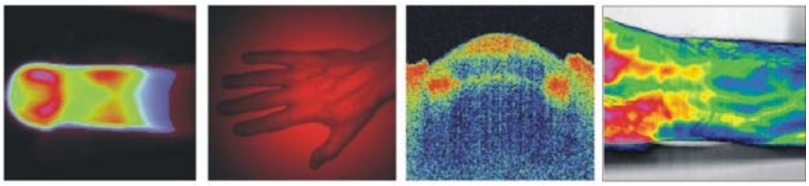
Applied Optoelectronics in Medicine

Aplikovaná optoelektronika v lékařství

Interdisciplinary course at the CTU Prague (P317APL-E, W, 4 credits)



Prof. Dr.-Ing. Vladimir Blazek, Dr. h.c.
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Helmholtz-Institute for Biomedical Engineering, RWTH Aachen University
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AOM course contents in the winter term 2016-2017

1. Introduction, HF technology & OE applications in BME

Chalenges, targets and applications of optoelectronics in focus of medical diagnostics. Noninvasive biosignal acquiring. Historical evolution and state of the art optoelectronic sensor examples.

2. Light and life – ecological and biophysical aspects

The earth in radiation field of the sun. Biosphere windows to the space. Earth´s energetic drive. Basic radiation laws. Optical radiation & human skin.

3. Metrological aspects in optoelectronics, light perception

Definitions of metrology, optoelectronics and photonics. Spectral radiation parameters, radiometry, photometry. Physiological optics, human eye as a high sensitivity "photo detector array", spectral sensitivity. Predecessor models of the human eye in the animal kindom.

4. Spectral reflection, transmission and scattering behavior of biotissue

Regular and diffuse reflection / transmission. Spectral optical devices. Integrating sphere theory. Experimental setup for spectral skin reflectance & transmittance detection. Tissue color analysis.

5. Tissue optics, describing light distribution in tissue, optical skin model

Fundamentals and basic definitions. Approaches for describing the photon penetration in tissue: numerical methods, radiation transport theory, Kubelka-Munk theory, Monte-Carlo method.

6. Biophysics of the human blood circulation, modelling haemodynamics
Human haemodynamics – a sophisticated transportation system, evolution steps, blood pressure terms, studies of peripheral haemodynamics using ultrasound. Simulation of the human blood dynamics using electrical-haemodynamical analogon and theory of electric lines.

7. Optoelectronic sensor concepts for functional vascular diagnostics – part I
Photoplethysmography (PPG) – basic facts and examination tests. Monitoring of peripheral venous blood volume changes. Venous muscle pump test. Venous occlusion test.

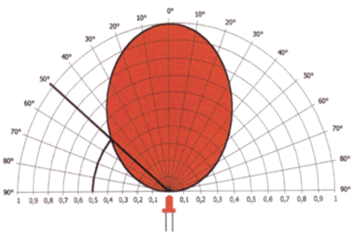
8. Optoelectronic sensor concepts for functional vascular diagnostics – part II
Non-invasive monitoring of distal blood pressure. Photoplethysmographic registration of peripheral arterial blood volume pulse. Multi wavelength plethysmography, arterial pulse oximetry. Rhythmical phenomena in dermal blood perfusion.

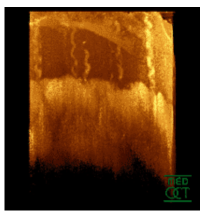
9. Optical imaging methods in medical diagnostics – part I
Historical arche types. IR photography, IR diaphanoscopy, laser Doppler perfusion imaging (LDPI) – concepts and typical applications.

10. Optical imaging methods in medical diagnostics – part II
Photoplethysmography Imaging (PPGI) and optical coherence tomography (OCT) – basic facts, realisation strategies, approaches and applications.

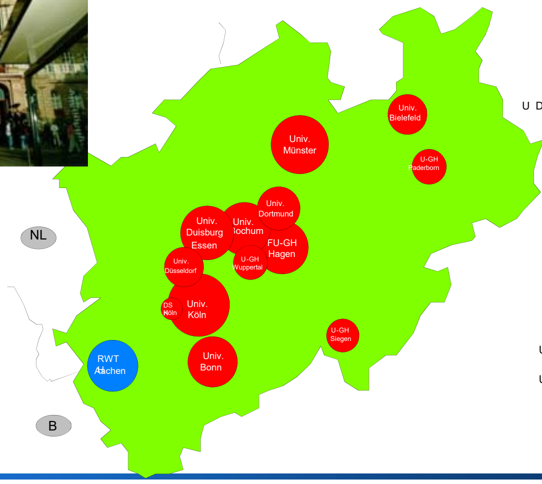
Learning aims of the first AOM lecture

- Biomedical Optics (BMO) and Photonics in relation to Biomedical Engineering
- Classification of optical radiation in the EM spectrum
- Optoelectronic Sensor Concepts - Introduction and Measurement Capabilities in medical diagnosis
- Research group BMO at MedIT - current R&D projects



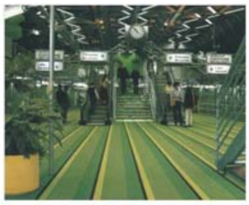


RWTH: Rhineland-Westphalia Technical University, founded in 1870



U Köln	42.075
U Münster	36.688
U Duisburg -Essen	30.727
FU-GH Hagen	37.494
U Bochum	30.849
RWTH Aachen	39.260
U Bonn	26.577
U Dortmund	21.110
U Düsseldorf	16.560
U Bielefeld	17.844
U-GH Paderborn	13.092
U-GH Wuppertal	13.822
U-GH Siegen	12.116
DSH Köln	5.019

... own Medical Faculty and University Hospital at RWTH ...



