Medical Engineering and Physics 38 (2016) 917–921

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Mathematical modeling to predict the sub-bandage pressure on a conical limb for multi-layer bandaging

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ARTICLE INFO

Article history:
Received 4 September 2015
Revised 19 April 2016
Accepted 1 May 2016

Keywords:
Pressure prediction
Bandage structure
Laplace law
Membrane shell
Multi-layer bandages

ABSTRACT

The effectiveness of the compression treatment by a medical compression bandage is dependent on the pressure generated at the interface between the bandage and the skin. This pressure is called interface pressure or sub-bandage pressure. The performance of a bandage depends upon the level of interface pressure applied by the bandage and the sustenance of this pressure over time. The interface pressure exerted by the bandage depends on several other factors like limb shape or size, application technique, physical and structural properties of the bandage, physical activities taken by the patient, etc. The current understanding of how bandages apply pressure to a limb is based on the Law of Laplace, which states that tension in the walls of a container is dependent on both the pressure of the container's content and its radius. This concept was translated mathematically into equation relating pressure to tension and radius by Thomas. In addition, a modified equation was generated by multiplying the model with a constant that represents the number of bandage layers in order to use the model to estimate the pressure applied by multi-layer bandages. This simple multiplication adjustment was questioned by researchers. They had doubts about the model validity and whether it can be used to predict the sub-bandage pressure applied by pressure garments. One of the questions that were raised regarding the bandage thickness affecting the sub-bandage pressure has been recently explored by Al Khaburi where he used the thin and thick cylinder shell theory to study the effect of Multi Component Bandage's (MCB) thickness on the sub-bandage pressure. The model by Al Khaburi and the earlier models developed for pressure prediction are all based on calculations considering the cylindrical limb shapes although the human limb normally is wider at the calf and reduces in circumference towards the ankle. So in our approach, the bandage is assumed to take a conical shape during application and membrane shell theory is used for developing pressure prediction model for multi-layers of bandage. Both analytical and experimental work showed that the effect of bandage thickness and the geometry of the limb on pressure produced by multi-layers of bandage are significant. The model developed when compared to the data obtained using experimental setup confirmed the validity of the mathematical model for multi-layers of bandage based on conical geometry of the limb.

1. Introduction

The current understanding of how bandages apply pressure to a limb is based on the Law of Laplace, which states that tension in the walls of a container is dependent on both the pressure of the container's content and its radius. This concept was translated mathematically into equation relating pressure to tension and radius by Thomas [1]. In addition, Thomas [2] modified equation by multiplying the model with a constant that represents the number of bandage layers in order to use the model to estimate the pressure applied by multi-layer bandages. The use of Laplace's law to determine interface pressure remains a controversial issue. Melhuish et al. [3] have demonstrated in their work that as the tension in the applied bandage increases, the pressure increases and the pressure decreases as the radius of the solid cylinder increases. But the amount of reduction in the applied pressure did not follow the predictions using Laplace Equation.

Basford [4] have reported that Laplace's law does not take into consideration the wall thickness. The error due to neglecting the wall thickness is as high as 5% when the ratio of vessel's wall thickness to its radius is 1:10 [4,5]. Dale et al. [6] compared the four different four-layer bandaging system and observed that the final pressure achieved by a multilayer bandaging system is not equal to the sum of the pressure exerted by each individual layer

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http://dx.doi.org/10.1016/j.medengphy.2016.05.006
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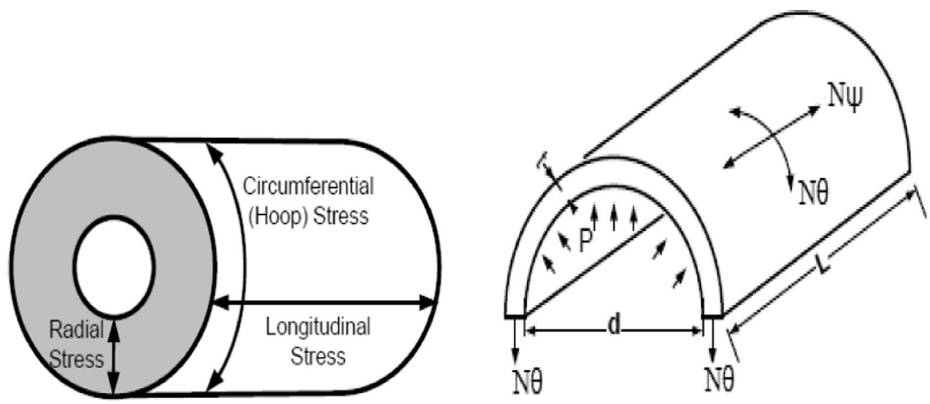

Fig. 1. Three principal stresses in the closed thin membrane shell.

