Chapter 2
Mobile Optical Sensing for Abdominal Aortic Aneurysm Monitoring

Johannes Maierhofer and Daniel J. Rixen

Abstract Abdominal aortic aneurysms (AAA) remain a life-threatening condition that often progresses without symptoms until rupture. Standard diagnostic imaging methods such as MRI or ultrasound, while effective, are not always ideal for frequent or accessible monitoring due to their cost, infrastructure requirements, and limited mobility. In the BioOptDyn project, we explore contactless optical sensing as a promising alternative for non-invasive AAA assessment.

This contribution presents two key developments. First, we introduce the BioScanRack, a mobile and modular test station designed to accommodate various optical sensor systems. The platform supports rapid deployment in both clinical and experimental environments, and enables flexible integration of laser-based techniques such as laser line triangulation sensors, laser Doppler vibrometry, and digital image correlation.

Second, we report on first in-vivo measurements conducted on patients with diagnosed abdominal aortic aneurysms. Using the BioScanRack, we recorded surface vibrations of the abdomen in a clinical setting, aiming to determine whether these dynamic signatures contain diagnostically relevant information about the aneurysm's mechanical state. We analyze the spatial and temporal characteristics of the measured signals and compare them across individuals and pathological conditions.

The abstract concludes with a critical discussion on the suitability and limitations of current optical techniques in the context of AAA monitoring, including challenges related to signal quality, motion artifacts, and inter-subject variability. These findings contribute to the long-term goal of enabling accessible, non-invasive, and repeatable AAA diagnostics, and lay the groundwork for further clinical studies and algorithmic interpretation of motion data.

Keywords Testing Equipment · Experimental Dynamics · Non-contact Displacement Measurement · Biomechanical Vibration Analysis

Introduction

The demographic shift toward an aging population has led to an increasing prevalence of abdominal aortic aneurysms (AAA), defined as localized dilatations of the abdominal aorta. With progressive enlargement, the risk of rupture rises substantially, often resulting in uncontrolled internal bleeding. The prognosis of rupture remains poor, with mortality rates of up to 90% before surgical intervention can be initiated. Current surveillance strategies rely on imaging modalities such as ultrasound, computed tomography (CT), or magnetic resonance imaging (MRI), while in clinical practice a pulsatile abdominal mass may also be detected during physical examination [5]. The BioOptDyn project was initiated to explore non-contact optical measurement techniques as a novel approach for monitoring biomechanical dynamics of the abdominal wall in AAA patients.

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Kristin B. Zimmerman, PhD (eds.), *Structural Health Monitoring, Metamaterials, Metastructures and Additive Manufacturing and Dynamics of Biomedical and Bioinspired Systems, 2026, Vol. 10*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-8-743-81449-8_2

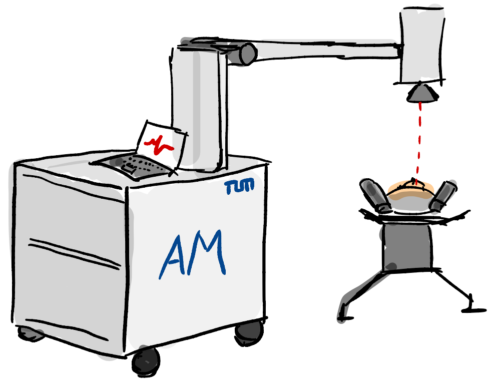


Fig. 1 BioOptDyn - mobile measurement platform to measure the skin motion of the abdomen to monitor abdominal aortic aneurysms.

Previous work in this field has been carried out in recent years through proof-of-concept studies [2, 3, 10]. Several studies have addressed the relationship between aneurysm wall motion and disease state, yet consensus remains elusive. While dynamic measurements of wall compliance and pulsatility have been proposed as potential markers for rupture risk [4, 8], clinical and experimental investigations have yielded conflicting results regarding their predictive value [1, 6]. Consequently, it remains an ongoing discussion whether quantitative assessment of wall motion can provide reliable information on the progression and stability of abdominal aortic aneurysms.