German Excellence Universities

TU9 German Institutes of Technology

- RWTH Aachen **E**
- TU Berlin
- TU Braunschweig
- TU Darmstadt
- TU Dresden **E**
- Leibniz Universität Hannover
- Karlsruhe Institute of Technology
- TU München **E**
- Universität Stuttgart

RWTH 2020: Meeting Global Challenges

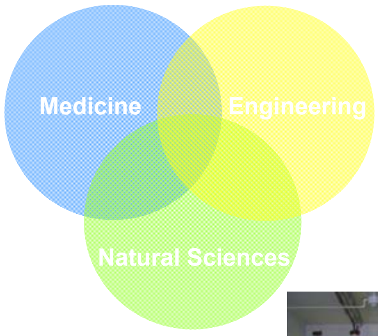
RWTH Aachen Campus I – Melaten
270.000 m²
start of construction in 2009

9 Exzellenz-Cluster

RWTH Aachen Campus II – Westbahnhof
276.000 m²
start of construction in 2012

6 Exzellenz-Cluster

Biomedical Engineering:
BR & IC activities at RWTH



- Faculty of EE and IT
- Faculty of ME
- Faculty of M, CS and NS
- Faculty of Medicine
- Faculty of CE
- Faculty of GR and ME

BME related education activities at RWTH:

- Faculty of EE and IT
- Faculty of ME
- Faculty of Medicine (interfacultative,
  interdisciplinary,
  international) since 2003

RWTH Master Programme **Biomedical Engineering:** Syllabus

1st semester	2nd semester
Basics of Medicine Basics of Engineering Basics of Natural Sciences	Biomaterials / Sensors & Microsystems Tissue Engineering
General Compulsory Courses	General Compulsory Courses
Optional Courses	Optional Courses

3rd semester	4th semester
Medical Imaging / Guided Therapy Artificial Organs / Devices	Master Thesis (6 month)
General Compulsory Courses	
Optional Courses	

Additional: **Internship (8 weeks during lecture-free period)**

RWTH Master Programme **Biomedical Engineering:** Courses

1th Module: General courses depending on first degree

General Courses	L	E	P	First Degree in Med	MeE	ElE	Bio	Che	Phy
Anatomy	3	-	-		#	#	#	#	#
Practical Course Anatomy	-	-	1		#	#		#	#
Physiology	3	-	-		#	#	#	#	#
Practical Course Physiology	-	-	1		#	#		#	#
Chemistry	2	-	1		#	#			
Biochemistry	2	-	1		#	#			#
Biology/Molecular Biology	2	-	1	#	#	#		#	#
Electrical Engineering	2	2	-	#	#		#	#	#
Mechanics/Biomechanics	2	2	-	#			#		#
Fluid Mechanics	2	2	-	#		#	#	#	#
Materials Science and Processing	2	1	-	#					
Mathematics	2	2	-	#	#	#	#	#	
Physics	2	-	-	#			#		
Control Engineering	1	1	-	#			#	#	
∑ SWS General Courses				26	25	25	26	25	26

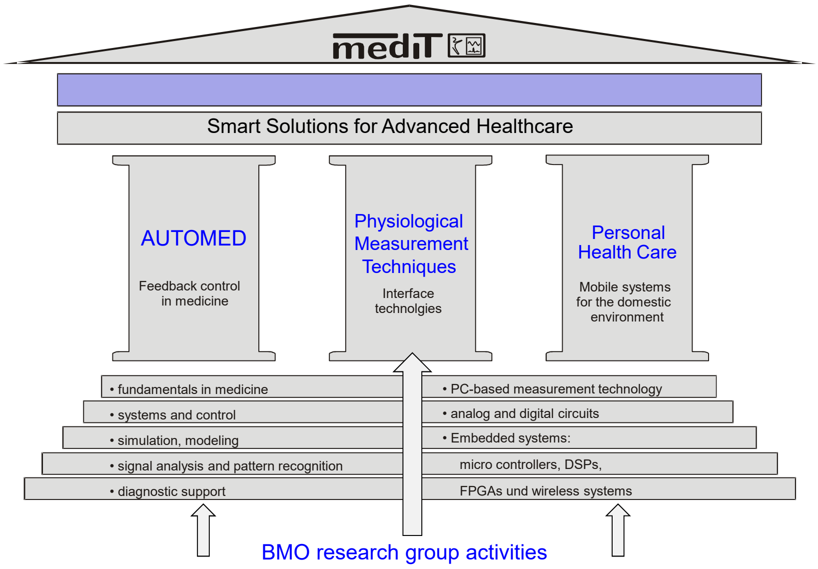
SWS – semester hours (**S**emester**w**ochen**s**tunden)
L – Lecture, E – Exercise, P – Practical Course

Med – Medicine
MeE – Mechanical Engineering
ElE – Electrical Engineering
Bio – Biology
Che – Chemistry
Phy – Physics

RWTH Master Programme **Biomedical Engineering:** Courses

2nd Module Tissue Engineering	Cell Culture and Tissue Engineering Biomaterials/ Biocompatibility Bioanalytics
3rd Module Medical Imaging / Guided Therapy	Medical Imaging, Molecular Imaging Basic Physics of Medical Imaging Image Processing and Management Image Guided Therapy / Navigation / Robotics
4th Module Artificial Organs / Devices	Artificial Organs and Implants / Assist Devices Biomedical Sensors and Microsystems
5th Module General Compulsory Courses	Basics German Language Course Ethics Intellectual Property and Regulatory Affairs
6th Module Optional Courses	Pre-course Mathematics / Neurosciences / Intensive care / Monitoring / Mechanics of living tissue Immunology & Microbiology / Med. Laser Techn.
7th Module Master Thesis	

Philips Chair for Medical Information Technology at RWTH



Helmholtz-Institute for Biomedical Engineering at RWTH

- Biomaterials: Prof. Elling (Faculty of Natural Sciences, Mathematics &Computer Science)
- Medical Engineering: Prof. Radermacher (Faculty of Mechanical Engineering)
- Medical Information Technology: Prof. Leonhardt (Faculty of Electrical Engineering)
- Applied Medical Engineering: Prof. Schmitz-Rode (Medical Faculty)
- Cell Biology: Prof. Zenke (Medical Faculty)
- Biointerfaces: Prof. Jahnen-Dechent (Medical Faculty)
- Molecular Imaging: Prof. Fabian Kiessling (Medical Faculty)

