Adjustability and Adaptability Are Critical Characteristics of Pediatric Support Surfaces

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Significance: Pressure ulcers (PUs) in newborns and children are remarkably different from those in adults, both in their possible causal factors and in the etiology and biomechanical pathways for tissue damage.

Recent Advances: Pediatric muscle and fat tissue structures are overall softer than those of adults, making newborns and young children more susceptible to deformation-inflicted injuries at their weight-bearing soft tissues.

Critical Issues: The unique medical environment of neonatal and pediatric intensive care units, which is overloaded with medical devices, wiring, tubing, electrodes, and so on, is, in fact, an extrinsic risk factor for device-related PUs, since accidentally misplaced tubes, wires, or electrodes can become trapped between the skin and the mattress, causing large sustained soft tissue deformations around them.

Future Directions: Mattresses that are being used in neonatal and pediatric intensive care units must be able to respond to frequent movements and changing positions and also be able to effectively adapt and conform around such misplaced tubing or wires, which might contact the body and deform soft tissues. We used computer simulations of a tube caught under a preterm neonate's arm in a supine position to illustrate what adaptability of the support surface means in such cases. Our present simulations indicate that an air-cell-based technology provides considerably better protection against PUs in such cases, as the air-cells are able to locally buckle and conform around objects that are stiffer than the pediatric tissues (*e.g.*, wires, tubes, electrodes), which minimizes exposure to tissue deformations.

SCOPE AND SIGNIFICANCE

PRESSURE ULCERS (PUs) are highly prevalent in neonatal and pediatric intensive care units (NICUs and PICUs, respectively) and are different from those of adults in their causal factors, etiology, and characteristics. However, current prevention and treatment protocols are extrapolated from adult practice, likely because empirical relevant data regarding infants are scarce. Furthermore, the unique medical environment of NICUs and PICUs is, in fact, an extrinsic risk factor for device-related PUs. Hence, special attention should

be given to support surfaces that are used in NICUs and PICUs, which should be able to provide adequate biomechanical protection to weight-bearing soft tissues.

TRANSLATIONAL RELEVANCE

In this article, we employed a finite element (FE) computational modeling method to investigate biomechanical interactions between the soft weight-bearing tissues of a preterm neonate's arm and a plastic tube, which is caught between the skin and the mattress. We were able to compare between two

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mattress technologies and designs, in a field where powerful statistical data regarding the biomechanical efficacy of support surfaces are extremely difficult to collect and, also, are only available after the PUs have already formed.

CLINICAL RELEVANCE

In the field of PU prevention, it is perilous to consider children simply as scaled-down adults. Their PUs are inherently different, often related to the use of medical devices such as tubes or wires that are contacting the skin and deforming soft tissues. Given the dramatic anatomical, physiological, and biomechanical differences between children and adults, the safety and clinical efficacy of extrapolating adult prevention protocols and products for neonates and children are questionable. Support surfaces used in NICUs and PICUs should be able to adjust and adapt to various pediatric-care-specific scenarios.

BACKGROUND

PUs in the pediatric population

PUs are known to develop when soft weight-bearing tissues of the body are subjected to sustained deformations, typically between a bony prominence and an external support surface, but in some cases, when an object such as a medical device is deforming the tissues.^{1,2} There are a number of known factors associated with PU development, such as impaired mobility and sensation, abnormal skin health, poor nutrition, and impaired perfusion.² The populations that are known to be at high risk are the elderly and frail, patients post-spinal cord injury (SCI), brain trauma or stroke, other patients with impaired mobility or sensory capacities, and patients who undergo prolonged surgeries.^{2,3} However, there is a growing understanding that acutely ill and/or immobilized neonates and children are also at increased risk for PUs and deep tissue injury (DTI).⁴ While progress in medical technologies and surgical techniques increases the survival rates of preterm neonates and infants, it also exposes them to the high-risk care environments of the NICUs and PICUs. The prevalence of PUs in NICUs and PICUs can be as high as 23% and 27%, respectively, with most of the PUs developing within 2 days of admission.⁴ Furthermore, the nature of injury and possible causal factors are inherently different between adults and children. While the sacrum, buttocks, and heels, which are associated with prolonged sitting and supine lying, are the most prevalent locations for PUs in adults, in the pediatric population, the occiput is the largest bony promi-

