



Post-operative monitoring of free flaps using a low-cost thermal camera: a pilot study

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Abstract

Background Careful post-operative monitoring of free flaps is important in flap survival; immediate action increases flap salvage rate. Although various methods are available, room for improvement remains. Thermal cameras have proven their value in medicine and are nowadays readily available at low costs. The objective of this study was to evaluate the potential of an affordable infrared thermal camera and software in the detection of failing free flaps during post-operative monitoring.

Methods Free myocutaneous rectus abdominis flaps were harvested in 16 female landrace pigs and replanted after several hours of storage. All flaps were assessed with indocyanine green fluorescence angiography as well as hourly clinical assessment of skin colour, turgor and capillary refill. Furthermore, thermal photographs were taken simultaneously with the FLIR One thermal camera smartphone module. These photographs were processed in MATLAB and evaluated on their additional value as an indicator for flap failure.

Results Out of 16 flaps, three flaps failed due to arterial failure and one flap developed venous congestion. The mean flap temperature compared to adjacent control skin proved to be most indicative for flap failure. All unsuccessful flaps showed lower temperatures after failure compared to the uncompromised free flaps.

Conclusions An affordable thermal camera module can potentially contribute to post-operative free flap monitoring. Vascular compromise in free flaps can be distinguished by investigating relative temperature differences between the flap and reference skin. Until the FLIR One camera has been extensively investigated in a human population, it should be used in conjunction with conventional monitoring techniques.

Level of evidence: Level IV, diagnostic study

Keywords Thermal camera · Flap monitoring · Innovation · Flap surgery · Smartphone

Introduction

Over the last decades, free tissue flaps have been extensively used for the reconstruction or coverage of large defects following trauma, burns, infection and tumour extirpation [1]. During this procedure, the flap is completely

separated from the donor site, and the blood supply is microsurgically restored by vascular anastomoses at the recipient site. Although the overall success rate of free flap transfer is high, 5–25% of transferred flaps require surgical revision due to circulatory compromise [2]. The majority of failures are caused by venous (54–57%) and arterial thrombosis (20–43%), mostly occurring within the first 72 h [3, 4]. It is of utmost importance that a vascular compromise of a free flap is recognized as soon as possible, so adequate action can be taken as the interval between compromise and re-exploration of a flap defines its chances of flap survival [5]. The maximum tolerable ischemia time depends on flap composition, but it is usually only a couple of hours before irreversible damage to the tissue occurs [6].

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Monitoring of free flaps can be done primarily by clinical observation, by assessing capillary refill, turgor, swelling, flap colour and/or pinprick testing. However, the interpretation of these findings is highly dependent on the clinical experience of the healthcare personnel. More technologically advanced methods such as handheld or implantable Doppler ultrasonography, tissue oximetry like non-invasive oxygen saturation via near-infrared spectroscopy (NIRS) or minimally invasive tissue oxygen tension have been practiced over the past years [7–10]. As each of these methods offers both advantages and disadvantages, room for improvement remains. Therefore, there is a continuous search for better monitoring techniques during the first crucial 72 h after free flap transfer.

Surface temperature measurement is one of the oldest techniques of post-operative monitoring. Measuring temperature can be performed either by placing a sensor directly onto the skin or by measuring temperature through a contactless method. In the latter technique, infrared thermometers are positioned above the surface. The emittance of infrared light from a body is proportional to its temperature. Thus, by measuring the amount of infrared radiation emitted, the surface temperature can be deduced [11, 12]. Several clinical studies have shown that free flap temperature obtained with an infrared surface thermometer (in an experimental setting) can be correlated with flap thrombosis and eventual flap failure [13–15].

Recent technical developments within the field of thermography allowed more affordable and small infrared cameras to come to market. These cameras may offer a convenient and, more importantly, objective way to post-operatively assess the viability of the flap in any hospital at low costs. The produced image is a colour image representing the temperature of the photographed surface. It would be beneficial to standardize these images and visualize the flap temperature differences over time in order to monitor the recovery of the transferred tissue.

The aim of this pilot study was to investigate the feasibility of using an affordable thermal camera module in combination with image software for post-operative flap monitoring, to detect acute vascular compromise in free flaps.