Hermann von HELMHOLTZ (1821-1894)

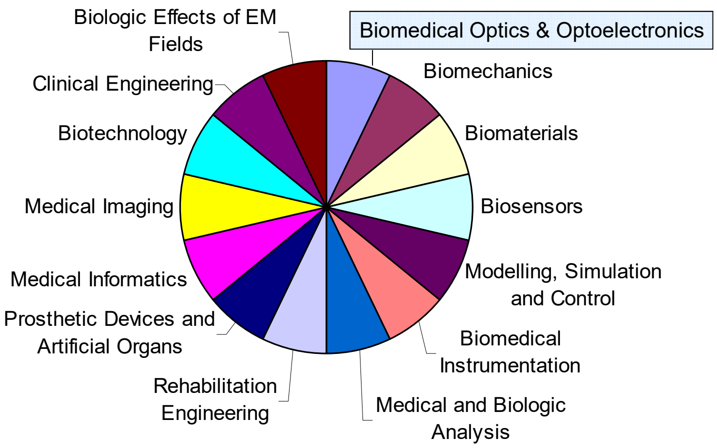
Biomedical Engineering
A Definition

"Bioengineering is the broad umbrella term used to describe this entire field, bioengineering is usually defined as a basic research-oriented activity closely related to medicine, biotechnology and genetic engineering."

"It is clear that bioengineers of the future will have a tremendous impact on the quality of human life."

Pacela: Bioengineering Education Directory. Quest Publishinh Co., 1990

The Disciplines of Biomedical Engineering



Biomedical Engineering at the RWTH Aachen

Mission & Vision:

"To support interdisciplinary and picked engineering education,
to integrate teaching and research across of humanities and medicine,
to organise new branch of knowledge and technological development,
to advance the science and technology in medicine,
to focus on areas of our own prime excellence and leadership,
to establish the RWTH as a pre-eminent school at the intersection of
engineering, medicine and life science
and
to help the sick ..."

Studies on BME acceptance in Germany

VDE-Studie zur Technikakzeptanz
03/2009

Für die Repräsentativbefragungen zur Technikakzeptanz wurden 1.000 in Deutschland lebende Personen ab 14 Jahren telefonisch befragt. U. a. wurden auch Gender- und Altersunterschiede festgestellt.

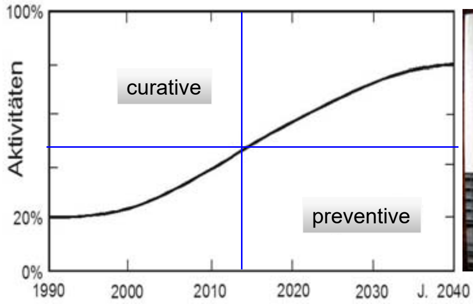
VDE-Studie MedTech 2020
09/2009

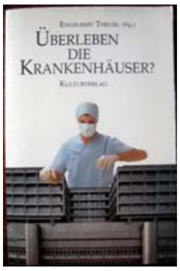
Ziel der Zukunftsstudie ist es, Technologie- und Forschungstrends, Innovationstreiber u. Technologieposition im internationalen Wettbewerberfeld, Erfolgsfaktoren, Chancen u. Perspektiven sowie Innovationshemmnisse im eigenen Land auszumachen.

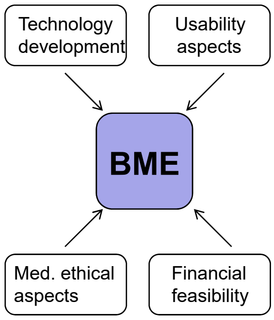
Current trends in Medicine - „3N“-Diagnostics:

Non-invasive, **N**on-burden, **N**on-expensive acquisition of functional bio-signals

From this follow new research and development challenges for the Biomedical Technology.





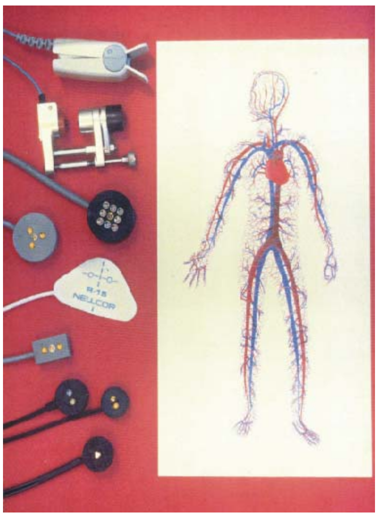


From: E. Theurl (10991): Überleben die Krankenhäuser?

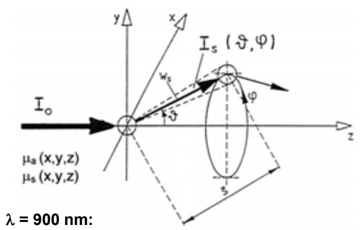
MedIT/BMO research interests I:

Fundamental questions on photon migration in bio-tissue

- How does optical radiation pass through high scattered biological objects?
- Which spectral range is useful?
- How does the detected radiation depend on the blood volume in transilluminated area?



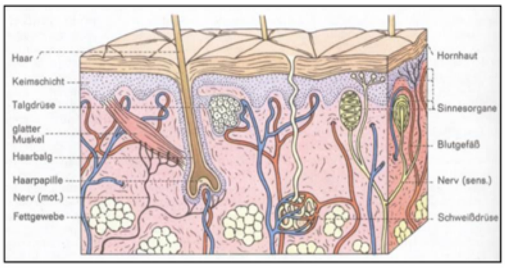
Light propagation in bio-tissue

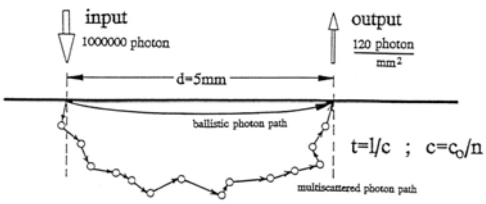


λ = 900 nm:
mean free photon path: s = 0.24 mm
absorption probability : w_a = 2 % per collision
scattering probability : w_s = 98 % per collision

Remember:

Probability of a photon scattering in bio-tissue is about 50 times higher as the probability of absorption.





