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Pressure distribution and flow characteristics during negative pressure wound therapy

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ABSTRACT

Aim of the study: Negative pressure wound therapy is thought to improve wound healing by altering capillary perfusion. However, despite many theories, the underlying mechanism of action remains controversial. Recent evidence suggests an increased tissue pressure and a temporary decreased microvascular blood flow as the main reasons for the good clinical results [1]. In an attempt to further explain the mechanism of action, we investigated the pressure distribution on the foam interface, and the influence on perfusion in a pre-experimental design.

Materials and methods: Pressure distribution was measured using a sensor based on a capacitive dielectric elastomer with flexible electrodes. In vitro flow measurements were done with vessel imitations in a block of 300 bloom ballistic gel to simulate soft tissue.

Results: A peak pressure of up to 187 mmHg (255 g/cm2) within the foam interface, as well as decreased perfusion, were found using a standard negative pressure wound therapy setup. In conclusion, negative pressure wound therapy applies positive pressure to adjacent tissue and decreases local flow. The amount of suction applied is proportional to the pressure on the foam interface and reduction in flow.

Conclusion: In line with previous studies investigating the underlying mechanism of action, these findings may contribute to possible alterations in the use of negative pressure wound therapy, e.g. lowering suction pressure in patients with diminished peripheral blood flow.

1. Introduction

The surgical treatment of chronic and infected wounds remains challenging [2,3]. Transient negative pressure wound therapy (NPWT) has become an integral part of wound conditioning after local debridement [4–9]. Despite undisputed positive effects of its healing potential, varied evidence exists about the underlying mechanism of action [1,10–17]. This variability may arise from the wide range of conflicting evidence regarding the effects on local pressure and capillary perfusion [18–23]. A common assumption is that the hypobaric pressure used to enable drainage of excess fluid leads to a reduction in tissue edema and facilitates blood flow [24]. Furthermore, a positive effect on the endothelial cell function, as well as the induction of angiogenesis and formation of granulation tissue has also been described [19,25]. Despite seemingly reliable evidence suggesting that NPWT increases tissue pressure and decreases capillary perfusion, numerous studies report otherwise [1,26]. A possible explanation for this apparent paradox has recently suggested that the perfusion measuring device may be the cause of the conflicting evidence [27]. Laser Doppler readings need to be interpreted carefully, since changes in the velocity of partially occluded vessels may indicate increased total perfusion. Due to the fact that further studies in the literature have failed to take these considerations into account, we attempted to contribute to the understanding of the underlying mechanism of action from a different angle. The intent of our study was to investigate the pressure distribution on the foam interface and the influence on perfusion. We hypothesized that the NPWT applies positive pressure to the surrounding tissue and thus decreases perfusion.

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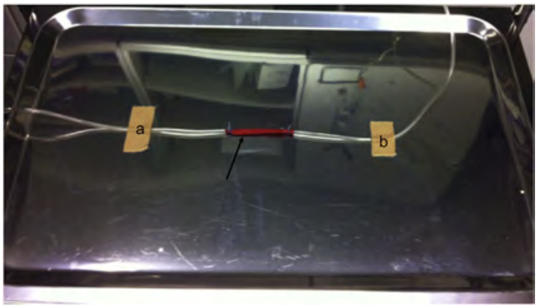

Fig. 1. Perfusion test using single vessel imitation (arrow) with afferent (b) and efferent (a) tube before covering with a standard NPWT system.

2. Methods

2.1. Perfusion setup

In the first setup, a rubber tube measuring 3 mm in diameter and 0.2 mm in wall thickness (to imitate a single vessel) was mounted on a rigid metal laboratory bench. The NPWT system (Info V.A.C. ™, KCI Medizinprodukte GmbH, Wiesbaden, Germany) was assembled to cover the entire tube, with the efferent end leading into a collecting cylinder on a gauged electronic scale. The intensity was set to medium in continuous pressure mode for all tests. The afferent tube was connected to a standard infusion system (Intrafix®, Braun, Germany) (Fig. 1).

In the second setup, multiple rubber tubes of 2mm diameter and 0.5 mm wall thickness were embedded in a block of 300 bloom ballistic gel to simulate soft tissue (Type A, TMP-products, Bad Camberg, Germany) (Fig. 2).

A cavitation leaving the tubes covered with at least 5 to 7 mm of gel was filled with the foam and sealed by a standard dressing. The afferent and efferent ends were connected similar to the first setup.