nence and most prevalent location for PUs.⁴⁻⁶ In addition, chronic risk factors of the adult population, such as SCI and diabetes, are replaced in the pediatric population by congenital conditions such as spina bifida and cerebral palsy.^{3,4} Importantly, in the pediatric population, more than 50% of PUs are related to equipment and devices.⁷ It is safe to assume that this value is an underestimation of actual incidence rates, due to insufficient knowledge of the risks and since reporting PUs that are associated with use of medical devices may expose the care facility to claims of malpractice. Undoubtedly, the unique medical environment of NICUs and PICUs is high risk in this regard, being overloaded with continuous positive airway pressure (CPAP) masks, tubes, catheters, pulse oximeters, wires, electrocardiogram (ECG) or electroencephalography (EEG) electrodes, and so on, which can potentially contact the body and deform soft tissues.

It is perilous to consider children simply as scaled-down adults. Their body dimensions, proportions, and biomechanical properties are markedly different from that of an adult and they deserve unique consideration in their medical and surgical care.^{8,9} However, in the context of PUs, most prevention and treatment protocols are extrapolated from adult practice, particularly since empirical relevant data on which to base guidelines for clinical practice for infants are scarce.⁴ The need for suitable support surfaces, designed to minimize not only contact pressure values but also internal tissue deformations in weight-bearing soft tissues, is comprehensively discussed in the literature, but specific insights and recommendations for the pediatric population are nonexistent. Given the anatomical, physiological, and biomechanical differences between children and adults and especially documented differences in the biomechanical behavior of pediatric soft tissues, serious concerns arise about the safety, clinical efficacy, and cost-effectiveness of extrapolating adult protocols and product designs for neonates and children.

DISCUSSION

Body habitus and tissue composition in pediatric patients

Inherent differences between adults and children in the context of PUs stem, as a starting point, from the differences in body composition and proportions. While the most prominent weight-bearing bony structures in the adult body are the pelvis and calcaneus, and this is indeed where most PUs develop in adults, in the infant's body, it is the occiput. This has to do with the fact that an infant's head is

proportionately larger compared with the adult.⁹ At birth, the brain is typically 25% of its adult size, although the body weight of the newborn is only about 5% of its adult weight. Furthermore, about half of the postnatal growth of the head and brain occurs during the first year of life, so actually, this disproportion persists during infancy. In a recent article published by Donati *et al.*, contact pressure maps were recorded for five infants aged between 10 and 22 weeks while in prone, supine, and seated positions. In the case of supine posture, peak pressure sites were obtained under the head in four of the five subjects, but the contact area under the head was consistently smaller compared with the trunk and pelvis.¹⁰ The increased relative weight load of the head, together with the diminished area for load transfer there, explains the increased susceptibility of infants to develop PUs at their occiput and emphasizes the need for a suitable support surface that will be efficient in reducing peak contact pressures as well as tissue deformations.

In addition to the relatively large head, newborn infants and especially preterm neonates are often born with a minimal subcutaneous fat layer.¹¹ However, body composition rapidly changes in preterm and term infants. Subcutaneous fat tissues tend to increase rapidly in mass and thickness during the first 9 months following birth, and then, this high incremental growth slows down so that by the age of 5 years, the thickness of the subcutaneous fat layer is about half the thickness of that of a 9-month-old baby.⁹ In the context of PUs, both excessive and deficit subcutaneous fat masses may impose an increased risk of injury, as lack of sufficient cushioning can be just as dangerous as the excessive weight load burdened by overweight individuals.¹² While subcutaneous fat mass is accumulated rapidly during the first year of life (4.25-fold after just 5 months), muscle mass increases at a much slower rate (twofold at 5 months).¹³ Furthermore, normal newborns are born with only about a half of an adult's muscle mass percentage and preterm neonates may be born with as little as a third.¹¹ Therefore, in general, infants possess less muscle and more fat tissues than adults do, which substantially influences their tissue deformation response in weight-bearing conditions (Fig. 1). As fat tissue is overall softer than muscles, the soft tissues of an infant will deform more under the same force, namely, pediatric tissues are more susceptible to deformation injuries (Fig. 1).