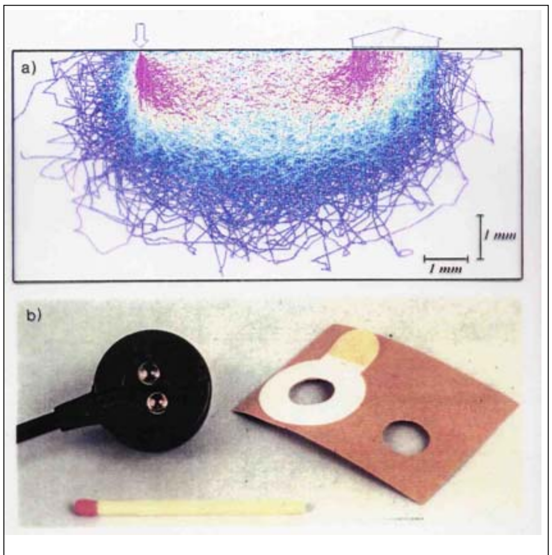
Speed of light in tissue (by n=1.5): **c = 2x10^8 m/s**
Shortest flight time of balllistic photons
(by l=d=5 mm)**: t = 25 psec**

“Ray tracing” simulation (Monte-Carlo Method) in optical range:

Infrared light distribution in skin-phantom simulated for a classical optoelektronic sensor (Fig. **b**, 1x IR-LED; 1x Si-PD; both with lenses)

Distance Light source-Photodetector: 5 mm
Penetration depth: up to aprox. 5mm at λ = 900 nm
Volume of P/T interaction: aprox. 150 mm^3

Shadow-projection of scattering photons which achieve the active sensor area (1516 from 3·10^6 photons).



Digression: Skin effect

$$J = J_S\, e^{-d/\delta}$$

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\,\sqrt{\sqrt{1+(\rho\omega\varepsilon)^2}+\rho\omega\varepsilon}$$

MedIT/BMO research interests II:

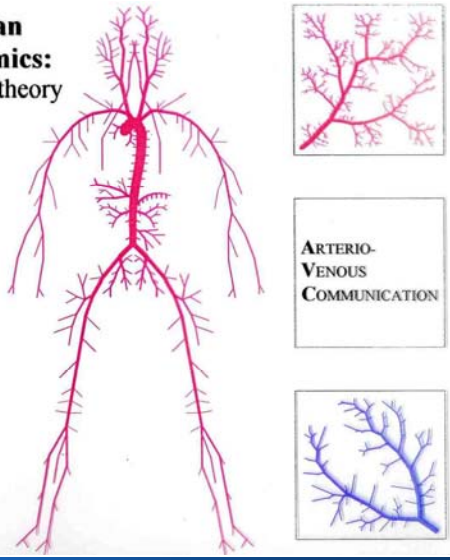
Computer modelling of human arterial and venous hemodynamics:
Simulation methods based on system theory

AIM:

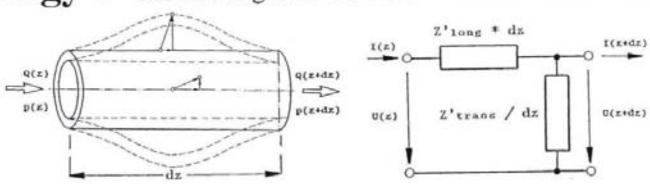
Realistic simulation of the physiological and pathophysiological dynamics of human vascular system

MODELLING PARAMETERS:

- Morphology of the vascular system
- Blood properties
- Properties of the vascular wall
- Peripheral vascular resistance
- Pathological alterations in vascular system



Analogy : vascular segment & electrical transmission line segment



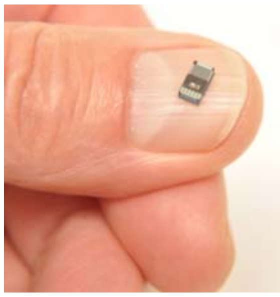
$$-\frac{\partial p}{\partial z} = \underline{Z}'_{long} \cdot Q \qquad -\frac{\partial Q}{\partial z} = \frac{1}{\underline{Z}'_{trans}} \cdot p$$

$$\underline{Z}_L = \sqrt{\underline{Z}'_{long} \cdot \underline{Z}'_{trans}}$$ ... Wave resistance

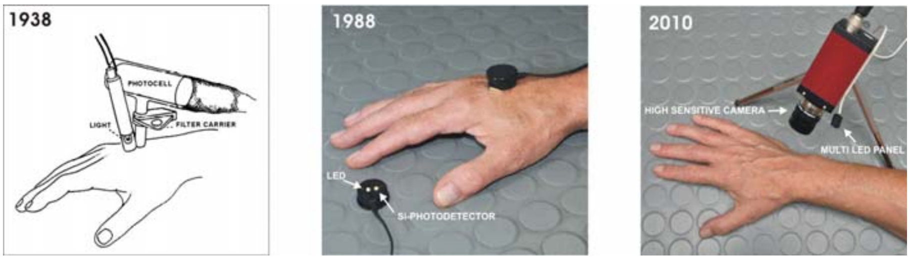
$$\gamma = \sqrt{\frac{\underline{Z}'_{long}}{\underline{Z}'_{trans}}}$$ ... Wave propagation coefficient

p ...	blood pressure [1 mmHg]	≙	**U** ...	electrical voltage [1 Volt]
Q ...	blood volume flow [1 cm³/s]	≙	**I** ...	electrical current [1 Ampere]
$\mathbf{R_p}$ ...	vascular resistance [1g/cm⁴s]	≙	**R** ...	electrical resistance [7.5*10⁻⁴ Ohm]

MedIT/BMO research interests III:
Design of optoelectronic sensors (OS) and their characterization



OS – historical precedents and current trends



Benefits of optoelectronic sensors in medical diagnostics:

- non-invasive and not disturbing method
- possibly automated, self-calibrating
- free region of interest
- small, light, hand-manageable, easy integration of different sensors
- low budget, disposable components
- flexible and reproducible application, long-term measurements possible
- multiple wavelengths recording possible (Optical Biopsy)
- Contact-less signal acquisition
- spatially resolved measurement possible (2D, Photoplethysmography Imaging)
- depth-resolved tissue-structure analysis possible (2D/3D,Optical Tomography).