Methods and materials

An animal experiment investigating the perfusion and replantation of free flaps in a porcine model was already planned for a different study. This unique opportunity allowed us to investigate a thermal camera in a closely controlled environment. In sixteen female Dutch Landrace

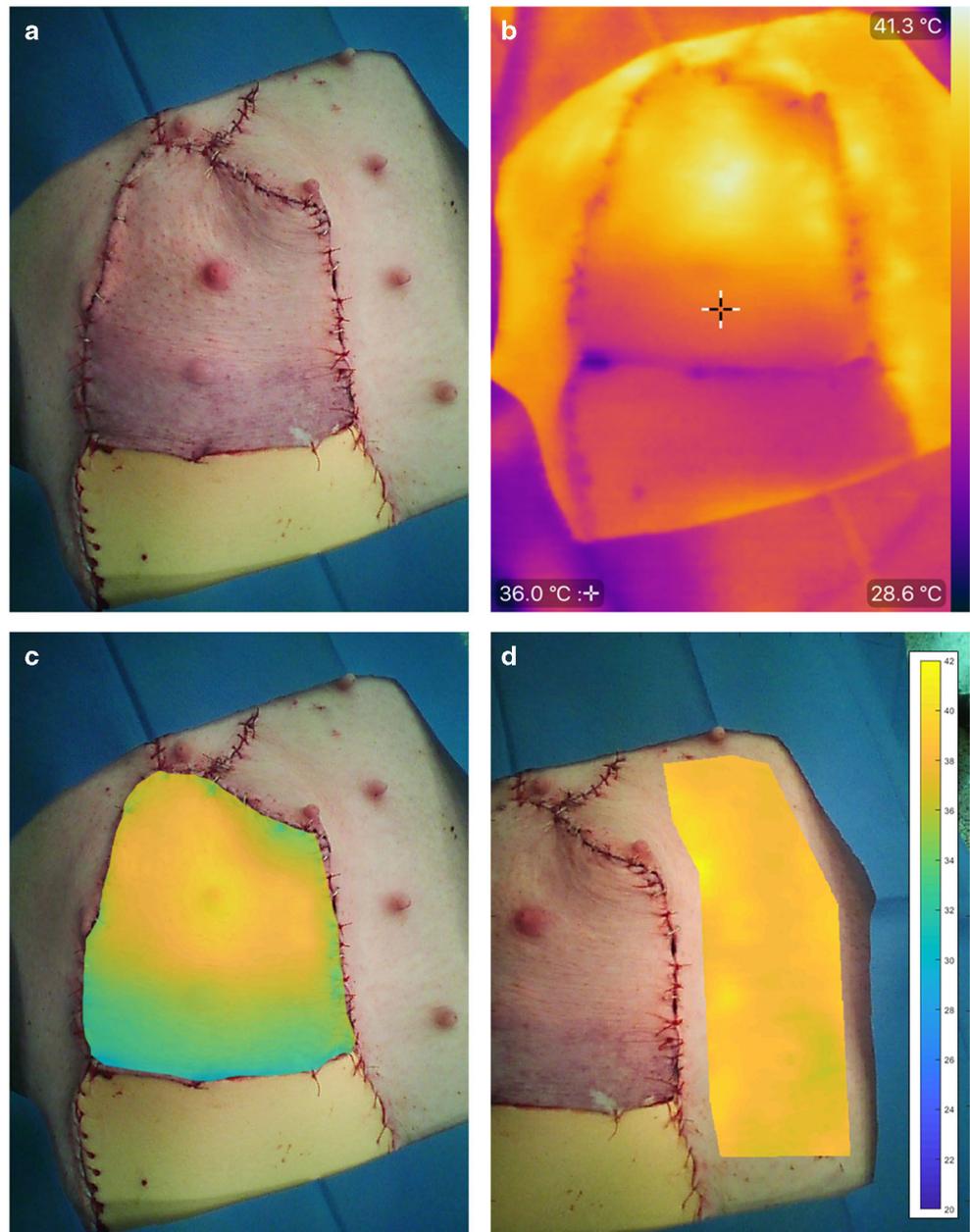
pigs, free myocutaneous rectus abdominis flaps measuring $12 \times 9 \text{ cm}^2$ were harvested under general anaesthesia, based on the superior epigastric artery and replanted to their original vascular pedicle. The use of animals with 12 h follow-up was approved by the local and national animal experimentation committee (Central Authority for Scientific Procedures on Animals, protocol-number: 2016-0034-002) and was in accordance with the EU Directive 2010/63/EU for the use and care of laboratory animals.