Vision

The long-term vision of the BioOptDyn project is to establish contactless optical sensing as a reliable and accessible tool for the diagnosis and follow-up of abdominal aortic aneurysms (AAA). By combining advanced laser- and camera-based technologies with intelligent signal processing, the project aims to move beyond the limitations of conventional imaging and provide a patient-friendly, mobile solution for routine monitoring. Ultimately, this approach seeks to enable earlier detection of critical changes, reduce dependence on costly imaging infrastructure, and open pathways for broader applications of optical vibration analysis in other areas of medical diagnostics.

Scope of the paper

This paper focuses on the selection of non-contact measurement methods by comparing the requirements with the physical principles. Three methods are selected and combined into a mobile test rig. With that, a pilot study is conducted in collaboration with the clinic on patients (ongoing, at the time of writing). First measurement datasets and corresponding signal pre-processing results are shown and discussed.

Abdominal Aortic Aneurysm

An abdominal aortic aneurysm (AAA) is a dilation of the aorta in the abdominal region. The aorta carries blood from the heart through the chest and abdomen, branching to supply major organs before dividing into the leg arteries. AAAs most often occur below the renal arteries and above the bifurcation to the legs (infrarenal AAAs).

The exact causes are not fully understood, but risk factors include arteriosclerosis, smoking, age, and male sex. Men are about six times more likely to develop AAAs, and prevalence increases with age. AAAs are often asymptomatic until they reach a critical size, when rupture risk rises sharply. Rupture causes severe internal bleeding and is often fatal. For this reason, ultrasound screening is recommended for men over 60. Depending on findings, patients may be monitored or treated.

While the typical diameter of the aorta is around $2\,\mathrm{cm}$, an aneurysm is classified as large or severe if its diameter exceeds $5.5\,\mathrm{cm}$ [7].

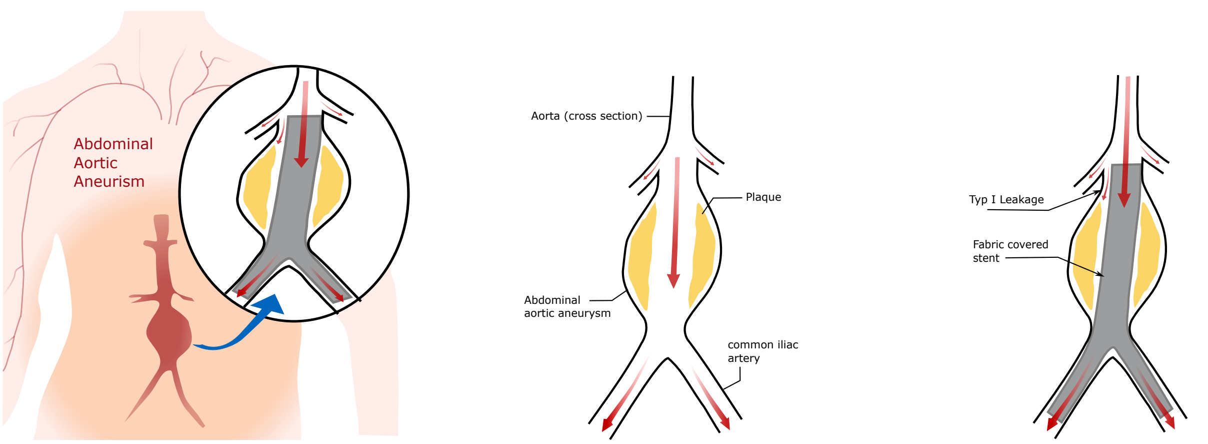
Aneurysm Repair

The goal of repair is to exclude the aneurysm sac from systemic blood pressure. Two main methods are established:

Open Surgery The diseased section is replaced with a synthetic graft. This approach is durable but highly invasive, requiring major surgery and long recovery.