> *Remember:*
>
> *Sensors are the hub and bridge of many BMI activities, they are germ cells for innovative system concepts in evidence based medical diagnostics*

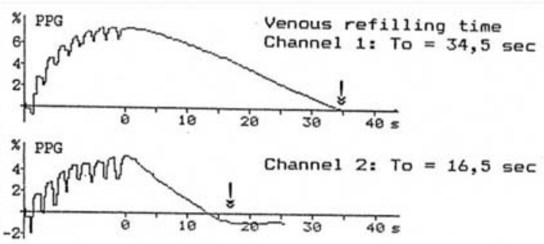
Some constructive implementations
of optoelectronic sensors

MedIT/BMO research interests IV:

Photoplethysmography (PPG): Non-invasive monitoring of dermal (venous and/or arterial) blood volume changes

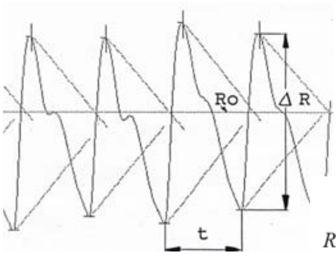
a) Venous hemodynamics

(PPG muscle pump test)



b) Arterial hemodynamics

(peripheral heart beat synchronous blood volume pulsation)



$$GPI = \frac{\Delta R}{t \cdot R_0}$$

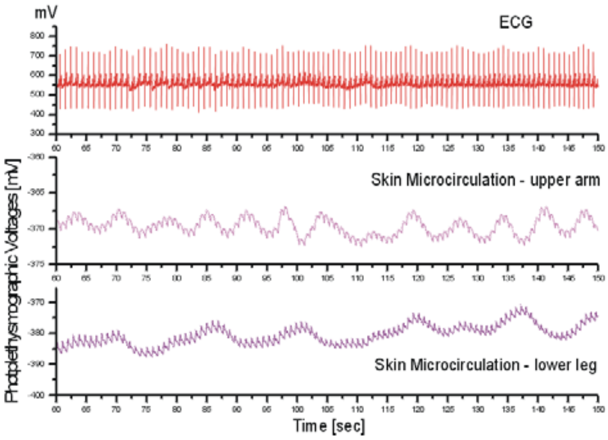
$$\overline{RR} = \frac{\sum_{i=1}^{n} RR_i}{n}$$

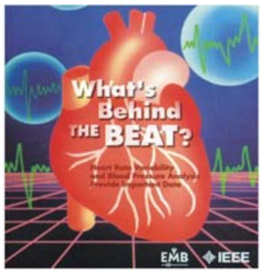
$$RR_{SD} = \sqrt{\frac{\sum_{i=1}^{n} \left(RR_i - \overline{RR}\right)^2}{n}}$$

Remember:

- *During each heartbeat, blood is pushed by the vessels of the skin, and the extension of vessels under the OES determines he amount of light reflected / scattered back.*
- *Peripheral arterial blood volume pulse assessment is well used in medical diagnostics, especially for the heart rate (HR) and heart rate variability (HRV) analysis by cardiovascular risk patients, but for example also as a bio-feedback control signal in stress and pain diagnostics.*

c) PPG assessment of dermal perfusion rhythmicity





IEEE ENGINEERING IN MEDICINE AND BIOLOGY MAGAZINE

Vol. 20, No 2 (2001)

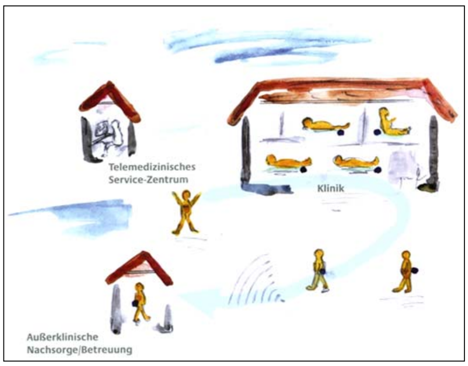
Remember:

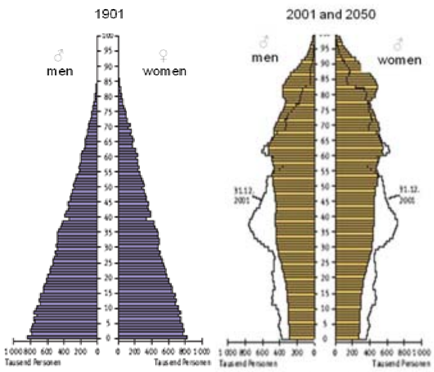
Besides the HB and respiratory synchronous rhythms also other perfusion rhythms can be detected optoelectronically, their origin and their behavior is currently being investigated

MedIT/BMO research interests V:

Optoelectronic sensor concepts for preventive long-term monitoring (24/7) of cardiovascular risk patients

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung





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Take home message: Germans are becoming less …

Take home message: Germans are getting older …

In-ear OES measurement scenario

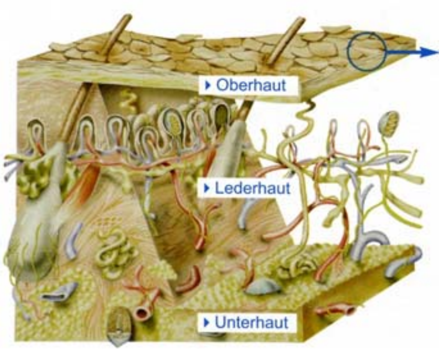
- Physiologically meaningful
- Metrologically advantageous
- Optimal application port

