BIOMECHANICS OF THE HUMAN UMBILICAL CORD UNDER COMPRESSIVE LOADS

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INTRODUCTION

Umbilical cord (UC) is a complex and fascinating structure that connects the fetus to the placenta, the organ providing blood oxygenation and fetal nourishment. UC encases three umbilical vessels (two arteries arranged in coils around a vein) that are immersed within the Wharton's jelly, a mucoid connective tissue very reach of water (about 90%), described as a three-dimensional spongy network of interlacing collagen fibers, small woven bundles of glycoprotein microfibrils and an interfibrillar soluble phase (hyaluronans, proteoglycans) [1]. Although the crucial importance of the UC for fetal well-being and development has been recognized by all obstetricians [2], this structure has not received much scientific attention up to now; particularly, its response to mechanical loading due to fetal movements and uterine contractions is not well understood. Dado and colleagues [3] recently found *in vitro* that at high UC deformations (compression, twisting or stretching) the venous flow notably decreases for constant hydraulic pressure drop.

To comprehend how the UC sustains physiological levels of loading, a knowledge of its mechanical properties as well as of its different components is indispensable. Tensile properties of UC were previously investigated [4], while no complete data on compressive properties are available up to date.

The aim of this study is to investigate the biomechanics of the human UC under compression, in order to give more insight into its role in protecting the umbilical circulation.

MATERIALS AND METHODS

Sixteen UC's from Caesarian sections were collected from neonates born at term, after an uncomplicated pregnancy (Sacco Hospital, Milan, Italy) and tested within 6 hours after delivery. Two different sets of experiments were performed: *i*) mechanical compression tests (10 cords) and *ii*) perfusion tests (6 cords).

Furthermore, a poroelastic finite element model was developed reproducing the experimental compression tests in order to interpret experimental findings.

Compression tests

Five specimens of 60 mm length were obtained from each cord. Specimens were immersed in a saline bath (temperature =22.5±2.5°C) and compressed laterally with a testing machine operating in displacement control (MTS Synergie 200H). The following tests were performed: (a) *total compression test* (with a plate through total length) at two strain rates ($0.1\text{-}10\cdot\mathrm{min}^{-1}$); (b) *localised compression test* (with a 10 mm-indenter in the central part of specimens) at the above strain rates; (c) *stress-relaxation test* with an initial load of 15 N monitoring force for 1,800 s after total compression at 10 s^{-1}.

Perfusion tests

Perfusion tests were performed to evaluate the hydraulic behaviour (pressure-flow relationship) of the UC's. Whole cords (length L = 38±6.6 cm) were connected to a perfusing circuit, after vein cannulation (arteries were not perfused). Cords were perfused with saline solution using a centrifugal pump (flow rates Q = 0.15-0.6 l/min); a differential water piezometer measured the pressure drop across the cord. Pressure at cord outlets was kept at about 10 cmH_2O. Hydraulic behaviour of the cord was investigated both with unloaded and compressed cords (total or localised compression). Compressive deformation (Δh) was stepwise (1 mm) increased at fixed flow rates while measuring applied force (F) and pressure drop (Δp).

Poroelastic model

Compression tests were simulated with a finite element model based on a coupled pore fluid diffusion and stress analysis. The commercial code ABAQUS (Hibbit Karlsson and Sorenses, Inc. Pawtucket, RI, USA) was used. The poroelastic model of the cord describes the Wharton's Jelly as a multiphase material constituted of an isotropic, linear, elastic solid phase and an incompressible fluid phase. The role of specific mechanical and fluid parameters (Young modulus E, Poisson ratio ?, permeability k, bulk modulus K_S, porosity f) was investigated. The value range for k ($1.3\mathrm{E}^{-13}\text{-}1.7\mathrm{E}^{-12}$ $m^4N^{-1}s^{-1}$) was estimated by performing confined compression tests on 5 mm-disks of Wharton's Jelly excised from 4 cords (three disks each).

RESULTS

Compression tests

Figure 1 shows an example of total compression F-? h/h_0 curves at different strain rates. Non-linear behaviour with increasing stiffness with strain and strain rate is evident. The slope of the experimental curves at low (S_{low}) and high stress (S_{high}), as well as the intercept (I_{high}) of the linear fitting at high stress with horizontal axis were evaluated (Table 1). Results of localised compression (normalised multiplying F times 6) are statistically equal to those of total compression, but I_{high} at high strain rate (paired t-test, $p<0.05$). S_{low} is notably lower than S_{high} at both strain rates. Furthermore, S_{low} and I_{high} depend on strain rate ($p<0.05$) while S_{high} does not.