Endovascular Repair (EVAR) A stent graft is inserted via the leg arteries and positioned inside the aorta to reroute blood flow. EVAR is less invasive and widely used, but carries risks of leakage (endoleaks), requiring lifelong imaging follow-up. CT scans and contrast-enhanced ultrasound are commonly used, though both involve some patient burden.

To reduce the invasiveness of follow-up, alternative monitoring methods are being explored. One idea is to analyze abdominal skin motion with optical techniques, assessing whether surface patterns can indicate complications such as endoleaks without radiation or contrast agents.



(a) Position of the AAA on the human schema. (b) Schematic AAA (c) Stent repaired AAA

Fig. 2 Overview of AAA location, schematic anatomy, and stent-graft repair.

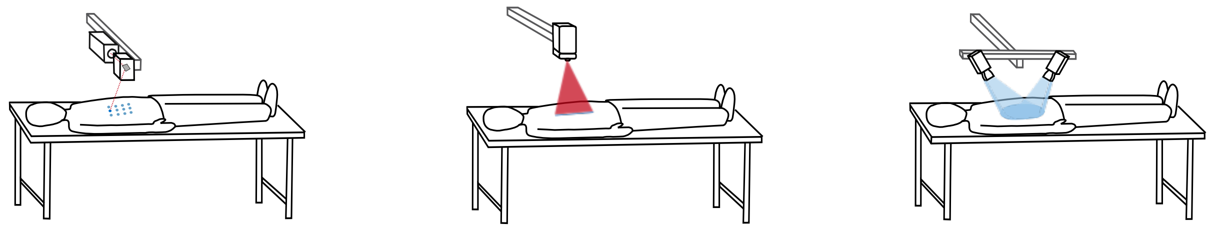
Physical measurement principles

Non-contact displacement approaches can be broadly divided into mechanical (acoustic) and electromagnetic domains. Acoustic approaches measure surface motion by detecting pressure fluctuations in air. In the electromagnetic domain, radar, infrared, and visible light are applied, with the transition from long to short wavelengths enabling progressively higher spatial resolution. The use of coherent light in laser-based methods further allows interference-based measurements with sub-micrometer precision.

Within the electromagnetic spectrum, different strategies exist: triangulation methods exploit geometrical relations between illumination and detection, whereas interferometric methods rely on coherent superposition of waves (e.g., quadrature demodulation of self-mixing or heterodyne laser signals). Another classification distinguishes active systems, which emit energy and analyze the reflected or transmitted signal, from passive systems, which rely only on the radiation naturally emitted or scattered by the body under investigation.

Selection

For the present study, three representative optical systems have been selected: (i) a Laser Doppler Vibrometer (LDV) with scanhead, enabling highly precise single-point measurements and rapid scanning; (ii) a Laser Line Triangulation (LLT) sensor, providing spatially resolved displacements along a line at medium sampling rates; and (iii) a stereo-camera system for Digital Image Correlation (DIC), which offers full-field displacement information but at the expense of high data volume and the need for surface preparation.



(a) LDV (b) LLT (c) DIC

Fig. 3 Overview of the three optical measurement modalities considered for abdominal wall motion sensing: (a) laser Doppler vibrometry, (b) laser line triangulation, and (c) stereo digital image correlation.

BioScanRack

The BioScanRack is a mobile test station carrying the different optical sensors under test. It was developed at the Chair of Applied Mechanics, TUM, to conduct an in-vivo study at the clinic.

Requirements

The design of the BioScanRack had to satisfy numerous requirements from different perspectives. First, the packaging needs to be compatible with ambulance door widths and at the same time transportable with standard vehicles to commute between lab and clinic. All measurement equipment has to be fully contained in the rack to enable a fast and complete retraction from the examination room in case of an emergency. Second, the distance between the surface of the patient's abdomen and the sensors needs to be adjustable to account for different examination table heights and body sizes. Finally, the ScanRack should be modular to serve as a platform for various different sensors.