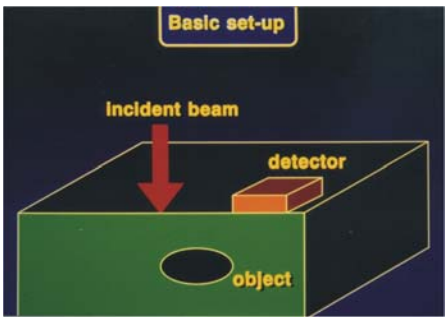
Vital signs monitoring with micro optical sensor PX 01-2 (CiS, Erfurt)

- Multi -λ-PPG-sensor in silicon-glass-ceramic technology
- Spectral sensitivity at 850 nm: 0.55 A/W
- Optical crosstalk at 640 nm: $<10^{-3}$
- Sensor dimensions: 8 x 4 x 1.5 mm^3

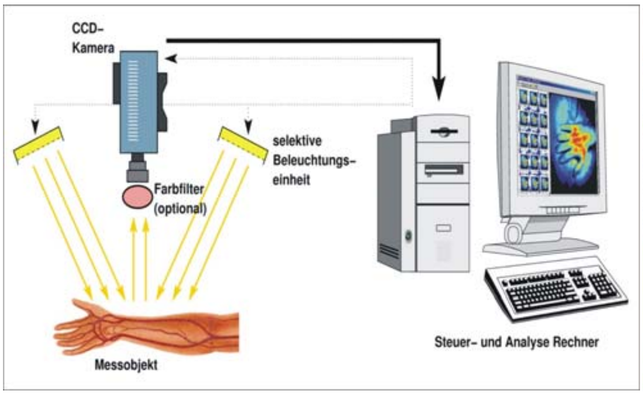
MedIT/BMO research interests VI:

OE Imaging methods in medicine –
„virtual images for virtuoso diagnostics“





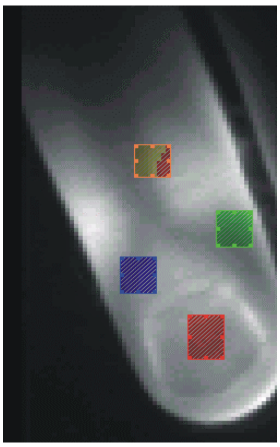
a) Photoplethysmography imaging (PPGI) –
contact-less 2D visualisation of tissue perfusion with spatial resolution

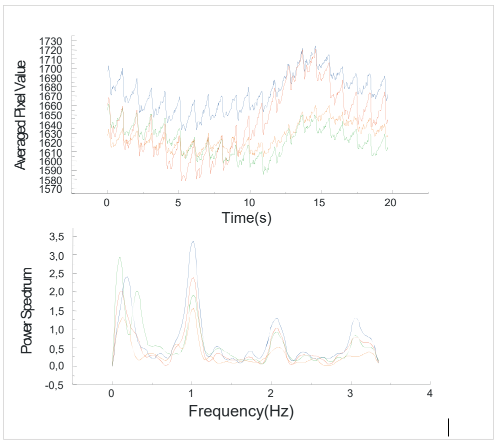


PPGI measuring set-up

Photoplethysmography Imaging (PPGI)

Example 1: Monitoring of distributed blood perfusion status in healthy skin



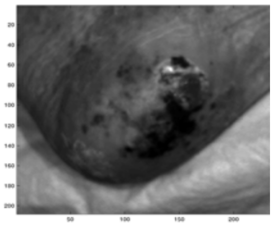


Photoplethysmography Imaging (PPGI)

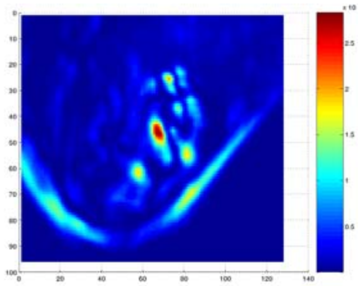
Example 2: Skin tumour perfusion status

Dokumentationsaufnahme mit einer konventionellen Digitalkamera

PPGI Bildaufnahme aus einer Bild-sequenz von 900 Aufnahmen

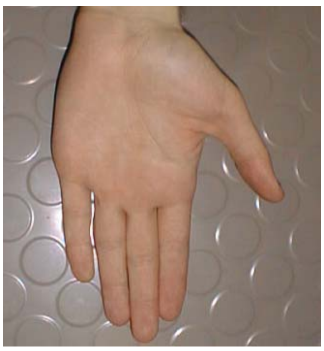


Virtuelles Perfusogramm. Farbkodiert ist die mittlere Amplitude des artertiellen (herzsynchronen) Blutvolumenpulses



Örtliche Auflösung 50x50 µm, zeilliche Auflösung 15 fps; Amplitudenauflösung 14 Bit

Example 3: Latest perfusion studies at RWTH Aachen using PPGI



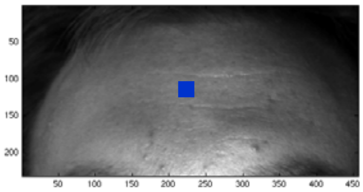
Standard image

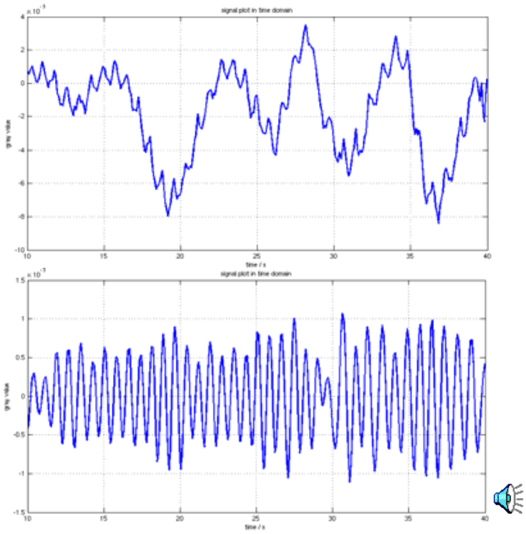
Post processed PPGI video

„Blood volume clouds“ - a new phenomenon in dermal microcirculation?

