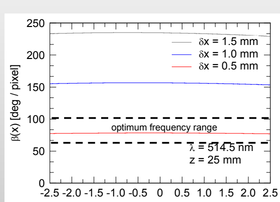
- Color CCD sensor 1/4”, 1/6”
- 180 degree redirection of the reference wave

Distal endoscopic ESPI

Adjustment of the spatial carrier frequency

Spatial carrier frequency:





$\delta x = 0.5$ mm $\Rightarrow \approx$ 170 fringes per 4.4 mm (780 CCD pixels)
$\approx$ 112 fringes per 512 Pixel $\approx$ 90 deg. per pixel

Distal endoscopic ESPI

Adjustment of the speckle size

Determination of the required aperture:

speckle size d_{sp}

$$d_{sp} \approx 1.22 \cdot \lambda \frac{l}{D_A}$$

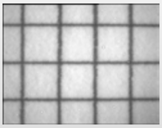
λ : light wavelength
l : distance to imaging lens
D_A: diameter of the aperture

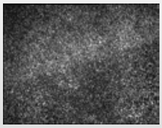
$l \approx 20$ mm, $\lambda = 514.5$ nm:

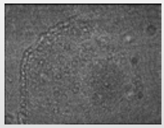
$D_A = 0.25$ mm: $d_{sp} \approx 50$ µm $\Rightarrow \approx$ 10.0 CCD pixel
$D_A = 0.50$ mm: $d_{sp} \approx 25$ µm $\Rightarrow \approx$ 5.0 CCD pixel
$D_A = 0.70$ mm: $d_{sp} \approx 17$ µm $\Rightarrow \approx$ 3.7 CCD pixel

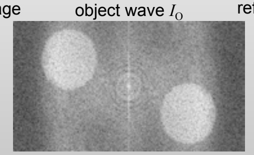
Distal endoscopic ESPI

Adjustment of the spatial carrier frequency


white light image


object wave I_O

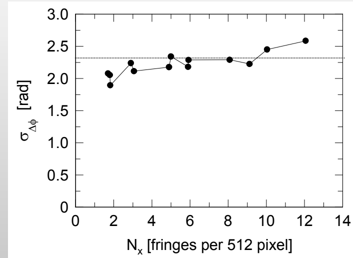

reference wave + object wave $|E_O+E_R|^2$


2D FFT

Distal endoscopic ESPI

Distal ESPI sensor (1/4" CCD sensor)

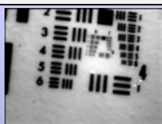
Standard deviation $\sigma_{\Delta\phi}$ of the phase difference vs. fringe density N_x :



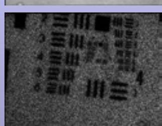
Distal endoscopic ESPI

1/4" CCD sensor

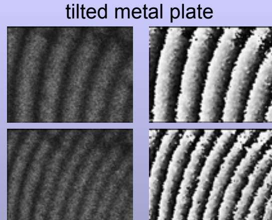
white light image



object wave



tilted metal plate

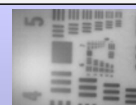

correlation fringes   filtered phase difference

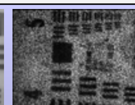
USAF 1951 reflection type test chart
group 5-6 $\Rightarrow$ 8.7 µm

Distal endoscopic ESPI

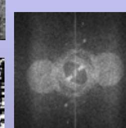
1/6" CCD sensor

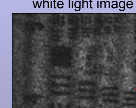
millimeter grating

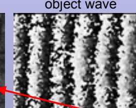

white light image


object wave

2D FFT




correlation fringes


filtered phase difference

tilted test chart

USAF 1951 reflection type test chart
group 6-1 $\Rightarrow$ 7.8 µm

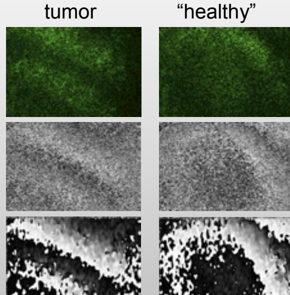
Distal endoscopic ESPI

Distal ESPI sensor

Human stomach
with adenocarcinoma:

stimulation with test needle

tumor   "healthy"



Microscope ESPI

Motivation

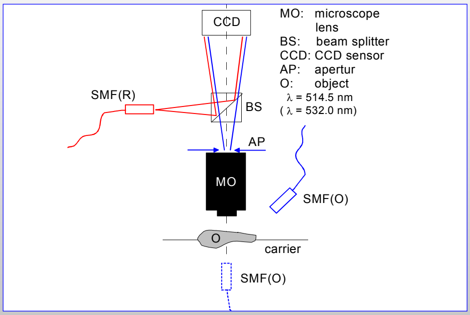
Enhancement of microscopy by additional high resolution for:

- detection and visualization of movements and displacements
- detection of refractive index changes

==> more information about tissues and cells

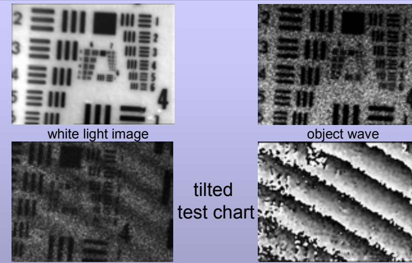
Microscope ESPI

Principle



Microscope ESPI

Magnification 10 x,
USAF 1951 reflection type test chart



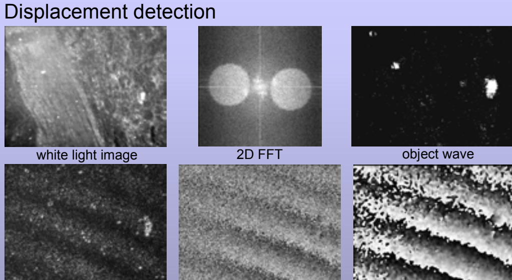
white light image, object wave, correlation fringes, tilted test chart, filtered phase difference

group 6-1 ⇒ 7.8 µm

Microscope ESPI

Magnification 10 x, intestine carcinoma

Displacement detection

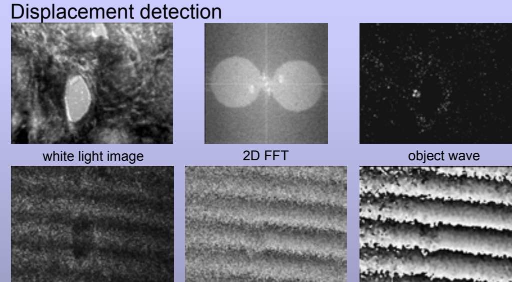


white light image, 2D FFT, object wave, correlation fringes, phase difference, filtered phase difference

Microscope ESPI

Magnification 10 x, carcinoma of ovary

Displacement detection

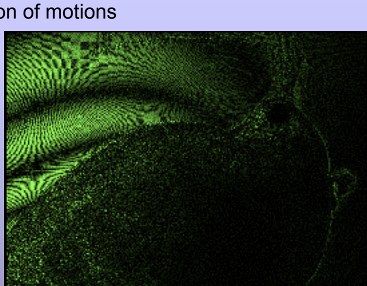


white light image, 2D FFT, object wave, correlation fringes, phase difference, filtered phase difference

Microscope ESPI

Magnification 10 x, “water flea” in vivo

Detection of motions



Conclusions

- ESPI is a tool for non destructive quality control of biological tissues
- Differences in elasticity of biological tissues are detectable even underneath the visible surface
- Lateral resolution in microscopic range
- In vivo application possible

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