2.2. Pressure tests

Pressure distribution was measured using a sensor based on a capacitive dielectric elastomer with flexible electrodes (XSENSOR, Interfaceforce, Tegernsee, Germany) (Fig. 3).

Under tensile loading, the distance between the electrodes decreases, leading to a change in voltage and thus increased capacitance. A standard NPWT dressing (KCI Medizinprodukte GmbH, Wiesbaden, Germany) connected to a NPWT device was centrally placed above the sensor mat for measuring. The intensity was set to medium in continuous pressure mode for measuring.

All data collected are presented as arithmetic means. To test for the probability distribution of the variables, the Kolmogorov-Smirnov test was used. Parametric data of linear variables were compared using the student T-test or the analysis of variance (ANOVA). A p-value < 0.05 was set to indicate significance for all tests. The software used to perform the statistical analysis was the "Statistical Package for the Social Sciences" (SPSS Inc., Chicago, IL, USA) Version 25.0 and Graph Pad PRISM, Version 5.0.

3. Results

3.1. Perfusion test

NPWT application in our experimental system led to a significant decrease in flow related to the amount of suction applied. Using a suction pressure of 125 mmHg and 200 mmHg, a flow rate of 60 ml/min and 20 ml/min was found, respectively (Figs. 4 and 5).

This difference was significant ($p = 0.02$) and lower than the baseline flow of 170 ml/min ($p = 0.01$). Using the ballistic gel with vacuum levels of 125 mmHg and 200 mmHg, a flow rate of 142 ml/min and 136 ml/min was observed, respectively. This difference was also significant ($p = 0.04$) and lower than the baseline flow ($p = 0.01$).

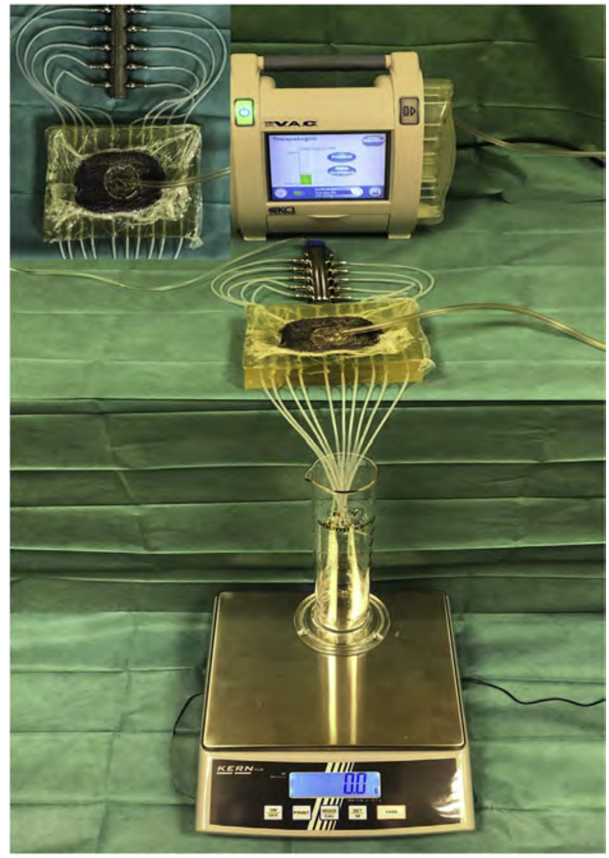

Fig. 2. Perfusion test with multiple rubber tubes embedded in a block of 300 bloom ballistic gel (Type A, TMP-products, Bad Camberg, Germany) covered by a standard NPWT system. The efferent tube endings lead into a collecting cylinder on a gauged electronic scale.

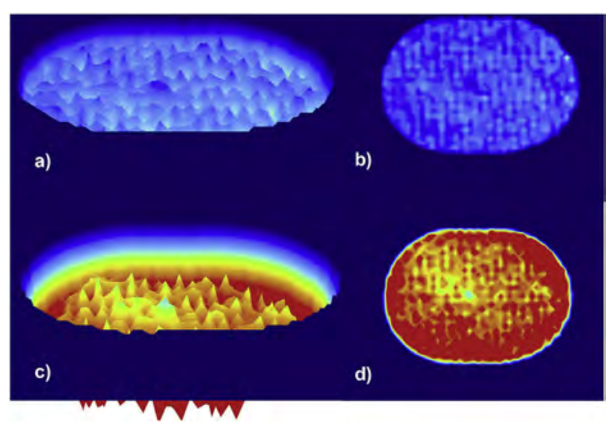

Fig. 3. Three (a and c) and two-dimensional (b and d) and pressure profile of the entire surface area of the foam (75 cm^2). Centrally, in close proximity to the trackpad is an area of significantly lower positive pressure.

