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Application of thermography for cerebral perfusion imaging during aneurysm surgery

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Abstract: The success of aneurysm surgery depends on complete clipping of the aneurysmal sacculcation without compromising quality of cerebral perfusion of vessels concerned. An established intraoperative method to visualize cerebral blood flow is a apparent vessels fluorescence via angiography based on indocyanine green (ICG). However, major disadvantages of indocyanine green video angiography (ICG VA) are the need of a specialized imaging system, potential drug side effects as well as the limited number of repetitions due to long decay time of ICG in blood circulation. In particular the last drawback prevents brain parenchymal perfusion monitoring with ICG VA. The application of time-resolved thermography as a fast, contactless, noninvasive, marker-free and harmless imaging tool became a promising approach for perfusion imaging and thus offers several advantages compared to ICG. Measurements of deep structures in heat traps for identification of internal patterns, essential for e.g. success monitoring of aneurysm clipping, are still unsolved challenges of thermography. This work reveals as a proof of concept that the combination of thermography and an intravenous cold saline bolus injection as a contrast agent is capable to detect arterial and parenchymal perfusion located in the surgical cavity during aneurysm surgery in comparison to state-of-the-art ICG VA. The investigations provide evidence that thermography has the capability to perform intraoperative imaging of cerebral perfusion at an advanced stage in surgery for vessels and parenchyma located both cortically and in the surgical cavity.

Keywords: thermography, aneurysm clipping, neurosurgery, intraoperative thermal imaging, indocyanine green, video angiography

1 Introduction

The examination of intravascular blood flow and cerebral perfusion is essential during neurovascular interventions to monitor surgical progress [1]. In clinical routine, the widespread approach for imaging of the cerebral blood flow is fluorescence, in particular indocyanine green videoangiography (ICG VA) [2]. The functional principle of ICG VA is linked to an imaging setup consisting of a near-infrared light source (wavelength $\lambda \approx 800 \text{ nm}$) and a camera sensitive for this specific spectral region detecting the emitted fluorescence light of the dye. After intravenous injection, ICG binds to plasma proteins and remains in the blood circulation. However, ICG VA has distinct drawbacks: a) as mentioned previously, its imaging system requires a special camera and light source, b) as a drug- and marker-based video angiography, it is not suitable for all patients, and c) it is not arbitrarily repeatable due to a specific decay time of intravascular ICG bondings up to 30 min. In contrast, the application of time-resolved thermography as a fast, contactless, noninvasive, marker-free and harmless imaging tool overcomes these challenges and became a promising approach for perfusion imaging in neurosurgery. Ours and other groups showed in preceded studies, that it is capable to monitor the temperature topography of the brain cortex [3], the blood flow through a cranial bypass [4] and to detect changes in the cerebral blood flow induced by neuronal cortical activation [5, 6]. Our group previously demonstrated that the combination of thermography and an intravenous cold saline bolus injection as a contrast agent is capable for in-vivo imaging of cortical perfusion [7, 8]. Moreover, a quantitative method for the cold bolus signal was developed that indicates the occurring temperature differences in cortical arteries [9]. The approaches listed were applied for the assessment of superficially located observation fields but have their limits in accessing blood flow in vascular structures located in the surgical cavity. Because of the superposition of thermal signals originating from distinct regions within the cavity, identification of specific vascular structures in heat traps is more challenging [10]. But in order to maintain comparability to the performance of ICG VA for aneurysm surgery, it is mandatory to visualize blood flow in involved vessels within the surgical cavity. This proof of concept case demonstrates the feasibility of the cold bolus approach to detect blood vessel and parenchymal per-
fusion located in the surgical cavity during aneurysm surgery and compares the findings to ICG VA.

2 Materials and Methods

2.1 Patient

The 57-year-old female patient underwent neurosurgical clipping of a right sided middle cerebral artery aneurysm. For investigation of cerebral perfusion and vascular imaging inside the surgical cavity, time-resolved thermography and ICG VA were performed simultaneously in order to allow comparability of both imaging modalities. ICG was added to a cold bolus of normal saline at 4°C temperature and injected intravenously via a peripheral venous access. Thermographic and fluorescence image series were recorded during injection for a time period of 60 s.

2.2 Time-resolved thermography

Thermography was performed by the uncooled infrared imaging system VarioCAM HD head (InfraTec GmbH, Dresden, Germany). It detects infrared radiation in the spectral range between 7.5 – 14 μm thereby providing resolutions up to 30 mK (at 30°C) and 125 μm per pixel at 30 cm object distance and a maximum acquisition rate of 60 Hz.

Thermal data processing

Image analysis for time-resolved thermography was performed only on pixels representing brain tissue, segmented using a binary mask. For reduction of background noise, the thermographic sequence was normalized by an average image, computed from a subsequence before cold bolus application. Furthermore, camera intrinsic drift and non-uniformity correction were compensated, to ensure a comparable signal behavior during data acquisition. Handling noise of higher frequencies than the observed cold bolus signal was realized by calculating the moving average of the whole sequence of 60 s applied on subsequences of 10 s each. As previous studies yielded a decrease of blood vessel temperature after cold bolus injection followed by an increase to baseline temperature, for evaluation of the present thermographic time series, only signal changes below baseline temperature were considered.