Mechanical Setup

The core frame of the BioScanRack is built from aluminum profiles on a wheeled platform. An electro-mechanical lift column with manual control carries a horizontal aluminum beam which is connected to the top of the column via a hydraulically damped hinge. This allows the system to safely fold-in for transportation. On the beam, different quick-release clamps are mounted which the individual sensors are attached to. The wiring harness connects the sensors to their control units which are stored in the box. Thin plates around the frame prevent objects from falling out.

Measurement Devices

To acquire useful data, an infrastructure needs to be set up that takes care of fully synchronized data with unique timestamps. The signal infrastructure is built around the open-source data acquisition board OASIS which is a long-term development of the chair.

open-source Data Acquisition - OASIS

The OASIS board serves as the central unit for synchronized data acquisition within the BioScanRack. It is an open-source hardware and firmware platform, originally designed for IEPE sensors but equally suited for direct analog and trigger signal sampling, as required in this setup. A Python API provides a straightforward interface for configuration, control, and data access, making integration into custom measurement pipelines efficient. The open-source nature of the firmware allows individual adaptations for special requirements, ensuring long-term flexibility of the system. All acquired raw data are streamed to the host computer while at the same time being redundantly stored on the internal SD-card, providing a reliable fallback option in case of transmission loss, [12].

Continuos arterial pressure - Finapres, Nova Scan

The Finapres Nova Scan device provides continuous non-invasive arterial blood pressure measurements based on the volume-clamp method originally introduced by Peňáz in 1973 [9]. The measurement principle relies on a finger cuff equipped with an

Fig. 4 BioScanRack - A mobile measurement platform with a vertical column that carries the different measurement devices.

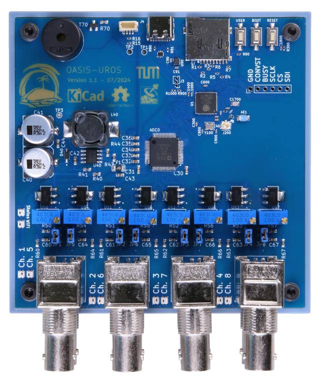


Fig. 5 Modified open-source OASIS system as core data acquisition system for the BioScanRack. All analog signals are gathered and synchronously sampled

inflatable bladder and an optical plethysmograph consisting of an LED and a light detector. The pulsatile changes of arterial diameter during each heartbeat modulate the detected light intensity. A servo-controller compares this plethysmographic signal, representing the unloaded arterial diameter, with a defined setpoint. The difference is amplified to generate an error signal which drives a fast pneumatic proportional valve in the NANO CORE® module. By dynamically adjusting the cuff pressure, the arterial wall is unloaded, such that the instantaneous cuff pressure follows the intra-arterial pressure waveform. This pressure signal thus provides an indirect but continuous measure of finger arterial pressure.

The Nova Scan additionally records ECG and respiration signals, enabling precise temporal alignment of cardiovascular parameters. For integration into the BioScanRack setup, the system provides an analog output channel that can be directly sampled by the OASIS board, ensuring full synchronization with other measurement devices. The raw physiological data are also redundantly stored on the internal memory of the Nova Scan device, guaranteeing a secure backup independent of the acquisition infrastructure.

Infrared Laser Doppler Vibrometer - Polytec RSV-150

The Polytec RSV-150 is a compact infrared laser Doppler vibrometer designed for precise, non-contact vibration measurements. It operates by emitting a laser beam onto the target surface and detecting the frequency shift of the backscattered light caused by the Doppler effect of surface motion. From this frequency shift, the instantaneous velocity of the surface can be derived with high temporal and amplitude resolution. The use of infrared wavelength ensures compatibility with biological tissue while minimizing interference from ambient light. The vibrometer provides the analog output of the measured velocity and integrated displacement signal, which are directly sampled by the OASIS board to achieve full synchronization with other sensor modalities.

