The role of the thermal conductivity of dressings in prevention and treatment of wounds

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The thermal conductivity of dressing materials and structures is a fundamental physical property of high clinical relevance in both prevention and treatment of acute and chronic wounds. The thermal conductivity measurement of a dressing expresses the extent of metabolic heat transfer from the tissues under the dressing, outward through the dressing structure. This value can provide a means to evaluate the expected heating of the skin under the dressing in both prophylaxis and treatment applications. Excessive heating of skin under a dressing leads to perspiration, which compromises the ability of skin to resist bodyweight and external forces and also, positively correlates with a state of tissue inflammation. The thermal conductivity of dressings should be assessed in the framework of contemporary efficacy research, performance evaluations and in the future, also as an integral part of dressing testing standards. This article provides an educational perspective regarding the importance of considering the thermal conductivity of dressing materials and structures in performance analyses. The work further describes basic concepts in bioengineering laboratory measurements of this important property in the function of dressings, in the physiological and clinical contexts of wound prevention and care.

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Wounds of all types, including traumatic injuries and burns, surgical wounds and all chronic wounds, such as pressure ulcers (PUs) and diabetic foot ulcers (DFUs) are considered one of the most important, impactful, expensive and common medical problems. All wounds are treated by means of dressings. In fact, wound dressings are likely the oldest type of a medical device, however, modern dressings have come a long way from the historically used cobwebs, leaves or other natural materials, or the cloths that followed. The performance of any contemporary, preventative or treatment wound care dressing is a function of their microarchitecture, resulting from their material composition, construction and manufacturing process.

One fundamental group of material properties that determine the function of dressings in prevention and treatment is their thermal properties. Thermal properties of dressings are those properties of each of their material components which altogether determine the conductivity (clearance) of heat from the skin-facing or wound-facing side of the dressing to the environment (which can be a contacting clothing item, the support surface or the ambient air). In general, there are a number of thermal transport properties used by engineers in various fields, such as the thermal conductivity, thermal diffusivity or specific heat capacity, and each of these characterises the ability of materials to conduct, transfer, store and release heat.

In the context of wound prevention and treatment, however, among the known set of different thermal properties, the thermal conductivity of dressing materials and structures is the most relevant property, particularly with regards to preventative applications, where the dressing is used as an interface structure between the body and the support surface, or between the body and a medical device. Of note, prevention of the heat buildup on and within skin by modulating excess inflammation is an important physiological benefit with regards to both prevention and treatment of wounds (Cutting and Gefen, 2019) and if performed effectively by a dressing, works synergistically with its thermal conductivity performances, as explained further below.

Focusing now on pressure ulcer prevention (PUP), PUs are caused by sustained mechanical loading and deformations of the skin and subcutaneous tissue layers between internal stiff anatomical structures and external support surfaces or devices. The skin microclimate (temperature, humidity and airflow near the skin surface) is an established indirect PU risk factor (Kottner et al, 2018). Temperature and humidity affect the structure and function of the skin, increasing or lowering the individual damage thresholds for the skin and underlying soft tissues.

From a PUP perspective, the effects of humidity and temperature close to the skin surface and directly on the skin and within skin tissues are inextricably linked to the concurrent skin and soft tissue deformations. This is because microclimate affects the skin morphology and mechanical properties, and these then influence the susceptibility of skin and underlying soft tissues to damage when the relevant body region is subjected to sustained pressures, frictional forces and shearing distortions. For example, Bhargava and colleagues (2014) reported that localised skin temperature rise of 0.25–0.9°C could be associated with an inflammatory process. While taking into account that PU risk profiles of patients vary substantially and depend on the skin and tissue fragility of the individual, for effective PUP, the lower the heat accumulation between the weight-bearing body and dressing/support is, or between a skin region and a contacting medical device, the better.

Skin temperatures are normally lower than the core body temperature (lower skin temperatures occur over the protruding body parts, e.g. the nose, whereas higher skin temperatures are characteristic to sites above skeletal muscle tissues). At the sacral area, which is considered to be at high PU risk in patients who are lying supine or in a semi-Fowler position, the baseline skin temperature (for healthy, intact skin) is typically in the range of 29–31°C, however, after 1 to 3 hours of continuous lying, the sacral skin temperature rises by 3–4ºC above the aforementioned baseline level, due to occlusion and accumulation of metabolic heat near and at the skin-support interface (Lechner et al, 2020). A dressing applied to the intact sacral skin in such a scenario, for prophylactic purposes, may or may not add significant additional heat to the occlusion caused by lying supine on the mattress alone, depending on the specific thermal properties of the added dressing and the support surface.