Example 3: Latest perfusion studies at RWTH Aachen using PPGI

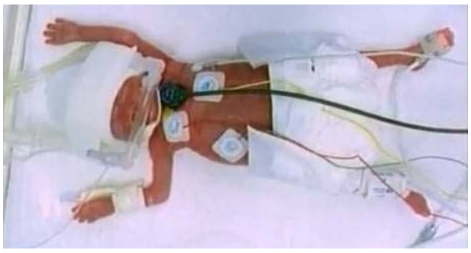
Example:
one ROI (virtual PPG sensor),
16 x 16 pixel = 5 x 5 mm



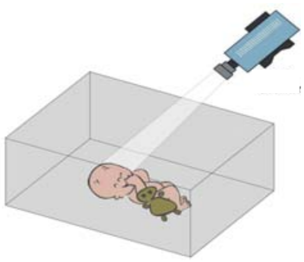


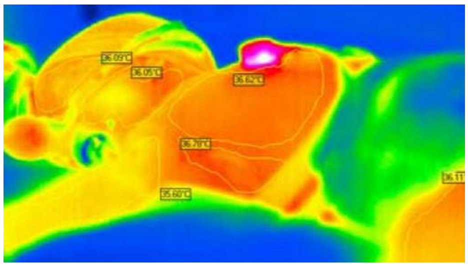
b) Infrared Thermography (FIRT)

Sensing modalities in today's incubator



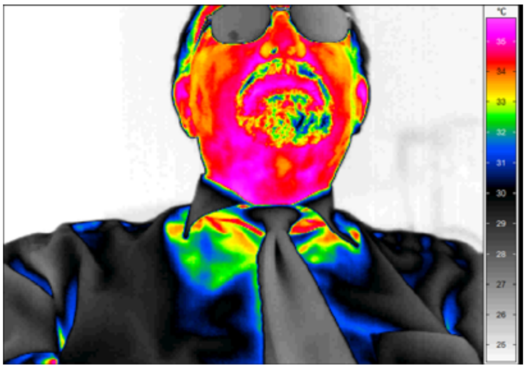
Our vision: smart incubator with wireless sensing





Example of FIRT non-contact breathing detection

Model Opti-Res Clinic
(Jenoptik, Germany)
www.inframedic.de



AlGaAS/GaAs **QWIP**
(Quantum well infrared photodetector)

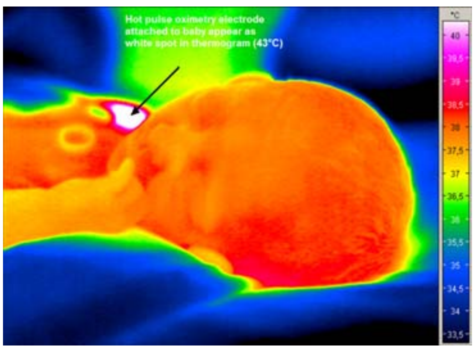
Spatial resolution: 384 x 288 pixel

Thermal resolution: 0.05 °C

Time resolution: 10 fps

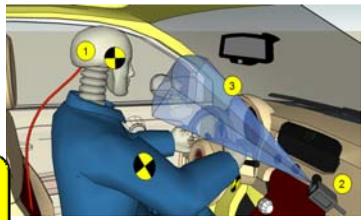
Thermal range: -40 °C – 1.200 °C

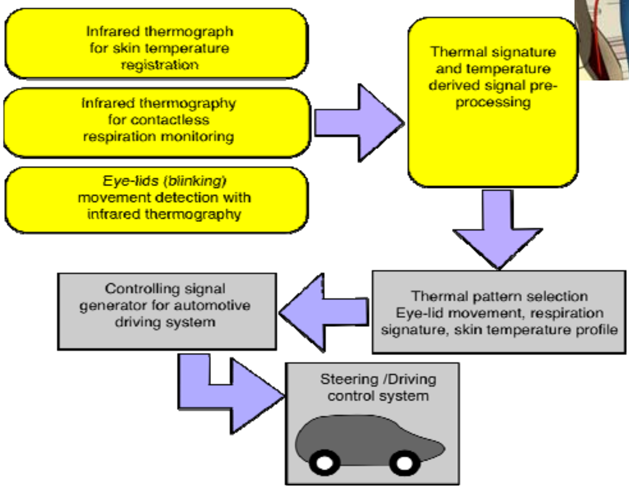
Example of neonatal breathing detection – our preliminary results