To position the laser measurement point, a Maul-Theet optical scanhead is employed, which allows dynamic redirection of the laser beam to different points on the measurement surface. The scanhead is operated using custom-developed firmware tailored to the requirements of the BioScanRack. Our firmware integrates seamlessly with Python, enabling straightforward configuration and scripted scan protocols directly from the measurement pipeline. This allows automated point-to-point scanning as well as complex predefined trajectories to be executed in synchronization with the other devices. As with all analog sensors in the setup, the scanhead signals can be routed to and synchronously sampled by the OASIS board, ensuring precise temporal alignment of all recorded data streams.

Line Laser Triangulation - Micro-Epsilon scanControl 3002

The Micro-Epsilon scanControl 3002 is a high-resolution laser line triangulation sensor that projects a laser line onto the measurement surface and records the reflected profile using a CMOS array. From the geometrical relation between projection angle, camera optics, and detected line position, the surface contour is reconstructed in real time. This enables the acquisition of dense profile data across a defined measurement width, making the sensor particularly suitable for capturing dynamic shape changes of the abdominal wall.

Within the BioScanRack setup, the scanControl 3002 transmits its profile data via Ethernet directly into the Python-based measurement pipeline, allowing efficient data handling and integration into automated processing workflows. To ensure precise temporal synchronization with the other devices, the scanControl additionally provides a hardware synchronization output. This sync-signal is fed as an analog input to the OASIS board, where it is sampled alongside all other channels. During post-processing, this allows accurate timestamp alignment between the profile data stream and the continuously recorded physiological signals.

Stereo Camera - Zeiss GOM Aramis

The Zeiss GOM Aramis system is a stereo digital image correlation (DIC) setup that consists of two synchronized cameras to capture surface displacements and strains over a defined region of interest. In contrast to full-field projection-based systems, the setup in the BioScanRack does not employ a projector, relying solely on natural or external illumination. The two-camera configuration allows the reconstruction of three-dimensional surface motion by tracking the displacement of speckle patterns applied to the measurement area.

Data acquisition is performed on a dedicated external computer, and thus runs independently from the OASIS-based infrastructure. Synchronization with the other devices is achieved by means of a cross-reference signal, which provides a temporal anchor point for aligning the recorded sequences. After acquisition, specific points of interest on the surface can be interactively selected in the post-processing software, and the corresponding displacement time series are exported. These displacement data are then incorporated into the unified measurement pipeline and can be precisely synchronized with the physiological signals of the other devices.

Data analysis

As a starting point, we adopt a systems-analysis view in which the cardiac cycle provides a periodic excitation and all measured observables are treated as responses to that input. For each spatial measurement point we acquire $\approx 10\,\mathrm{s}$ of data (> 10 heartbeats), including the ECG (excitation), noninvasive blood pressure, and optical skin-motion signals from our vibrometry/triangulation/DIC modalities. The ECG was treated as the excitation signal, while blood pressure and optical skin-motion signals were considered as responses. The ECG peak detection procedure is described below. All signals were temporally aligned such that corresponding heartbeats, pressure curves, and displacement patterns coincided across modalities.

After alignment, the signals were mapped onto a normalized cardiac phase using global least-squares beat alignment, allowing beat-wise averaging. In this way, mean values and standard deviations acquired a physiological meaning, as they represented variations of the cardiac response rather than timing differences or sensor latency. This procedure enabled a robust comparison of measurement points within an individual and, importantly, allowed consistent comparisons across different subjects.

The Wiggers diagram (fig. 6) illustrates the temporal relationships between pressure, volume, flow, and electrical stimulation during the cardiac cycle. In the reduced version, it relates the electrocardiogram (ECG) with the aortic pressure, allowing a comprehensive visualization of systole and diastole. By aligning these parameters on a common time axis, the diagram highlights the interplay between electrical excitation, mechanical contraction, valve motion, and blood flow.