Post-operative flap monitoring was performed every hour until the end of the experiment, 12 h post-replantation of the myocutaneous rectus abdominis flaps. Parameters evaluated were skin colour, turgor and capillary refill. Every 4 h, indocyanine green (VERDYE 25 mg powder, Diagnostic Green, Germany, reconstituted to 5 mg/ml with sterile water for injection) was injected intravenously. The visualized perfusion was assessed using the Hamamatsu PDE Photo Dynamic Eye system (Hamamatsu Photonics, Japan) for homogeneity of the perfusion pattern throughout the flap, and the time was recorded for the intensity of the indocyanine green (ICG) signal to reach its maximum (time to peak, TTP). When flap assessment was indecisive, a milking test was performed on the anastomosed pedicle. Flaps were categorized into either viable, venous congested or arterial compromised flaps. In case of complications, revision surgery would be undertaken aiming to salvage the flap.

Thermal and visual photographs were taken prior to raising the flap and consecutive to the default hourly post-operative monitoring protocol. Thermal photographs were acquired using a FLIR One iOS second generation Thermal Camera Smartphone Module (FLIR Systems, Wilsonville, OR, USA) through the app ‘Thermal Camera+ For FLIR One’ inserted and installed on an Apple iPhone 6. The emissivity in-app setting was set to ‘matte: 95%’ to approach the emissivity of human skin of 98% [16]. Prior to taking a thermal picture, the thermal camera was re-calibrated via a built-in function in the app to minimize noise. One thermal and one visual photograph were taken centred at the free flap, approximately 15 cm from the surface (Fig. 1). Consecutively, the adjacent abdominal skin was thermally and visually photographed, serving as reference images.

The output of the FLIR One Thermal Camera Module was displayed as a heatmap image, where a colourbar correlated to the colour of a pixel to a specific temperature. Raw, numerical temperature data of each pixel were unavailable. To facilitate calculations on the acquired photographs, the images were analysed in a Matlab script (Matlab 2016a, MathWorks, Natick, MA, USA). The

Fig. 1 **a** Visual photograph taken with an iPhone 6. **b** The thermal photograph acquired with the FLIR One. **c** Converted thermal data merged with visual photo for the free flap and **d** adjacent skin as temperature reference



temperature range of the colourbar imprinted on the thermal image was read-out and converted to numerical data. Consecutively, each pixel in the thermal image was mapped to the colour bar numerical data, providing a numerical temperature dataset to be used for intra- and interflap calculations. The standardized thermal photograph was then registered onto the visual photograph by manually selecting a minimum of four characteristic reference points (e.g. flap outline, nipples) in each

photograph. The registered thermal data image was displayed as a semi-transparent overlay over the clinical photo to verify whether the image registration has been performed accurately. After verification of the matched thermal and visual photo, the entire flap and reference skin were delineated on all available visual photos, simultaneously including thermal data from the underlying thermal photograph. Visualization of the processed temperature was done by depicting the thermal information

using a standardized colour scale identical for all flaps and merged with the clinical photo (Fig. 1).

Having temperature and visual photos available simultaneously, surface temperature differences can be calculated and linked to clinical appearance. In this study, the surface temperature of the replanted flap was compared to the reference skin, and the temperature difference of the free flap calculated over time.

Results

The thermal data of flaps harvested from 16 healthy female pigs (63–84 kg) were retrospectively analysed to find correlations between the obtained thermal images, clinical observations and ICG perfusion patterns. Out of the 16 replanted flaps, four flaps suffered from post-operative complications. For the 12 healthy flaps, the mean temperature and 95% confidence interval were calculated for each time point to serve as a baseline for analysis. During ICG perfusion analysis, a homogenous perfusion pattern, taking < 30 s to peak, was witnessed in all successfully replanted flaps. Two flaps (#1 and #11) were insufficiently perfused directly after replantation. Flaps #5 and #14 displayed signs of acute arterial thrombosis during the observation period.

Flap #1 showed clinical signs of venous congestion directly after replantation, for which immediate action was taken. An extra venous anastomosis was created; however, this proved to be unsuccessful, as no clinical improvement of the free flap was witnessed throughout the experiment. ICG injections showed impaired, inhomogeneous perfusion throughout the flap with prolonged time to peak (Table 1) even though the arterial anastomosis was patent. This observation correlated with the overall lower temperature of this flap compared to both the

reference point and to the mean temperature of the healthy flaps, as can be seen in Fig. 2.