Excessive trapped heat under a dressing used for prophylaxis has several undesirable effects on skin and subdermal tissues, which synergistically increase the risk for PU development. Firstly, a warmer skin increases the metabolic tissue demand for cellular oxygen and nutrients by approximately 10%/°C (Stone et al, 2015), hence, warm skin subjected to pressure and shear is more susceptible to ischaemic damage than skin at a normative temperature. Accordingly, the 'Norton Plus scale' assigns high-risk scores to fevering patients (core temperature >37.6 °C) based on clinical experience indicating that such patients are more susceptible to PUs (Berglund and Nordström, 1995). Furthermore, when the skin temperatures increase over a threshold of approximately 33°C (depending on the core body temperature of the individual), local perspiration is triggered, which results in moisture on skin (McCaffrey et al, 1979; Gefen, 2011; Zeevi et al, 2018).

This increases the stratum corneum hydration and may result in dissolution of crosslinks between dermal collagen molecules and, thereby, cause softening and weakening of the skin, which becomes more susceptible to failure and tearing at lower force and deformation levels (Lachenbruch, 2005; Reger et al, 2007; Cravello and Ferri, 2008; Gefen, 2011). Moreover, when the skin becomes moist, its coefficient of friction (COF) with any contacting materials or objects, including dressings, is approximately doubled (Gefen, 2011; Sopher and Gefen, 2011; Shaked and Gefen, 2013; Schwartz et al, 2018). This proportionally increases the skin and underlying tissue distortions in shear and further contributes to a PU risk or the risk of further breakdown of periwound skin if an injury already exists.

Importantly, there is an established continuum between prevention and treatment of existing wounds, particularly PUs and DFUs. Even if such chronic wounds already exist, prevention is still fundamentally relevant and critical for protecting the periwound tissues from the forces, pressures and shear that have caused the original wound and which further threat adjacent non-injured tissues. Noteworthy, in an existing chronic wound, the ongoing inflammatory process adds risk to periwound tissues that may be affected by localised oedema; the periwound oedema may compromise blood perfusion into the wound-bed, which is essential for healing (Gefen, 2018; Gefen et al, 2019a). Hence, understanding the thermal function of dressings in the context of prevention may apply to treatment as well. For example, theory and experimental findings applied to intact skin in the context of PUP may be indicative of outcomes in periwound skin of existing PUs, as relevant to pressure ulcer treatment (PUT).

Thermal conductivity and its role in the performance of dressings

The impact of microclimate conditions on skin and deeper tissue integrity, viability and function, as reviewed above, highlights the importance of analysing the thermal properties and specifically, the thermal conductivities of prevention and treatment dressings, whether such dressings are already commercially available, or where new dressings are under development.

Thermal conductivity refers to the intrinsic ability of a material to transfer or conduct heat. Conduction of heat is one of the three physically-possible methods of heat transfer, the other two being convection and radiation. The reciprocal of thermal conductivity is thermal resistivity, which measures the ability of a material to resist the heat transfer, i.e. serve as a good thermal insulator. The rate at which heat is transferred between sites within a material depends upon the magnitude of the temperature gradient between the respective sites (for instance, if one face of a material is kept at a higher temperature than the opposite face), as well as on the specific thermal characteristics of the material. The latter property is called the thermal conductivity coefficient which is often marked as 'k' and is measured in Watt per metre kelvin [W/m·K].

In physical terms, the thermal conductivity is formulated as $k = QL / A\Delta T$ where Q is the amount of heat transfer through the material or structure (i.e. combination of different materials) in Watt [W], L is the thickness of the material or composite structure [m], A is the area of the specimen in square metres [m^2] and ΔT is the temperature difference across the specimen in kelvin [K]. In general, a material or structure with a large k is a good heat conductor, whereas a material or structure with a small k is known as a good thermal insulator. The 'k' of materials or structures may further depend on the internal water content, which is highly relevant in the context of dressings.