Mechanical properties of pediatric tissues

Not only do infants possess more fat and less muscle than adults do but also the biomechanical

properties of their muscles and fat are overall softer, while their skin is less compliant compared with adults. Adipose tissue consists mostly of fat stored in adipocytes, but its composition varies considerably with age. Adipose tissues of a newborn baby contain 56.5% water and 35.5% lipids, while the corresponding figures in the adult are 26.3% and 71.7%, making fat tissue of newborns and infants inherently softer and more deformable.¹³ Furthermore, muscle tissue composition also changes dramatically throughout early development. The endomysium (intramuscular connective tissues) of infants and children is thinner, making their relaxed skeletal muscles significantly softer than those of adults.^{14,15}

Skin tissue is another example of the immense differences between infants and adults in the context of the risk for PUs. First, the thickness of skin tissues in children younger than 5 years of age is lower compared with adults and closer to that of a senior, older than 75 years.¹⁶ Furthermore, the mechanical properties of skin tissues, namely, the way in which the skin responds to stretch or other forms of deformations such as shear, change drastically throughout life.^{16,17} Skin tissues of adolescents and young adults are compliant and can extend easily, but toddlers and elderly have more stiff inextensible skin tissues that bear more mechanical stress when being deformed. The coefficient of friction of human skin also changes with age, however, since it is relatively low in early life, it does not appear to be an additional biomechanical risk factor for the pediatric population.¹⁸ Nonetheless, the skin of preterm neonates is entirely different altogether. A competent epidermal barrier (in the stratum corneum) is necessary at the time of birth for maintaining fluid homeostasis in the extrauterine environment. Unlike full-term infants, who seem to possess stratum corneum with adult barrier properties, in infants born earlier than 30 weeks of gestational age, there is substantially increased transepidermal water loss.¹⁹ In addition, the structure of preterm skin is different from that of term newborns, with thinner stratum corneum and epidermis and fewer and smaller anchoring fibrils and filaments, which lead to decreased anchoring of the epidermis and increased susceptibility to shear-force-inflicted skin damage.

Overall, the decreased stiffness of muscle and fat tissues, together with the reduced extensibility of skin tissues, exposes infants and children to an increased risk for developing PUs. Since softer tissues will deform more under the same force, pediatric tissues are more susceptible to deformation injuries (Fig. 1). Hence, it is of great importance, particularly

Figure 1. An illustration showing the differences in anatomy, physiology, and tissue biomechanics between adults and infants, in the context of pressure ulcer risks: **(a)** adult MRI tissue structures in an axial cut through the arm. **(b)** An increased fat/muscle ratio in an infant's arm compared to that of a scaled-down adult. **(c)** Increased deformations in muscle and fat tissues, due to reduced tissue stiffness in an infant's arm, compared to those in a scaled-down adult. To see this illustration in color, the reader is referred to the web version of this article at www.liebertpub.com/wound

for the pediatric population, to use a mattress, which will maximize immersion and envelopment and will hence minimize soft tissue deformations during weight-bearing.

Body motility in pediatric patients

Spontaneous general movements are present from the fetal period to ~20 weeks postnatal. They are complex, often involving the whole body, are frequent, present during either wakefulness or sleep, and exhibit pattern changes, as the infant grows older.²⁰ Furthermore, their quality, frequency, and

intensity are commonly associated with the infant's functional integrity of the central nervous system (CNS). While recent improvement in both prenatal assistance and neonatal intensive care considerably decreased neonatal mortality, preterm neonates are now more susceptible to CNS dysfunctions related to cerebral insults that occur prenatally or during birth.²⁰ Different CNS-associated abnormalities in motility can range from generalized hypotonia to persistent frantic flailing movements, which are both introducing risks to tissue integrity. While generalized hypotonia suggests prolonged periods in static

positions and hence increasing the risk of exceeding tissue tolerance levels, intense jerky movements of the legs, for example, may inflict repetitive compression and shearing forces on the skin and subdermal tissues, subjecting the affected tissues to compressive and shear-force-inflicted damage.

Preterm neonates are often born with decreased muscle tone, as their neuromuscular system is underdeveloped. Usually, extremely premature neonates and especially those born with congenital heart defects have difficulties with breathing, oxygenating, feeding, and thriving. Since it is customary to postpone heart surgery until the baby is strong enough, these newborns experience prolonged and sedentary hospitalization, which by itself elevates the risk for PU development.²¹ Furthermore, in severe cases of infant respiratory distress syndrome, high-frequency oscillatory ventilation (HFOV) is being used, instead of traditional mechanical ventilation. This type of ventilation, which is confined to the neonatal and pediatric populations, delivers over 150 breaths per minute, causing high-frequency shear and frictional forces between the support surface and the vibrating infant's body. Indeed, a higher incidence of skin breakdown in patients ventilated with HFOV than in those ventilated with conventional ventilation has been reported.⁶ In addition, the sedation and neuromuscular blockades used to maintain optimal positioning of the rigid oscillator tubing might add to the risk of PU formation.⁶

The altered motility of hospitalized newborns, infants, and children highlights the need for adjustable and adaptable mattresses, which should conform to their body shape and changing positions, as well as minimize shear-deformation-inflicted damage to the skin and subdermal tissues, such as due to repetitive spontaneous movements and HFOV-induced vibrations.