Flap #5 rapidly turned white with no measurable capillary refill close to 12 h after replantation. The clinical diagnosis of acute arterial failure was made. As this reached the end of the experiment, no revision surgery was performed. Minimal ICG perfusion was observed after this event. Thermal information revealed a steep decrease in temperature difference from 0.5 °C to –5.5 °C after this event. Additionally, the mean temperature of this flap greatly differed from the flaps showing no complications. After ending the experiment, the vascular pedicle was dissected and arterial thrombosis at the anastomosis was confirmed.

Flap #11 presented discoloured, purple areas directly after replantation. In addition, the flap was more pink in the centre in compared to the top and bottom. Initially, the colour seemed to improve spontaneously. However, the flap's clinical appearance did not improve after 6 h of monitoring and revision surgery was performed. An arterial thrombus was removed in this process; however, the flap did not show any improvement afterwards. Following the graph in Fig. 2, a decrease in temperature was observed, even after re-exploration with revision of the arterial anastomosis. At the end of the experiment, the free flap was investigated, revealing another arterial thrombus in the main arterial branch within the flap (in-flap thrombosis).

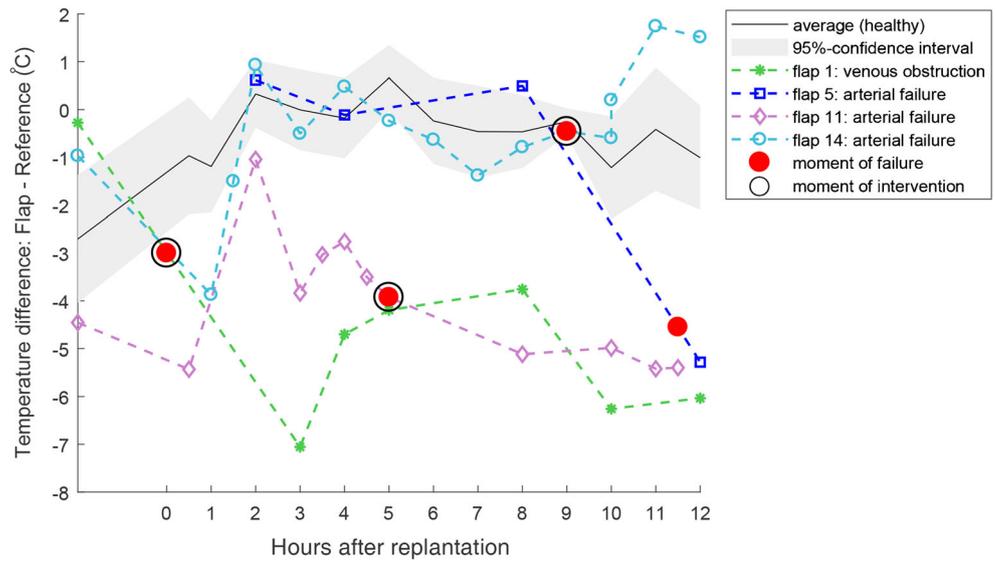
Flap #14 did not show abnormalities during the hourly flap flap monitoring, until approximately 9 h after replantation. The flap quickly turned pale with no measurable capillary refill, despite a normal turgor. Revision surgery was performed within the hour, after which the flap clinically improved (Fig. 3). The temperature graph in Fig. 2 reflects this observation by an increase in temperature over time after revision surgery. Inspection using ICG revealed normal perfusion patterns throughout the rest of the experiment.

Table 1 Findings of systemic injection of indocyanine green in the failed flaps. Values in italics indicate moments of flap failure

	Flap #1		Flap #5		Flap #11		Flap #14	
	TTP	%	TTP	%	TTP	%	TTP	%
1 h post-repl.	NA	100	< 30 s	100	< 30 s	30	< 30 s	100
4 h post-repl.	NA	90	< 30 s	100	> 5 min	5–10	< 30 s	100
8 h post-repl.	> 5 min	30	< 30 s	100	> 5 min	5–10	< 30 s	100
12 h post-repl.	> 5 min	30	> 5 min	10	> 5 min	5–10	< 30 s	100
	Venous congestion		Arterial thrombosis		Arterial thrombosis		Arterial thrombosis	

NA not available, TTP time to peak (ICG), % homogeneity of flap perfusion pattern

Fig. 2 The difference between the replanted flap and adjacent reference skin temperature. Failed flaps are indicated in dashed lines with a red dot marking their moment of failure



Discussion

The aim of this study was to investigate the feasibility and potential of using a FLIR One thermal camera in post-operative free flap monitoring for detection of vascular compromise.