3.2. Pressure test

The sensor recorded a significant increase in pressure after the onset of suction. With respect to the entire surface area of the foam (75 cm^2), an average pressure of 78 mmHg (1.04 N/cm^2) was detected until 125 mmHg of vacuum was reached (Fig. 6).

A maximum pressure of 187 mmHg (2.5 N/cm^2) was detected

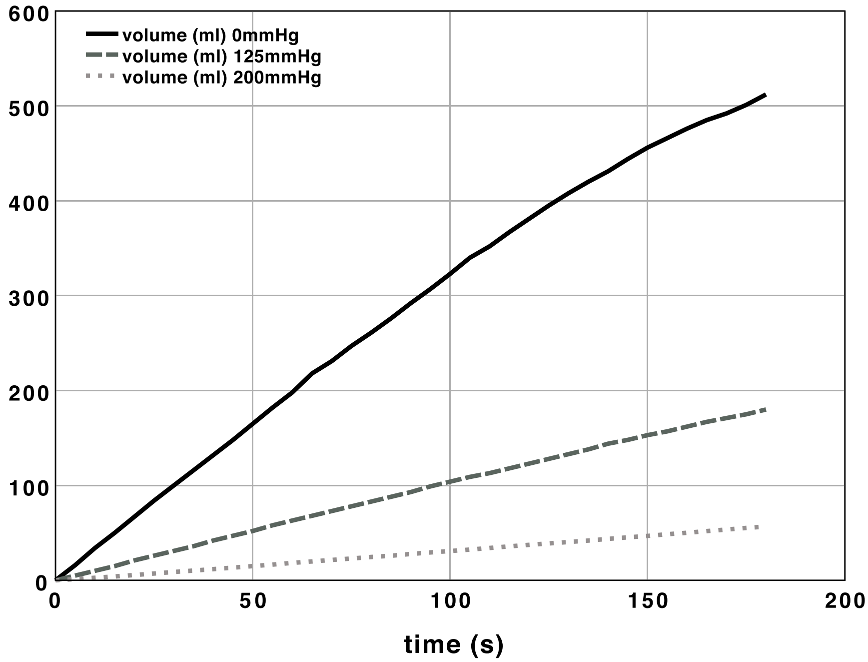

Fig. 4. Results of the simple perfusion test using a single vessel imitation. A significant difference between 125 mmHg (dashed line) and 200 mmHg (dots) of suction pressure was found in comparison to baseline flow (solid line).

around the foam edges. An area of about 2 × 2 cm beneath the trackpad showed a significantly lower average pressure of 60.7 mmHg ($p = 0.02$).

4. Discussion

The effects of NPWT on soft tissue perfusion and pressure distribution around adjacent tissue are not consistently described in the literature. Since certain measuring techniques for local blood flow need to be interpreted carefully, we attempted to contribute to the explanation of the underlying mechanism of action by focusing on a different investigational aspect where compressive forces of the foam were quantified to create a three-dimensional pressure profile. We also investigated the effects of vessel perfusion during NPWT in an experimental in vitro design. Results from these experiments show that a peak pressure of up to 187 mmHg (255 g/cm^2) within the foam interface, as well as decreased flow, were found using a standard NPWT setup. In line with previous investigations, our results show that NPWT applies a positive pressure to its surrounding area, and thereby increases tissue pressure, which in fact is incongruous with increased perfusion.