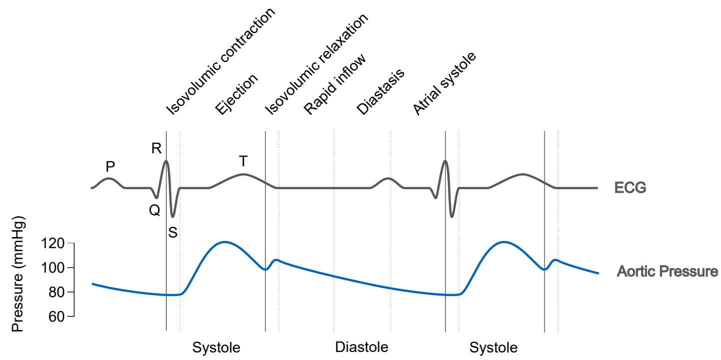


Fig. 6 Wiggers diagram

Electrocardiography (ECG)

A person's heartbeat is triggered by electrical impulses, which are generated by the SA node (sinoatrial node), a small mass of specialized tissue located in the right upper chamber (atria) of the heart. The electrical activity of the heart spreads through the walls of the atria and causes them to contract, forcing blood into the ventricles. Each contraction of the ventricles represents one heartbeat.

The electrical activity of the heart describes the controlled spread of electrical depolarization through the heart mass from one cardiomyocyte (heart cell) to its neighbors, as well as via a specialized electrical conduction system.

The mechanical activity of the heart is a synchronized muscular contraction that is produced as a result of the heart's electrical activity. This contraction of the ventricles forces open and shut specific heart valves, thereby allowing the pumping of blood towards the periphery.

Three-lead ECG refers to the basic configuration of electrocardiographic monitoring, typically involving one positive, one negative, and one ground electrode placed on the body surface. The most common variants are:

Lead I potential difference between the right arm (-) and left arm (+).

Lead II potential difference between the right arm (-) and left leg (+).

Lead III potential difference between the left arm (-) and left leg (+).

These bipolar limb leads form the classical Einthoven triangle, providing orthogonal projections of the cardiac electrical vector in the frontal plane. They allow continuous monitoring of heart rhythm and basic morphology of the P wave, QRS complex, and T wave. We decided to use the Lead II signal for the QRS complex detection.

Pan–Tompkins QRS Detection Algorithm

The Pan–Tompkins algorithm detects QRS complexes by enhancing high-frequency components, extracting energy, and applying adaptive thresholds [11]. Given an ECG signal $x[n]$ sampled at frequency f_s, a band-pass filter (h_{bp}, (≈ 1 Hz to 100 Hz)) is applied to emphasize the QRS energy:

$$x_{bp}[n] = (x * h_{bp})[n],$$

the asterisk $*$ denotes the discrete convolution of the signal with the band-pass filter impulse response. To highlight the slopes, the signal is differentiated:

$$x_d[n] = x_{bp}[n] - x_{bp}[n-1]$$

Squaring makes all values positive and accentuates steep slopes:

$$x_s[n] = \big(x_d[n]\big)^2$$

To obtain waveform features, a moving-window integration is applied over $N = T \cdot f_s$ samples (typically $T \approx 120\,\mathrm{ms}$ to $150\,\mathrm{ms}$):

$$x_i[n] = \frac{1}{N} \sum_{k=0}^{N-1} x_s[n-k]$$

The peak detection can be determined from the rising edge of the integration waveform. For irregular heartbeats, an adaptive threshold is implemented. Additionally, a physiological refractory period of $\Delta t \geq 200\,\mathrm{ms}$ is enforced.

The detected indices correspond to QRS candidates; the final R-peak is localized within a short window of the original $x[n]$ by maximal absolute amplitude.