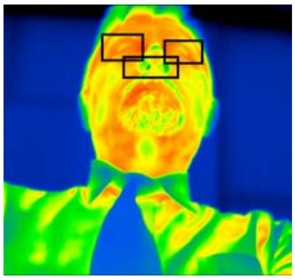


VIDEO

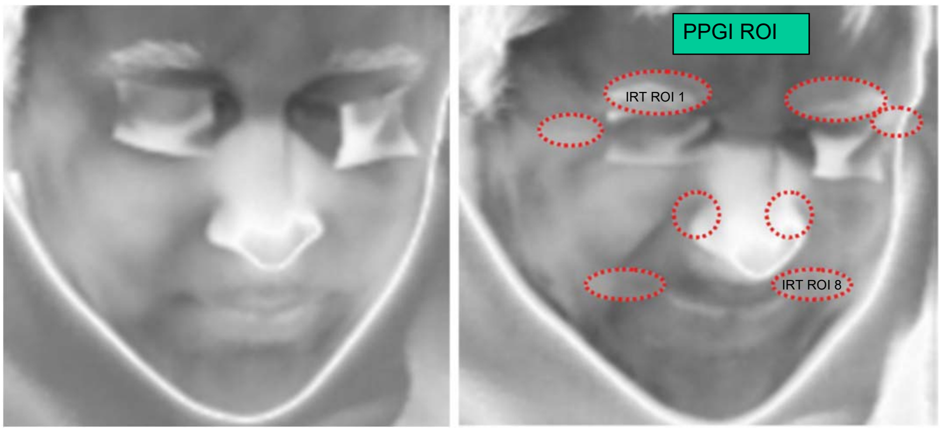
Automotive applications of FIRT





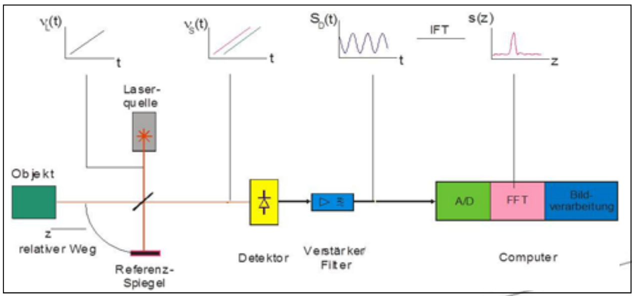


c) Hybrid imaging strategies -
PPGI & FIRT monitoring of pain and stress

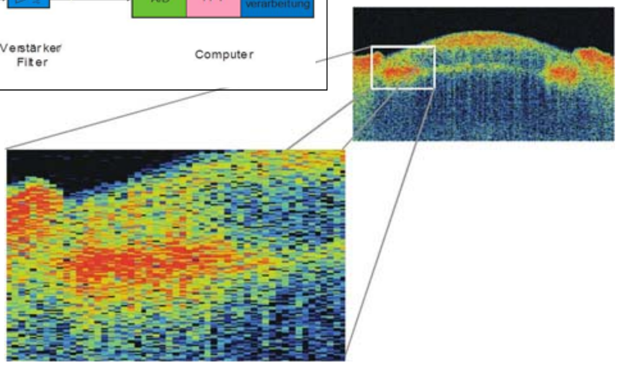


Impact of pain sensation to the facial expressions and skin perfusion (left: normal, right: pained face). Identification of facial features according to Facial Action Coding System (FACS)

d) Optical Coherence Tomography (Chirp-OCT)



Measuring setup



OCT image example:

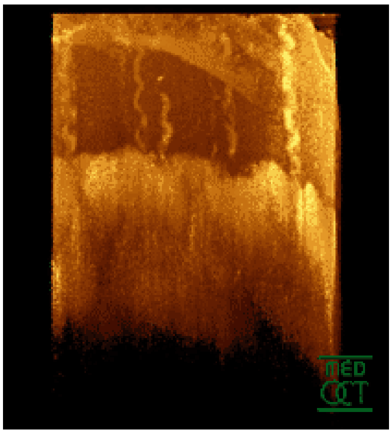
Optical coherence tomogram of the fingertip with sweat transitions in the dermis

Remember:

***Optical coherence tomography (OCT)** is an optical signal acquisition and processing method. It captures micrometer-resolution, three-dimensional images from within optical scattering media (e.g., biological tissue).*

OCT is an interferometric technique, typically employing near-infrared light. The use of relatively long wavelength light allows it to penetrate into the scattering medium. Confocal microscopy, another similar technique, typically penetrates less deeply into the sample.

Depending on the properties of the light source (super LEDs, ultrashort pulsed lasers and supercontinuum lasers have been employed), OCT has achieved sub-micrometer resolution (with very wide-spectrum sources emitting over a ~100 nm wavelength range).



Side length 1x1 mm
Dept ca. 600 μm
Axial resolution ca. 5μm
Source: wikipedia.org/wiki/Optische_Kohärenztomografie (4/2012)

MedIT/BMO research interests VII:
Behavior of human hemodynamic under microgravity

Background:
All astronauts/cosmonauts travel into space complain about fluid shifts from the legs to the head, known as ***"puffy faces"*** or ***"bird legs"***. Until now, it has been difficult to study the amount and the dynamics of these fluid shifts.

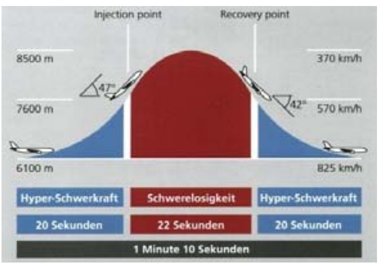
Astronaut Story Musgrave
(Space Shuttle Challenger, Mission STS6, April 1983)
kurz vor dem Start und in Orbit

Astronautin Saly Ride
(Space Shuttle Columbia, Mission STS7, Juni 1983)
Beinumfangmessung in Orbit

Figures: NASA

Experiment for the 7th German parabolic flight campaign:
Rapid fluid shifts along the body axis in humans during parabolic flights

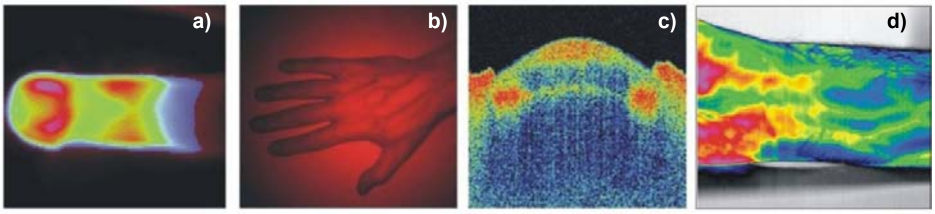
Partner: Center of the Space Medicine Berlin, Charité University Berlin (Prof. H. C. Gunga)
Institute of High Frequency Technology, Aachen University RWTH (Prof. V. Blazek)
Management: DLR, German Aerospace Center, Space Management Bonn



weightlessness.swf

Typical optical imaging results a. D. 2016

a) PPGI optogram of a finger, transilluminated with visible light
b) Dermal vessels of a hand visualised using PPGI in reflection mode by 900 nm
c) Chirp OCT tomogram: Depth-cut through human eye with 30μm resolution
d) Space resolved skin temperature visualisation with FIRT



Citát pro první přednášku / Quotation of the lecture 1:

„Mit Eifer hab´ ich mich den Studien beflissen; zwar weiß ich viel, doch möcht´ ich alles wissen“

Wagner in J. W. von Goethe´s FAUST, Part I