A recent study by Kairinos et al. described the flaws of laser Doppler flowmetry (LDF) as one of the main reasons for the conflicting evidence

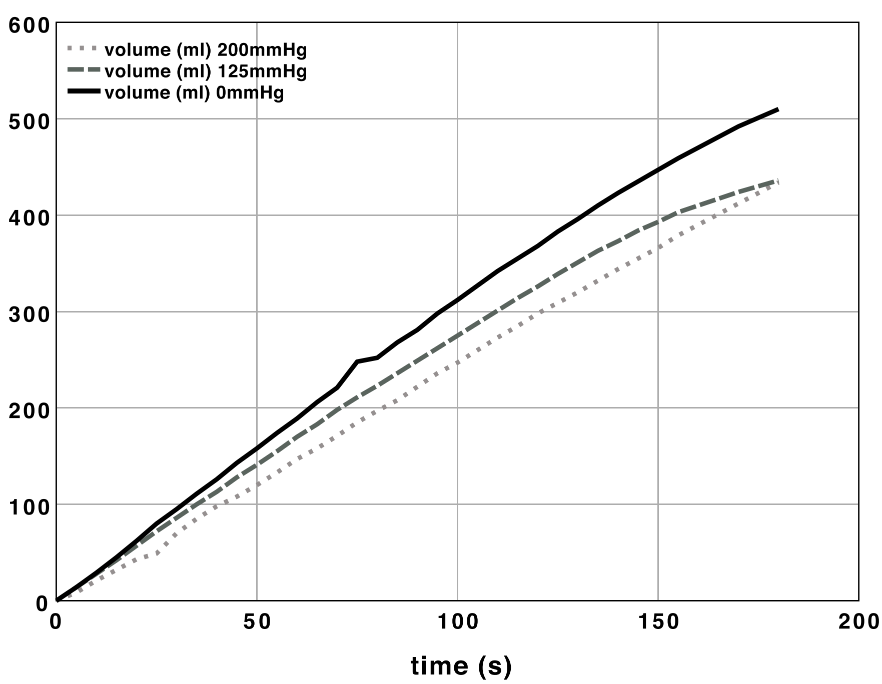

Fig. 5. Results of the perfusion test using ballistic gel. A significant difference between 125 mmHg (dashed line) and 200 mmHg (dots) of suction pressure was found in comparison to baseline flow (solid line).

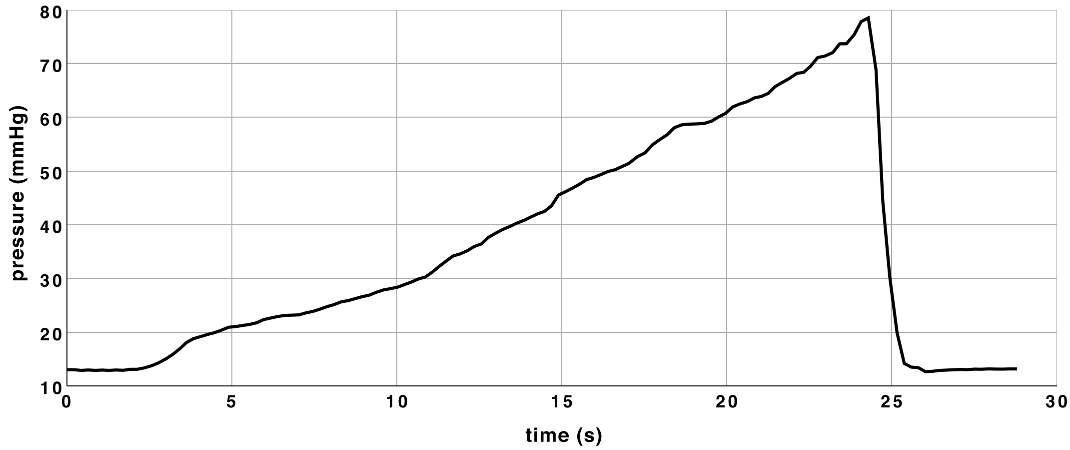

Fig. 6. Rise in average pressure up to a maximum of 78 mmHg (1.04 N/cm2) at 125 mmHg of vacuum.