For example, a certain foam dressing may have a greater k when it becomes moist due to absorption of sweat or other body fluids with respect to its dry condition, because as the dressing absorbs and retains the fluid, the fluid in the dressing also participates in the heat transfer. That is, the dressing in fact becomes a bi-phasic foam-fluid composite material, where the increasing fluid weight fraction gradually elevates the 'k' since water is a better heat conductor than foam.

Specifically, typical thermal conductivity values for open-cell polyurethane foams which are commonly used in dressing materials are in the range of 0.02 to 0.06 W/m·K at the dry foam state (Glicksman, 1994; Pau et al, 2014). These are rather low values due to the air trapped in the micro-pores of the foam (air and other gases are good insulators, specifically when they are trapped in foam so that there is no gas movement and, therefore, nearly no convection). Contrarily, water at 30°C (the approximate skin temperature) have thermal conductivity of 0.615 W/m·K which is more than 10-fold the aforementioned thermal conductivity of the dry foams.

Hence, the thermal conductivity of a foam dressing applied to skin is bounded between that of the dry foam material and the physical limit of water thermal conductivity; the thermal conductivity of the moist foam will increase with the retained perspiration, exudate or other fluids, that is, dressings will transfer heat from the skin more effectively when moist. Another important factor that affects the 'k' of dressing materials is the magnitudes of pressure and shear applied to the dressing (if any), as these will act to distort the microarchitecture of the foam and, in particular, will change the shapes and sizes of the pores in foam dressings, thereby affecting the amount of the air trapped in the dressing and, hence, the thermal conductivity *[Figure 1a]*.

Thermal conductivity properties vary substantially between material types and will, therefore, highly depend on the structure and composition of each specific dressing product, even in the dry state. In foam dressings, for example, this variation may be partially attributable to the amount of the air present within the foam structure, i.e. low-density foams with a large number of air pockets will theoretically act as thermal insulators (as there is more trapped gas), while those foams that are relatively more densely packed will be better conductors.

Nevertheless, the sizes of air pockets in foams will decrease if moisture is absorbed in the foam, or when the foam is deformed under external

