Legal Medicine 15 (2013) 193–201

Contents lists available at SciVerse ScienceDirect

Legal Medicine

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

Compressive rib fracture: Peri-mortem and post-mortem trauma patterns in a pig model

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ARTICLE INFO

Article history:
Received 11 November 2012
Received in revised form 6 January 2013
Accepted 16 January 2013
Available online 27 February 2013

Keywords:
Forensic science
Rib fracture
Trauma
Wounding

ABSTRACT

Despite numerous studies on high impact fractures of ribs, little is known about compressive rib injuries. We studied rib fractures from a biomechanical and morphological perspective using 15, 5th ribs of domestic pigs *Sus scrofa*, divided into two groups, desiccated (representing post-mortem trauma) and fresh ribs with intact periosteum (representing peri-mortem trauma). Ribs were axially compressed and subjected to four-point bending in an Instron 3339 fitted with custom jigs. Morphoscopic analysis of resultant fractures consisted of standard optical methods, micro-CT (μCT) and scanning electron microscopy (SEM). During axial compression, fresh ribs had slightly higher strength because of energy absorption capabilities of their soft and fluidic components. In flexure tests, dry ribs showed typical elastic-brittle behaviour with long linear load-extension curves, followed by relatively short non-linear elastic (hyperelastic) behaviour and brittle fracture. Fresh ribs showed initial linear-elastic behaviour, followed by strain softening, visco-plastic responses. During the course of loading, dry bone showed minimal observable damage prior to the onset of unstable fracture. In contrast, fresh bone showed buckling-like damage features on the compressive surface and cracking parallel to the axis of the bone. Morphologically, all dry ribs fractured precipitously, whereas all but one of the fresh ribs showed incomplete fracture. The mode of fracture, however, was remarkably similar for both groups, with butterfly fractures predominating (7/15, 46.6% dry and wet).

Our study highlights the fact that under controlled loading, despite seemingly similar butterfly fracture morphology, fresh ribs (representing perimortem trauma) show a non-catastrophic response. While extensive strain softening observed for the fresh bone does show some additional micro-cracking damage, it appears that the periosteum may play a key role in imparting the observed pseudo-ductility to the ribs. The presence of fibrous pull-out and grooving of the outer tensile surface associated with periosteal stretching suggests that the periosteum under tension is able to sustain very high strain and bridge the mouth of the extending butterfly crack, thereby contributing to the observed strain-softening behaviour.

1. Introduction

Recently, Yang et al. [1] drew attention to the difficulties in diagnosing compressive rib fractures resultant from cardio-pulmonary resuscitation. While rib fractures are often diagnosed in blunt force trauma to the chest, such as in road traffic accidents, industrial accidents and in assault [2–6], little is known of compressive costal fractures. Yet despite its obvious importance, the biomechanics of such fractures in adults are not well understood. In fact, Love and Symes [7] have recently concluded that current bone biomechanics literature could not explain the rib fracture patterns they observed in their study of 43 blunt force thoracic injuries to the chest. Additionally, the morphology of rib fracture is often used by forensic and archaeological investigators to determine whether trauma was sustained peri- or post-mortem, yet the distinction between such fractures is still not fully resolved [8–10].

Although a large number of experimental studies have focused on the biomechanical properties of bone (reviewed by Currey [11]) and its fracture mechanics (reviewed by Gao [12]), only a small number have explicitly addressed the issue of rib fractures. Moreover, these studies have all been restricted to the consideration of bone alone, and have not included consideration of the effects of the periosteum on fracture patterns observed. Hashimoto et al. [13] and more recently, Yang et al. [1] have emphasised the importance of being able to differentiate perimortem and post-mortem artifacts from injuries of legal significance, specifically in cases of rib fracture related to CPR. Yang et al. [1] further stressed that while complete rib fractures are obvious at post-mortem, incomplete fractures are difficult to detect even at autopsy. In light of

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1344-6223/$ - see front matter
http://dx.doi.org/10.1016/j.legalmed.2013.01.001

the foregoing, the objectives of this paper were to analyse the biomechanics and morphology of experimentally produced fractures in freshly harvested (representing peri-mortem trauma) and dry (representing post-mortem trauma) pig ribs and to relate this to existing knowledge about the biomechanical behaviour of bony and collagenous failure.