For the next step, the time-series data are cut into pieces around the detected R-peak with a length of $1\,\mathrm{s}$. The alignment of these pieces is then further improved by applying a small time shift in such a sense that the cross-correlation between all pieces is maximized.

Global Least-Squares Beat Alignment

We refer to this approach as **Global LS Alignment (GLSA)**. To align individual beats without assuming a predetermined wave form, we estimated relative time shifts between beats using cross-correlation. For two beat segments $x_i(t)$ and $x_j(t)$, the lag Δt_{ij} is defined as

$$\Delta t_{ij} = \arg\max_{\tau} \int x_i(t)\, x_j(t+\tau)\, dt$$

which corresponds to the shift of beat j relative to beat i. Collecting these relations yields an overdetermined system

$$s_j - s_i \approx \Delta t_{ij}$$

where s_k denotes the unknown global shift of beat k. The set of shifts $\{s_k\}$ is obtained by minimizing the least-squares cost

$$\min_{\{s_k\}} \sum_{(i,j)} \Big((s_j - s_i) - \Delta t_{ij}\Big)^2.$$

This procedure yields consistent global alignment across all beats, with one beat fixed as reference ($s_0 = 0$) to remove the gauge freedom.

Preliminary In-Vivo Measurements

Pilot Study Design

A monocentric pilot study (ongoing at the time of writing) evaluates contact-free optical monitoring of abdominal aortic aneurysms (AAA) using a mobile measurement platform (“BioScanRack”).

The study comprises a transversal phase and a longitudinal phase. In the transversal phase, 10 adults (5 patients with AAA prior to treatment and 5 healthy controls; BMI $<$ 35) will attend one study visit in the vascular surgery outpatient clinic.

During this visit, abdominal wall motion will be recorded with Laser Doppler Vibrometry, Laser Line Triangulation sensor, and (at a later stage) stereoscopic motion capture, synchronized to ECG; continuous noninvasive blood pressure and respiration (CNAP) are acquired in parallel.

In the longitudinal phase, 15 adults with AAA are examined twice: (i) at the pre-admission visit before planned EVAR and (ii) at routine follow-up one month post-procedure.

The primary objective is to assess feasibility and data quality of optical measurements in AAA patients; secondary analyses compare AAA patients with healthy controls and correlate optical metrics with clinical imaging findings.

Exemplary Measurements

As a first exemplary evaluation, measurements with the LDV were processed for one central abdominal point in a control subject and in a patient with an abdominal aortic aneurysm, fig. 7. For each case, individual heartbeats are displayed as transparent lines, while the thick line represents the mean and the surrounding colored band the corresponding standard deviation.