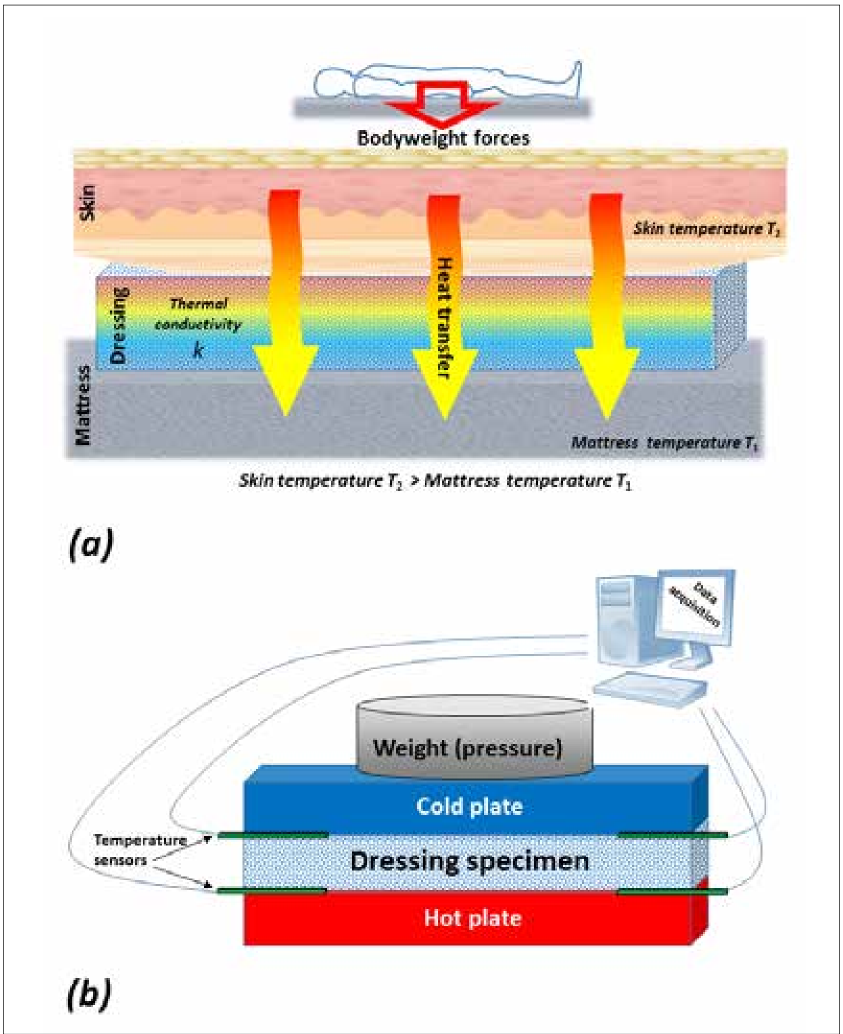

Figure 1. Thermal conductivity of dressing materials and structures: (a) The physics and physiology of heat transfer between the body and mattress, through a prophylactic dressing: The skin can be considered as a heat source which constantly produces metabolic heat. A dressing applied on the skin should transfer that heat continuously so that it is ultimately released to the environment through convection and radiation, or is conducted onwards to an interfacing object such as a mattress. If the thermal conductivity of the dressing k is low, heat will not be able to effectively leave the skin surface via conduction away from the skin and will, therefore, become trapped under the dressing. This would increase the metabolic demand of cells under and near the dressing and thereby, increase the risk for ischaemic damage. The excessive, trapped heat will also promote perspiration which may damage the stratum corneum and dissolve collagen that provides mechanical strength and stiffness to the skin. Eventually, the skin may tear or fail due to maceration, thereby creating an injury or exacerbating an existing wound. (b) A schematic of a laboratory testing setup to measure the thermal conductivity k of a dressing material or structure.

forces as explained above. Hence, ultimately, it is the interaction of 'k' with the fluid handling and the stiffness properties of the foam that will determine the ability of a PUP or a PUT dressing to effectively release heat from the skin surface to the environment.

Accordingly, from a microclimate performance perspective, a prophylactic dressing should have a high thermal conductivity k value, to be able to conduct any excessive heat away from the skin, including when a patient is fevering (which is common in COVID-19 cases and, thereby, also highly relevant in view of the coronavirus pandemic) (Gefen and Ousey, 2020). High thermal conductivity would allow a prophylactic dressing to spread any accumulated metabolic heat uniformly under the preventative dressing, so that there is no one specific dressing-covered spot which becomes substantially overheated.

In addition, a greater k value facilitates transfer of the excessive heat to the aspect of the dressing that faces the environment, from which that body heat can be transported to a contacting object (e.g. a support surface or a medical device) through thermal contact conduction, if there is contact between the dressing and the said object. Alternatively, if there are no contacting objects, the heat from the dressing can be absorbed through convection and radiation to the ambient air. Likewise, for a PUT or DFU treatment dressing, the inflammatory process that produces localised heat is interacting with the thermal conductivity of the dressing and periwound skin would be subjected to similar considerations as discussed above for intact skin, including the interactions of the dressing materials with fluid (not only perspiration but also exudate) and the impact of such interactions on the 'k' of the dressing.

To experimentally determine the thermal conductivity of dressing materials in a laboratory setting, we have developed a custom-made 'heat flow meter' testing device based on the 'cut-bar' technique (Schwartz and Gefen, 2020) *[Figure 1b]*. Dressing specimens are placed within this device, between brass and aluminum blocks. Thermocouples soldered at equal distances along these brass and aluminum blocks provide temperature readings that are digitally and automatically recorded. An electrical silicon heating mat placed on top of the brass block transfers a heat flux which is controlled using a power supplier. An inferior cooling plate, located underneath the aluminum block is cooled using a water flow system to create a relatively large temperature gradient over the smaller (test chamber) distance in the testing device, where the dressing specimens are placed. The silicon heating mat, brass block, dressing specimen and aluminum block compartments are all isolated to impose a nearly-unidirectional heat flux through the testing system, perpendicularly to the dressing sample (i.e. the heat flux is transferred along the thickness axis of the dressing).

The testing device further allows to apply external pressure on the tested dressing specimens by means of precision weights.

Readings are taken after the system with the tested dressing specimen has reached a steady-state heat distribution (i.e. when readings from all the temperature sensors stabilise). Finally, the thermal conductivity k of the tested dressing material is calculated using Fourier's law for one-dimensional heat transfer.