as predicted by Laplace's law. So, the Laplace's law should be used carefully to predict sub-bandage pressure especially in case of multilayer application of bandages. Al Khaburi et al. [7,8] proposed a model based on thick wall cylinder theory to predict interface pressure by multiple layers of medical compression bandages.

$$P = \sum_{i=1}^{n} \frac{T[d+t+2t(i-1)]}{((1/2)w[d+2t(i-1)]^2) + (wt[d+t+2t(i-1)])}$$

where P is the total pressure due to n layers of bandage (N/m^2), T is the tension in the bandage (N), d is the limb diameter (m), w is the bandage width when it is extended (m), t is the bandage thickness when it is extended (m), and n is the number of layers wrapped. But this model is developed for a cylindrical limb shape. So this paper presents the work carried out to develop a pressure prediction model based on conical limb geometry and also re-examines the physics of compression therapy. It reports the experimental work done to compare the developed model with the Thomas, Al Khaburi model by simulating the pressure applied by a bandage to a mannequin leg and finding which of them estimates the pressure applied most accurately.

1.1. Sub-bandage pressure model using membrane shell theory

The bandage material is thin and pliable, so it can be considered as a closed thin shell. In shell theory [9], a shell is considered thin if the maximum value of the ratio h/R, where h is the thickness of the shell and R is the radius of curvature of its middle surface, can be neglected in comparison with unity. Taking typical values of h and R in case of bandage wrapped on a limb as 0.0834 cm and 38.5 cm, respectively, the above ratio becomes 0.002, which is much less than unity, and hence it is reasonable to consider the development of pressure in bandage as a class of problem of closed thin shell. The bandage material is further simplified to be a 'membrane' [9,10]; membranes can support only forces which act parallel to the tangential plane at a given point of the middle surface of the shell and unable to support any transverse force and bending or twisting moments [11]. The forces are distributed uniformly over the thickness of the shell. So the bandage is regarded as a closed membrane shell and it can be assumed that the hoop/circumferential stress (N_θ) and longitudinal/ meridional stresses (N_ψ) are constant across the wall thickness, and the magnitude of the radial stresses is very small compared to the other stresses (Fig. 1); thus, it can be ignored (7).

Based on the above assumptions, it can be shown that the hoop/circumferential stress can be expressed as given in the following equation:

$$N_\theta = \frac{Pr_\theta}{t} \tag{1}$$

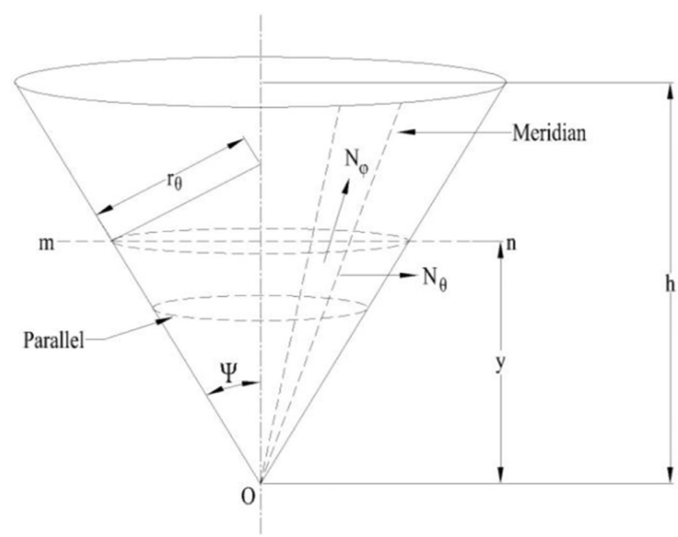

Fig. 2. Longitudinal stress (N_ψ) and circumferential stress (N_θ) in the conical segment.

where N_θ is the membrane stress in circumferential direction (N/m^2), P is the internal pressure in (N/m^2), r_θ is the radius of curvature in circumferential direction in (m) and t is the bandage thickness in (m).

1.2. Analysis of stresses in a conical segment

Fig. 2 shows the conical segment where Ψ is the semi-vertex angle of the cone. The principal radius of curvature, $r_\varphi = \infty$ but r_θ depends on the distance of the parallel circle from the vertex o. For the parallel circle along the line mn, which is at a distance y from the vertex, the radius of curvature, r_θ, will be

$$r_\theta = \frac{y\tan\Psi}{\cos\Psi} \tag{2}$$

Now putting the value of r_θ from (2) in (1)

$$N_\theta = \frac{P.r_\theta}{t} = P.\frac{y\tan\Psi}{t.\cos\Psi} \tag{3}$$

The hoop or circumferential stress increases with the increase in the distance y from the vertex. If h is the height of the cone, the stresses at the cone base will be

$$N_\theta = P.\frac{h\tan\Psi}{t.\cos\Psi} \tag{4}$$

In order to simplify this expression for circumferential stress in the conical limb, the values of tanΨ and cosΨ have to be known