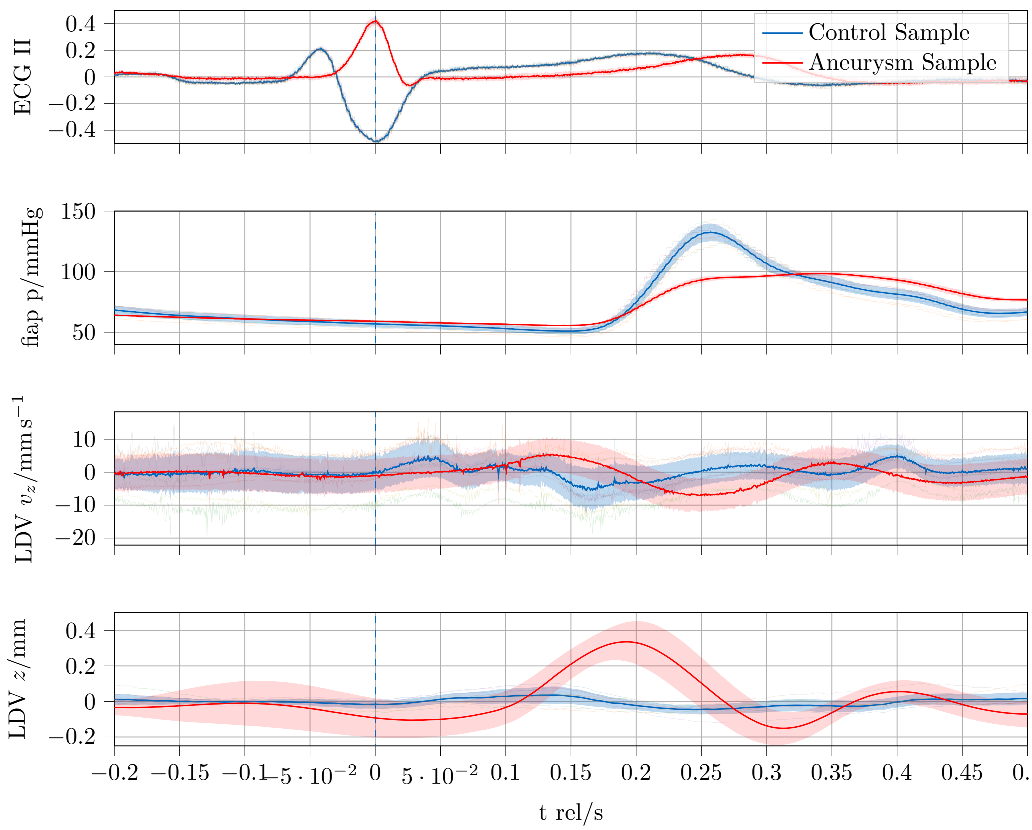


Fig. 7 A single measurement was randomly sampled from one subject of the control group and one subject of the aneurysm group.
Note: The polarity of the QRS complex is not invariant. In slender, tall individuals with a more vertical orientation of the heart, the main depolarization vector may align away from certain leads, resulting in a predominantly negative QRS complex even in physiologically normal cases.

The ECG waveforms appear highly repeatable in both subjects, confirming the robustness of the alignment procedure. The finger arterial blood pressure (fiap) trace of the aneurysm patient, however, shows a visibly less prominent peak compared to the control subject. In addition, the displacement signal, after removal of the respiratory component (by low-pass filtering), is markedly more pronounced in the aneurysm patient. These findings illustrate the potential sensitivity of the approach, yet no conclusions can be drawn at this stage. The observations are based on single individuals, and further measurements on a larger cohort will be required to enable a reliable interpretation.

Conclusion

This contribution shows the first steps in the direction of a non-invasive, non-contact and non-harmful examination method for the monitoring of AAA patients.

The three investigated optical measurement systems differ considerably in terms of spatial coverage, temporal resolution, and practical feasibility. This assessment is independent of the exact sensor type or manufacturer and instead focuses on the general measurement principles.

The point-wise laser Doppler vibrometer (LDV) offers excellent precision in the axial (z-) direction and can achieve very high sampling rates, but it is limited to single-point measurements and entails relatively high cost. Laser line triangulation (LLT) provides a compromise: it captures spatially resolved data along an entire line simultaneously, at moderate sampling rates, and with comparatively low system costs. Digital image correlation (DIC), by contrast, delivers full-field information but at the expense of extremely high data volumes, the need for artificial surface patterns (speckle), and substantial system cost. Considering these trade-offs, LLT emerges as the most favorable method for the current application, with the perspective of extending to three parallel LLT lines as the most promising future option.

However, many future steps remain to achieve a practical system and a robust data extraction which can be utilized in medical practice. As a next step, the full approved pilot study needs to be conducted and evaluated to provide evidence for the relationship between abdominal skin motion and aneurysm size.

Acknowledgments The project is carried out in collaboration with Univ.-Prof. Dr. Dr. med. Daniela Branzan at the TUM University Hospital **Klinikum rechts der Isar**. The project is funded by the German Research Foundation (DFG), project number 517562839. Study BioDynOpt-Pilot; DFG 5320727; subproject 2020-286_1-S-NP.

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