In our published work, we have reported that the thermal conductivity values for dressings depend (as indeed expected from the above theoretical considerations) on the structure and composition of the specific dressing. For example, the thermal conductivity of a polymeric membrane dressing (PMD; PolyMem, Ferris Mfg. Corp., TX, USA) was k=0.089 W/mK, which is statistically significantly ~1.5-time greater than the thermal conductivity of a regular foam dressing at the high-end of the 'k' range for open-cell polyurethane foams (k=0.058 W/mK). The PMD is, therefore, a superior heat conductor with respect to the regular polyurethane foam dressings (Schwartz and Gefen, 2020). Interestingly, we also found that the tested regular foam dressing had a 2.1-times greater stiffness with respect to the PMD dressing, hence, the regular foam might have not been able to release the trapped air through structural deformations under the applied loading during the testing, which caused the inferior thermal conductivity performances (Schwartz and Gefen, 2020).

Noteworthy is that for foam materials, better thermal conductivity is known to be empirically correlated with lower density and stiffness (Schwartz and Gefen, 2020). Accordingly, a more compliant foam dressing would not only have better modulus-matching (also known as 'biomechanical compatibility') with the skin (Bader et al, 2019), which lessens the skin and underlying tissue loads, but also, have better performances in transferring excessive heat from the skin to the environment through the dressing structure.

Infrared thermography to evaluate the intact skin temperatures under dressings

An infrared thermography (IRT) camera converts the thermal radiation emitted by the human skin to a quantitative temperature diagram, thereby facilitating mapping of skin temperatures. Localised skin temperatures are affected by external phenomena and interactions at the surface of the body, such as warm or cold contacting objects and the ambient conditions. Intrinsically, the skin temperature may be affected by an inflammatory process, superficial malignancy or localised ischaemia (Gefen et al, 2019b). As such, IRT offers effective and powerful means for research and clinical diagnostics in wound prevention and care (Gefen, 2020).

A typical IRT image contains plentiful heterogeneous visual information concerning the local skin temperatures, which reflects the local heat levels at the different skin layers and the function of the near-surface blood vessels. The spatial distribution of skin temperatures allows to accurately detect localised temperature gradients, thereby revealing hot spots or cold spots that may indicate a forming or existing lesion under intact skin (Gefen et al, 2019b). While simple outcome measures to quantify such gradients, for example, subtracting the temperature of the suspected lesion from that of an adjacent skin region that is assumed to be healthy, are commonly employed in the literature, IRT images contain more subtle information that is clinically relevant. Accordingly, advanced IRT image analyses extract texture-based features.

Entropy is one such important IRT image feature that quantifies the randomness of the temperature intensity distributions and was found to be useful in our efficacy research of dressings for PU prophylaxis (Amrani et al, 2020). The author's team published IRT work demonstrated that application of PMD on the sacral skin of subjects who were positioned supine resulted in lower entropy, i.e. more uniform skin temperature distributions at the sacral region of application after 1-hour sessions, compared to a regular foam dressing (Amrani et al, 2020).

A lower measured entropy value, therefore, correlates with the ability of the PMD dressing structure to transfer the excessive heat away from the skin under the dressing through adequate thermal conductivity. Importantly, while thermal conductivity is a property of a material or a structure, which is measured in a laboratory setting as described above, entropy of the skin at a certain body site is a physiological measurement that is acquired, by means of IRT, from a subject who uses the dressing (Amrani et al, 2020).

Skin temperatures as related to the modulation of topical inflammation

Elevated skin temperatures leading to increased localised perspiration, the buildup of moisture and thereby, a greater COF causing higher frictional forces on skin by any contacting objects (leading to increased tissue shearing levels), is a recognised damage pathway in the aetiologies of PUs and skin tears (Schwartz et al, 2018).

Increased skin temperatures have also been suggested to relate to expression of specific inflammatory markers. In particular, a localised increase in skin temperature correlates with a rise in the concentration of interleukin-1α (IL-1α), which is released by activated macrophages, neutrophils, epithelial cells and endothelial cells, as well as with an increase in tumour necrosis factor-α (TNF-α) that is produced by irritated or damaged endothelial cells (Lee et al, 2014; Worsley et al, 2016).