In case of arterial obstruction, blood flow is abruptly halted. As the flow of warm oxygenated blood stagnates,

the temperature of the flap decreases and the flap becomes pale. Venous obstruction leads to congestion of blood which can give a transient increase in temperature [13]. As the pressure builds and the congestion upholds, the blood flow will decrease and eventually stagnate. This causes loss of tissue oxygenation, increased hydrostatic pressure, and leakage of fluid into the interstitium (oedema). In turn, increased interstitial pressure may inhibit

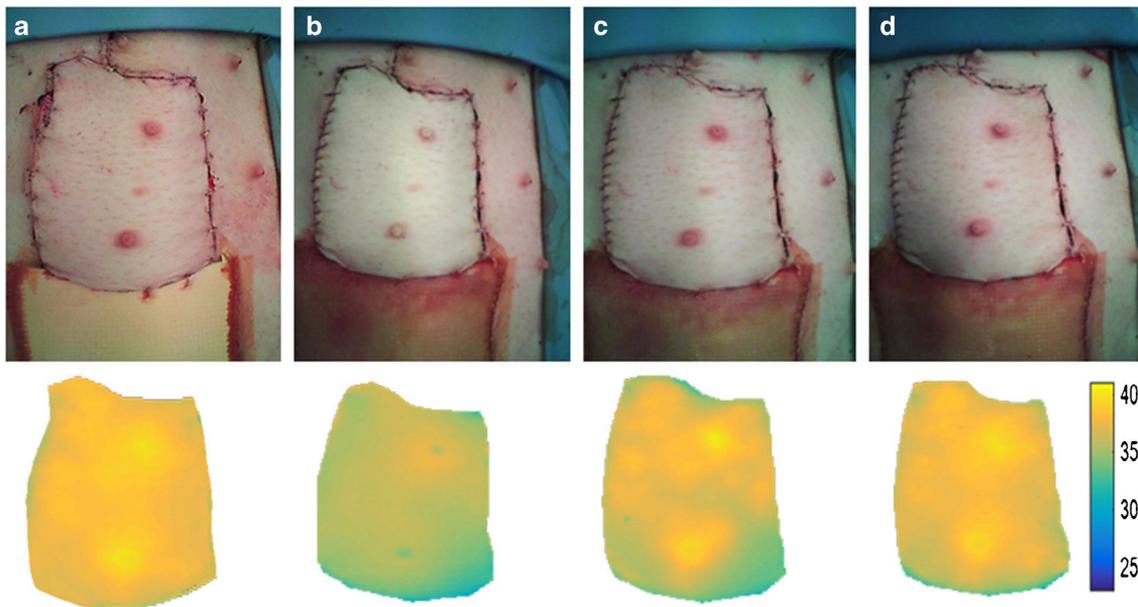


Fig. 3 Visual and thermal photographs of flap #14 which suffered from acute thrombosis. **a** Flap prior to failure (5 h post-replantation). **b** Nine hours after replantation, a pale colour on the visual photograph and a

lower temperature on the thermal photograph can be witnessed. **c** One hour after revision, temperature has increased. **d** Photo at 12 h; 3 h after revision

arterial inflow, causing a decrease in temperature and eventually flap failure resulting in a uniform temperature decrease. The gradient of the flap's temperature may therefore be indicative to distinguish between arterial or venous failure. Following this pathway of physiology, most literature studies suggest to compare the average flap temperature to adjacent skin as reference temperature [14, 15]. Effects of environmental conditions that affect the flap temperature, such as air flow or coverage by blankets, can be minimized this way. In this pilot study, all failed flaps could be distinguished from flaps without post-operative complications when assessing the mean temperature of the flap with the adjacent skin as control region.