The unique medical environment in neonatal and pediatric care

The most substantial and apparent difference between adult and neonatal/pediatric intensive care settings is the extensive use of medical equipment. The unique medical environment of the NICU and PICU is saturated with equipment, plastics, and tubing, such as CPAP masks, feeding tubes, catheters, pulse oximeters, and ECG/EEG wires and electrodes, which can potentially contact the body, including at unintended body sites, and deform soft tissues, especially if accidentally misplaced between the skin and the support surface. Standard PU risk assessment tools do not account for contact with medical devices and nurse inspections can overlook

misplacement of devices and tubing under the body, and so, in theory, if a plastic tube, for example, is caught between the skin and the mattress it is likely to initiate deformation-inflicted soft tissue damage. Indeed, and very differently from adults, among neonates and children, more than 50% of PUs are related to equipment and devices,⁷ and this is likely a conservative number considering the poor understanding of the risks and potential claims of malpractice. Together with poor oxygenation, which is especially common in preterm neonates, sustained contact with tubing or electrodes, even without weight-bearing, will eventually cause necrotic damage to soft tissues. Hence, new bioengineering strategies are needed in this field to target the relevant medical devices, assess risks that they impose, and possibly redesign them so that when they function in isolation or while interacting with other equipment or support surfaces, the risk for device-related PUs will be minimal.

As an illustrative example for such interactions of a device with a support surface and with an infant's body, we developed computer simulations. Specifically, to investigate how a rigid plastic tube deforms the soft tissues of a preterm neonate's arm, when the tube is accidentally left between the skin and the mattress, we developed two configurations of a three-dimensional FE computational model of a 3-mm-thick axial cut through the upper arm of a preterm neonate (Fig. 2). We used an idealized cross-sectional geometry of the arm to describe the internal anatomy, including the humerus, muscles, and subcutaneous fat tissues of a 1.5 kg newborn. The proportions, dimensions, and mechanical properties of the tissues were all adopted from the literature.^{22–24} Then, we positioned a 2-mm rigid tube under the arm between the subcutaneous fat layer and either a flat foam mattress with stiffness (elastic modulus) of 25 kPa or an air-cell-based (ACB) mattress, modeled similarly to the flat foam cushion and the ACB cushion in our previous work.²⁵ To simulate the worst-case scenario, we positioned the tube on the top of the air cell (as opposed to in the groove between adjacent air cells). Next, we fixed the front and back planes of the arm, mattress, and tube in the simulation in the perpendicular direction, to prevent out-of-plane translations so that thin slice modeling conditions were obtained. We prescribed vertical displacements to the humerus, until a target reaction force of 0.015 N (corresponding to the slice volume, assuming an average tissue density of 1 g/cm³) was achieved. Finally, we compared the local tissue deformations around the tube and the mechanical strains and stresses in the fat and muscle tissues of the simulations.

Figure 2. Finite element (FE) computational model of an axial cut through the upper arm of a 1.5 kg preterm neonate, in supine position, when a 2-mm tube is left between the skin and either a flat foam mattress (*top panel*) or an air-cell-based mattress (*bottom panel*). Zoom-in on the deformed FE meshes around the tubes is provided in the *middle frames*. Effective mechanical stress distributions in muscle and fat tissues are on the right. B, bone; M, muscle; F, fat; T, tube. To see this illustration in color, the reader is referred to the web version of this article at www.liebertpub.com/wound

Overall, the use of an ACB mattress resulted in substantially lower fat and muscle tissue deformations, strains, and stresses around the tube compared to the flat foam mattress, even in the worst-case scenario that was simulated (Fig. 2). The envelopment offered by the ACB mattress allowed for increased contact area and diminished contact pressures between the mattress and the tube/skin. Furthermore, the ACB mattress's adaptability, namely, its ability to conform (buckle) around the rigid tube, in this case, allowed for reduced deformations of the subcutaneous fat layer and reduced peaks of effective stresses in the subcutaneous fat and muscle tissues (Fig. 2).