Elevated concentrations of the above cytokines may influence an injury to not progress onwards in the healing process (by fading away from the inflammatory phase) (Cutting and Gefen, 2019). The methods for detection of IL-1α and TNF-α are based on immunoassays of collected skin sebum and enzyme immunoassays (Worsley et al, 2016). In the context of dressing design and performanc-es, the above implies that a dressing design which minimises heat accumulation at the skin-dressing interface would also modulate an inflammatory process under the dressing. This is an important topic for further research, given the growing understanding that monitoring inflammatory markers as personalised computerised diagnostics of wounds is the way forward, e.g. in ensuring effective PUP or verifying that PU and DFU treatments are progressing adequately (Lindley et al, 2016).

Summary and conclusions

While the fluid handling and mechanical behavior and properties of dressings are more commonly referred to in the literature, the thermal conductivity of dressings has been rarely addressed. In the few relevant recent (and sparse) reports that have been published, the thermal conductivity properties of dressing materials or structures were measured for characterising a so-called 'thermal comfortability' (Uzon et al, 2017), or as part of collecting a set of physical properties of novel dressing materials or products of new manufacturing techniques (Tong et al, 2015; Asayesh et al, 2019).

The Uzon and colleagues (2017) study suggested that a lower thermal resistance of a dressing material, i.e. a greater thermal conductivity, contributes to subjective comfort. Nonetheless, the author's team published work focused on PMD is the only literature to-date on determining the thermal conductivity properties of dressings in the context of heat accumulation at the skin-dressing interface, which may lead to excessive heating of the skin that would increase the risk for PUs (Amrani et al, 2020; Schwartz and Gefen, 2020).

The thermal conductivity of dressing materials and structures is a fundamental physical property of high clinical relevance, in both prevention and treatment of acute (e.g. surgical) and chronic wounds, such as PUs and DFUs. The thermal conductivity of a dressing can be considered a comparative measure of the expected heating of the skin under the dressing, either in prophylactic applications or in treatment usage (for periwound skin).

For two hypothetical dressings that are compared against each other, the dressing with the lower thermal conductivity will cause more heat accumulation in skin under the dressing. Excessive heating of skin tissues leads to more perspiration which, in turn, compromises the ability of skin to tolerate bodyweight and external forces. Moreover, in studies reviewed here which were focused on inflammatory markers (Lee et al, 2014; Worsley et al, 2016), elevated localised skin temperatures positively correlated with the levels of the inflammatory cytokines in skin and hence, with a state of tissue inflammation.

The thermal conductivity of dressings should therefore be assessed in the framework of contemporary efficacy research, performance evaluations and in the future, also as an integral part of dressing testing standards. The present article has provided the educational perspective regarding the importance of considering the thermal conductivity of dressing materials and structures. This work also described some basic concepts in bioengineering laboratory measurements of this important property in their physiological and clinical contexts. Work is under way in our research group to develop cost-effective methods for robust testing of thermal properties of dressings. Reporting the thermal properties of dressings in a standardised and quantitative manner facilitates advanced multiphysics computer modelling studies, which consider the structural-thermal interactions between the body tissues (either intact skin or wounds), an applied dressing and other adjacent objects, such as a support surface or medical device (Zeevi et al, 2018; Schwartz and Gefen, 2020), towards improved wound prevention and treatments.

So far, the only published quantitative bioengineering evaluation of thermal conductivity of non-fabric, foam dressing materials is for PMD and equivalent 'placebo' foam without the active components in the PMD (Schwartz and Gefen, 2020). The present article highlights the fundamental importance of determining the thermal conductivity 'k' of dressing materials used in both prevention and treatment of wounds. Once additional advanced dressings will be similarly tested to determine their 'k' values, the 'k' property can be used as an objective, quantitative and standardised parameter for rating the microclimate management capacities of different dressings. This would drive the discussion about the microclimate under dressings from a qualitative clinical language towards quantitative bioengineering standards (likely with a certain numerical range of desirable 'k' values). Until this information becomes available, clinicians should be alerted to the accumulation of moisture on skin under preventative dressings and on periwound skin under treatment dressings, as this may, among other deleterious phenomena, be an indication of heat trapping under the dressing in use. WINT

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