When comparing the mean flap temperature after replantation to the reference adjacent skin, flap #5 reached a 6 °C temperature difference between the measurements before and after arterial failure. This observation is in line with a study of Kraemer et al., which argued a sudden drop of 3 °C is indicative of arterial thrombosis [13]. Coincidentally, a thrombosis occurred during clinical inspection of flap #14, for which re-exploration could be performed within 10 min after witnessing this event. Blood flow was re-established 45 min later. The lack of detecting the expected decrease in temperature on the thermal images might be due to the sudden onset of the thrombosis and adequate action; there was little time for the flap to cool down. ICG was injected per protocol every 4 h; the event and successful revision surgery occurred within this period and does therefore not show an increase in time to peak nor inhomogeneous perfusion patterns in Table 1.

Apart from distinguishing between successful and failed flaps, the overview of surface temperatures that the FLIR One photographs provide enables the clinician to detect localized temperature variations throughout the flap, which are impossible (or very elaborate) to detect with a regular skin thermometer. With this information, special attention can be given to these colder areas. Localized peripheral temperature drops are no immediate indication for revision surgery but may be a reason to increase clinical attention and inform the patient of potential flap necrosis. For example, Fig. 1 shows a temperature gradient over the flap, where the proximal side is warmer in contrast to the distal area. In clinical context, partial flap loss may occur in such areas.

This animal model provided a unique opportunity to collect data using the FLIR One thermal camera after replantation of a free flap without interfering with the clinical results of the original research. Due to the observational character of this study, several photos at the

fixed time points could not be recorded for practical or logistical reasons. However, with the majority of data successfully recorded, troubled flaps could be distinguished from uncomplicated replanted flaps.

Available evidence suggests that the FLIR One camera module does not appear suitable for accurate temperature measurements [17]. However, when evaluating temperature differences, temperature values as such seem clinically of less importance. For future research, direct comparison to skin thermometer measurements would help establishing the accuracy and reliability of the FLIR One thermal readings for both temperature differences in skin temperature.

Apart from monitoring post-operative transplanted tissue such as free flaps, the FLIR One may be used for additional applications. In essence, the FLIR One might be useful in any condition that influences the surface temperature. Brushing on the area of transplantations, thermal imaging could have added benefit in monitoring replanted tissue, e.g. after traumatic amputation of limbs. This low-cost device may aid in the assessment of the level of tissue viability and peripheral circulation in ischemic limbs [18–22]. Furthermore, it may have its purpose in the detection of perforators and their perfusion area [23–27]. It may also be used to assess subclinical inflammation in pressure ulcers and diabetic feet or act as an early warning sign for ulcers [28–30]. Lastly, the FLIR One camera could be used in the assessment of burns [31, 32].

Conclusion

The FLIR One application has potential use in post-operative monitoring and early detection of vascular compromise in free flaps. Particularly, comparing mean flap temperature difference to an adjacent reference location seemed to be effective in retrospectively distinguishing failed flaps from viable flaps. In addition, the overview provided by the thermal photographs might point to areas that need special attention. However, due to the limited number of animals in this study, further investigation is needed before the FLIR One thermal camera should be used as a modality on its own (replacing the skin surface thermometer). Until then, the FLIR One should always be used in conjunction with other monitoring techniques such as Doppler, capillary refill, skin colour and turgor.

Author's contributions 1. S. Hummelink: the conception and design of the study, analysis of data, drafting the article, revising the article critically for important intellectual content and final approval of the version to be submitted.

2. A.S. Kruit: the conception and design of the study, acquisition of data, analysis and interpretation of data and final approval of the version to be submitted.

3. A.R.W. van Vlaenderen: analysis and interpretation of data, drafting the article and final approval of the version to be submitted.

4. M.J.M. Schreinemachers: the conception and design of the study, revising the article critically for important intellectual content and final approval of the version to be submitted.

5. W. Steenbergen: the conception and design of the study, revising the article critically for important intellectual content and final approval of the version to be submitted.

6. D.J.O. Ulrich: the conception and design of the study, acquisition of data, revising the article critically for important intellectual content and final approval of the version to be submitted.

Compliance with ethical standards

Conflict of interest S. Hummelink, A.S. Kruit, A.R.W. van Vlaenderen, M.J.M. Schreinemachers, W. Steenbergen, and D.J.O. Ulrich declare that they have no conflict of interest.

Ethical approval This study was approved by the Central Authority for Scientific Procedures on Animals (protocol-number: 2016-0034-002) and was in accordance with the EU Directive 2010/63/EU for the use and care of laboratory animals.

Patient consent Patients provided written consent for the use of their images.

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