Large force-relaxation was observed (Fig.2). The contribution of viscous stress to the total stress was $(F_0\text{-}F_{1800})/F_{1800} = 0.964\pm0.013$.

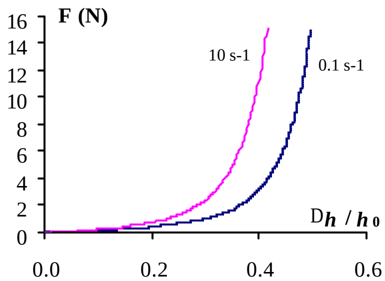

Figure 1 - Total compression curves at different strain rates

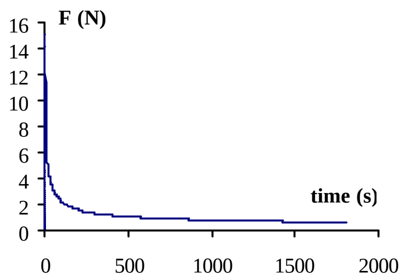

Figure 2 - Force-relaxation curve

Table 1 - Compression results

COMPRESSION		S_{low}	S_{high}	I_{high}
total	**0.1 s^{-1}**	1.27±0.87	190.62± 26.46	0.40±0.04
total	**10 s^{-1}**	2.55±1.90	393.04±474.82	0.30±0.13
localised	**0.1 s^{-1}**	1.30±0.67	193.61±37.18	0.49±0.05
localised	**10 s^{-1}**	3.90±1.30	155.04±25.00	0.33±0.04

Perfusion tests

Figure 3 shows hydraulic behaviour of the six unloaded cords. Obtained pressure drops are compatible with *in vivo* venous umbilical pressure measurements (10-15 mmHg) except for one single case showing numerous arterial blood coagula. Following cord compression the pressure drop increased notably when deformation exceed 0.5 (Fig. 4, values normalised on $\Delta p_{Ref} = \Delta p$ at Q = 0.45 l/min and $\Delta h = 0$).

Poroelastic model

Experimental compression curves at low deformation were well simulated by the model when suitable poroelastic parameters were adopted. Conversely, the very high stiffness observed at larger deformations could not be reproduced by the simulations; though a slight non-linear model response was present due to geometric effects, non-linearity of solid matrix should be taken into account.

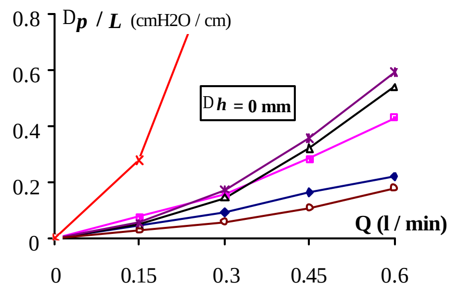

Figure 3 - Hydraulic behaviour of unloaded umbilical cords

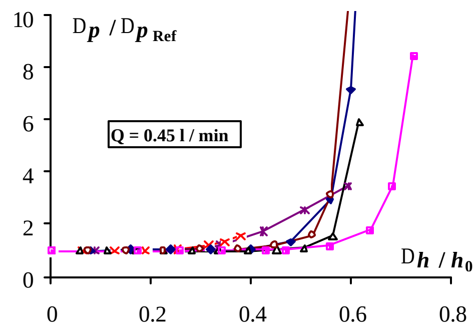

Figure 4 - Change in hydraulic behaviour of umbilical cords due to compressive deformation (D*h*)

CONCLUSIONS

The present results showed pronounced non-linear and viscoelastic behaviour of UC's compressed according to different modalities. Compressive properties of connective tissues are generally dictated by proteoglycan content, molecular organization and water content: a poroelastic approach is thus necessary to describe the UC behaviour under compression.

A complex mechanisms of protection of the umbilical vessels against external compressive forces acts to avoid an excessive reduction of vessel lumens and the umbilical blood flow. The absence of pressurization of umbilical arteries during perfusion tests is the main limitation of this study and further works are in progress.

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