The tubing/wiring-rich medical environment of the NICU and PICU is, in fact, an extrinsic risk factor for the development of PUs and DTIs in the pediatric population. Since most of the tubing, wires, and medical devices that are designed to contact the infant's body are overall stiffer than the infant's soft tissues, every sustained contact, especially under weight-bearing conditions, is a tangible threat to tissue health and integrity. Hence, based on the information presented in this article, new specifications should be considered in the design and selection of support surfaces that are to be used in NICUs and PICUs for protecting against PUs.

Such mattresses must be adjustable to the infant's or child's body, as it changes during the period of hospitalization (particularly in chronic care), and adaptable, for example, to be able to conform around accidentally misplaced tubes, wires, or electrodes so that tissue deformations in such cases are minimal (Fig. 2). Since standard foam hospital mattresses are stiffer than the soft tissues of the body, stiff objects caught between the mattress and the skin will ultimately inflict larger deformation on the tissues rather than on the foam mattress, increasing the risk of PUs and DTIs (Fig. 2). We demonstrated in this study that the ACB-technology is superior in this regard, as it allows extra adaptability, which is not offered by foam technology.

SUMMARY

PUs in the pediatric population are markedly different from those in adults. The important differences between adults and newborns/children are in body dimensions and proportions, biomechanical tissue properties, and motility characteristics, and together, they all warrant taking a separate approach with regard to PU prevention. Hospitalized newborns are also more susceptible to deformation injuries of their weight-bearing soft

tissues and to shear-forces-induced skin damage, due to their soft muscle and fat tissues and skin structure and properties. Furthermore, the unique medical setting of NICUs and PICUs, which is saturated with medical equipment and devices such as tubing and wires, introduces additional risks for device-induced PUs and DTIs. Hence, newborns and children deserve unique consideration regarding their PU risk assessment, prevention strategies, support surface design and selection, and treatment protocols.

Importantly, the increased susceptibility of newborns and children to deformation-induced PUs and device-related DTIs, in particular, calls for specific design features that are required from support surfaces used in NICUs and PICUs. First, such support surfaces should be able to respond to frequent movements and changing positions, while providing the appropriate amount of immersion and envelopment that will keep the weight-bearing soft tissue deformations to a minimum at each posture. Second, especially in chronic care, support surfaces should be able to adjust to longer term changes such as body growth and changes in body mass, tissue structure, and composition, a feature often termed adjustability. Third, and as emphasized in this article, support surfaces for the pediatric population, particularly in NICUs and PICUs, should be able to effectively adapt and conform around accidentally misplaced tubes, wires, electrodes, or other devices that might contact the skin and deform weight-bearing skin and subdermal soft tissues. The results of our present computer simulations (Fig. 2) indicate that an ACB mattress provides superior protection against increased soft tissue deformations around a misplaced tube—a scenario that happens so commonly in NICUs and PICUs (hence the high prevalence of device-related PUs in pediatrics). An ACB mattress protects the infant's tissues in such incidents better than foam mattresses, thanks to the adaptability feature of the ACB support, which in this case manifests as its ability to buckle around the tube, take the deformations off the adjacent tissues, and thereby minimize mechanical strains and stresses in skin, muscle, and fat.

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TAKE-HOME MESSAGES

- PUs in the pediatric population are markedly different from those in adults.
- Newborns and children deserve unique consideration regarding their PU risk assessment, prevention strategies, support surface design and selection, and treatment protocols.
- Support surfaces for the pediatric population should be able to respond to frequent movements, adjust to longer term changes such as body growth, and also effectively adapt and conform around accidentally misplaced tubes, wires, and, electrodes that might contact the skin and deform weight-bearing soft tissues.
- Computer simulations indicate that an ACB mattress provides superior protection against increased soft tissue deformations around a misplaced tube compared to a foam mattress.

in the United States for “Clinical Evaluation of Neonatal and Pediatric Full Support Surfaces to Minimize Tissue Deformation and Prevent Tissue Injury.”

AUTHOR DISCLOSURE AND GHOSTWRITING

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Abbreviations and Acronyms

ACB = air-cell-based
 CNS = central nervous system
 CPAP = continuous positive airway pressure
 DTI = deep tissue injury
 ECG = electrocardiogram
 EEG = electroencephalography
 HFOV = high-frequency oscillatory ventilation
 NICU = neonatal intensive care unit
 PICU = pediatric intensive care unit
 PU = pressure ulcer
 SCI = spinal cord injury