2.3 ICG video angiography

ICG VA was performed using an OPMI® Pentero® surgical microscope from Carl Zeiss Surgical GmbH including an INFRARED 800 fluorescence module. This incorporates an excitation module for wavelength of 700 to 780 nm and a detecting component recognizing emitted fluorescence radiation in the wavelength range from 820 to 900 nm. The ICG (ICG Pulsion®) was diluted in 50 ml physiological saline solution resulting in a concentration of 1 mg/ml.

Fluorescence data processing

For each pixel of the recorded ICG image series, the raw intensity profiles were extracted. To handle with background and high-frequency noise, the data cube was decomposed using principal component analysis. The time course was reconstructed using components with a high variance and a resulting cumulative sum of above 95%. The recording imaging system has an internal gain correction causing sharp intensity decreases, expressed as a characteristic zigzag-shaped curve. The compensation occurred by an offset subtraction and intensity correction at corresponding time points. Subsequent to that, the time courses for each pixel were normalized to the overall maximum.

3 Results and Discussion

Fig. 1A and B display the surgical field after trepanation of the calotte, opening of the dural brain covering and exposure of the blood vessels concerned. The unprocessed passive thermal imaging (without cold bolus injection) displayed in Fig. 1B did not reveal perfused areas in the surgical cavity. The results of both ICG and thermal video angiography are in extracts shown in Fig. 1C and D. The exposed aneurysm before clipping and surrounding arterial vessels are apparent and their boundaries clearly definable in both imaging modalities. The different camera positions and a thermal camera focus position inside the surgical cavity provided different viewing angles with slight variations in the visualized details. Therefore, the main attention of this work lies within three specific regions with various functional tissue characteristics (arterial vessel, aneurysm and parenchyma) visible in both perfusion imaging approaches. Characteristic values for three pixels located each in one specified region 1-3 are listed in Tab. 1 and their temporal signal behaviors are displayed in Fig. 1E and F. In this context the time elapsed until signal appearance is defined as the time point of minimal temperature in the
Fig. 1: A White-light image of the exposed aneurysm before clipping and B average thermographic image computed from a subsequence of images before cold bolus application. The white dashed line surrounds the surgical cavity, where no internal structures visible in white-light (A) as 1: arterial vessel, 2: aneurysm or 3: parenchyma are apparent in the thermographic image (B) regions 1 up to 3. Extracted images of the simultaneously performed video angiographies at its maximum expansion for C ICG 21 s and D cold bolus 25 s after injection. The point of views slightly differ between the imaging modalities. The surgical cavity is here again surrounded by a white dashed line. For further analysis three areas located in the specified regions 1-3 (same functional areas as in A and B) were considered to compare both perfusion imaging approaches.

Tab. 1: Tabular comparison of the time elapsed until signal appearance for the three predefined regions

<table>
<thead>
<tr>
<th>region</th>
<th>characteristic</th>
<th>ICG  in s</th>
<th>cold bolus  in s</th>
<th>time difference  in s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>arterial vessel</td>
<td>13</td>
<td>19.4</td>
<td>6.4</td>
</tr>
<tr>
<td>2</td>
<td>aneurysm</td>
<td>12.7</td>
<td>17.3</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>parenchyma</td>
<td>20.7</td>
<td>25.2</td>
<td>4.5</td>
</tr>
</tbody>
</table>

cold bolus profile and corresponding to that ICG at 90% of its maximum signal intensity. Tab. 1 indicates that the signal appearance of thermal imaging is delayed between 4.5 s and 6.4 s compared to fluorescence imaging. This is due to different measuring principles with specific signal properties for the various approaches. Temperature transmission through the vascular wall layers took more time until signal appearance than the corresponding process for fluorescence. Furthermore, a difference occurred in the arrival time between the arterial vessel and parenchyma. Fig. 1E and F display the time courses indicating the region characteristics more detailed. The signal appeared in parenchyma shows for both modalities the latest and smallest signal peak reached. The most noticeable difference between fluorescence and thermal imaging in the temporal signal behavior can be spotted in the peaks of aneurysm and arterial vessel. While in thermographic time courses the larger peak occurred in aneurysm, in ICG time courses the arterial vessel reached the higher signal intensity. The authors hypothesize that this pattern could be because larger volume of cold saline solution in the aneurysm generated a larger temperature drop to the vascular wall, but it deserves more detailed consideration in future research.

The results demonstrate that thermography used with the cold bolus approach allows the identification of vascular structures within a surgical cavity despite of superposition of thermal signals of the surrounding tissue. The approach performance is similar to ICG VA in particular for the differentiation between various perfused vessels of specific functional regions in the field of view.
4 Conclusion

This work compared the thermographic cold bolus with a simultaneously performed ICG VA for imaging cerebral perfusion in a surgical cavity. The results reveal that both methods provide reliable outputs in accordance to one another in the temporal signal properties. The investigations provide evidence that thermography has the capability to perform intraoperative imaging of perfusion at an advanced stage in surgery for vessels located both cortical and in a surgical cavity in a noninvasive and marker-free manner. This will create opportunities for the use of thermography as a intraoperative perfusion imaging tool for visible vessels and parenchyma to provide diagnostic information and influence intraoperative decisions regarding regional perfusion deficits. Due to the gain of information about successful vessel preservation and tissue perfusion using thermography, the evaluation on a larger database should be topic of future research.

Author Statement

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