regarding the underlying mechanism of action [27]. In theory, laser Doppler measures blood flow by multiplying the concentration and velocity of red blood cells through a shift in light wavelength [28]. Although numerous studies using LDF have found increased perfusion during NPWT, our results indicate that perfusion is in fact reduced, at least temporarily. Similar to the kinking of a garden hose, compression of a vessel and thereby increasing the velocity of red blood cell flow is the most likely explanation for the LDF findings. Timmers et al. investigated the response of cutaneous blood flow to NPWT on the intact skin in healthy volunteers [26]. According to LDF readings, the perfusion was constantly increased up to a maximum suction pressure of 500 mmHg. Compared to our setup, they used a quadrupled intensity of suction pressure. Since the capillary perfusion pressure of normal skin ranges between 10 and 30 mmHg, the intensity used is most likely to compress the underlying capillaries and result in decreased total perfusion. The partially occluded vessels lead to an increase in the velocity of red blood cells, thus explaining the perfusion readings by LDF. Direct measurements of tissue pressure were made by Kairinos et al. using a Codman's intracranial pressure sensor during NPWT in chronic wounds [1]. Covered by 5 and 10 mm of soft tissue, the sensor detected an increased pressure of up to 16 mmHg. A wide variation in the pressure distribution was found for different wound localizations, reflecting the different consistencies of the soft tissue. In conjunction with our results, this demonstrates that the amount of pressure absorbed within the first 10 mm of the adjacent tissue leads to increased local pressure.

Regarding the pressure distribution in the three-dimensional profile of the foam, a significantly higher intensity close to the foam edge in comparison to the central part beneath the trackpad was found. With respect to the interpretation of LDF readings, these findings were partially confirmed by Borquist et al. [18]. They found a decrease in microvascular blood flow 0.5 cm from the wound edge as soon as suction pressure was applied. Simultaneously, an increase in perfusion 2.5 cm away from the wound edge was also described. In light of the better understanding revealed from our experiments, the increased flow more distal to the wound reflects the increase in velocity of the red blood cells rather than an increased total perfusion. In close proximity to the wound, where increased tissue pressure most likely occluded all capillaries, the LDF correctly recorded reduced perfusion. Our results therefore suggest that LDF readings detect velocity rather than perfusion changes, providing a possible explanation for findings from other studies [29].

In the context of the current study, and considering the pressure profile of the foam, the total size of the foam influences the sum of pressure to the adjacent tissue in plane wounds. A smaller foam will apply less pressure since the size of the trackpad remains constant. This might explain the findings of Ichioka et al. who created superficial wounds in mice [30]. Perfusion was monitored by directly visualizing the subdermal capillaries with an intravital fluorescent microscope. However, the polyurethane sponge used in the experiment was significantly smaller than the wound itself and placed along the wound margin covered by a transparent dressing. At 125 mmHg, increased perfusion was detected. Our results might partially explain these findings since the small sized foam is less likely to apply any compressive forces to the distantly observed capillaries and influence perfusion. Most likely, stretching of the adjacent soft tissue led to an increased diameter, observed subdermal plexus and increased perfusion. To our knowledge placing the sponge outside the wound itself seems to differ significantly from the standard treatment and is thus not subject to the biomechanical properties of normal NPWT.

Our investigation was designed to shed further light on the underlying mechanism of NPWT and found a peak pressure on the foam interface of up to 187 mmHg (255 g/cm^2) in conjunction with decreased flow. These findings contradict the common assumption of a reduction in local tissue pressure and confirm the results of other recent studies. Nevertheless, there is no doubt in the long term that NPWT increases the overall perfusion of the wound bed. The reduction of tissue edema and stimulation of angiogenesis may contribute to this effect. However, this influence cannot be assessed by our investigation. Similar to pharmacokinetics and dynamics, we observed the dynamics of NPWT dressing in relation to the local environment. The kinetics may represent hormonal and biochemical stimuli of perfusion which need further investigation.

Notably, our study was subject to limitations since all our experiments were carried out using an experimental in vitro design. This includes difficulties in rebuilding the complex anatomy of multilayered vessels and the capillary bed. Furthermore, no investigation directly measuring LDF readings was carried out. Nevertheless, we contend that there are no appreciable differences in the pressure measurements and three-dimensional profile in tissues versus using an in vivo design. Regarding the flow readings, ballistic gel has also been determined to reliably imitate human tissue in forensic sciences [31,32]. Considering our current findings, additional studies investigating in vivo perfusion without using LDF are needed to further understand the mechanism of action in NPWT.

5. Conclusion

For now, we conclude that NPWT applies pressure to adjacent tissue and decreases local blood flow, at least temporarily. The amount of suction applied is proportional to the pressure on the foam interface and reduction in perfusion. In line with previous studies investigating the underlying mechanism of action, our findings may contribute to possible restrictions in using NPWT in patients with diminished peripheral blood flow.

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Declaration of competing interest

Dr. Taeger is a consultant for Kinetic Concepts, Inc. The other authors have no financial interest to declare in relation to the content of the article.

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