2. Materials and method

The ribs used in this study were obtained from freshly slaughtered, one year old male domestic pigs, *Sus scrofa*, with hanging weights ranging from 85–115 Kg. Pig bones have previously been shown to be a good model for trauma analysis [14,15]. For the sake of uniformity, only the 5th ribs were used and these were divided into two groups; fresh ribs with retained periosteum and desiccated ribs. The latter were dried in a custom made desiccator cabinet fitted with moisture-proof seals, and inlet and outlet ports that allow air to be purged, for 5 days at 30 °C.

Two experiments were designed to evaluate the biomechanical behaviour of dried and wet ribs under different loading regimes, and also to investigate fracture morphology using standard optical methods, micro-CT (μCT) and scanning electron microscopy (SEM). Common causes of rib fracture include mechanical loads due to compression and flexure (bending). The experimental studies incorporated axial compression tests and four-point bending tests. Axial loading of the ribs in compression was undertaken to identify the deformation and failure sites that developed. Here, two load cases were considered, cyclic axial compression and monotonous axial load to failure. In the first of these, ribs were axially compressed in an Instron 3339 (Canton USA) fitted with a custom jig and a 50 kN load cell. Ribs were held in position on a preformed acrylic base to ensure stability, and were measured from tip-to-tip, as the length of a line segment. Five ribs in each category were loaded under compression at a rate of 10 mm/min up to 150 N, when the displacement was stalled for 1 min before unloading at the same rate. This process was repeated 5 times with loading to failure at the end of the final cycle. As part of this experiment, 5 ribs in each category were then loaded to failure, without cycling. Fracture sites were measured relative to the total length of each rib and then photographed and prepared for SEM.

Five dry and five wet specimens were prepared for SEM analysis by fixing in 2.5% glutaraldehyde in PBS for 2 h. Following buffer washes they were dehydrated in a graded series of ethanol, then critical point dried in a Bal-Tec CPD-030 critical point dryer (Bal-Tec AG, Balzers, Liechtenstein). Specimens were then mounted on aluminium pin stubs using double-sided carbon tape. They were coated with approximately 5 nm chromium in an Emitech K575X peltier-cooled high-resolution sputter coater (EM Technologies Ltd., Kent, England) and viewed under a JEOL JSM-6700F field emission scanning electron microscope (JEOL Ltd., Tokyo, Japan).

In the second experiment, 20 dry and wet ribs were subjected to 4-point bending at the site of fracture noted in the first experiment under axial loading. A custom jig was designed with the distance between the two inner loading points being positioned 20 mm apart to accommodate the 12 mm range we found to be prone to failure from the axial compressive loading tests (experiment 1). Eleven of the ribs were obtained 5 days earlier and placed in a dryer at 30 °C to produce a desiccated state, while the other 9 ribs were obtained fresh on the day of testing (Fig. 1). All rib specimens had their flesh stripped, but the periosteum was left intact so as to avoid compromising the structure and biomechanical properties of the bony rib itself. Loading was applied at a rate of 10 mm/min until structural failure was observed and the maximum load was recorded. Bluehill software (Instron Corporation, Canton Ma USA) was used during testing to record and calculate the maximum load (N), the maximum flexural load (N), the maximum flexural deflection (mm), from which the maximum flexural stress (MPa) and the maximal flexural strain (mm/mm) was determined. Flexural load is the derived channel calculated as the standard load with the sign inverted, while the flexural stress I was subsequently calculated using the following formula:

$$\sigma_f = Fat/2I$$

where F is the maximum load, a is the moment arm as shown in Fig. 1, $2t$ is the thickness of the specimen and I is the area moment of inertia. An approximate estimate of the area moment of inertia I for a rib bone about its central axis normal to the transverse loading direction can be obtained by assuming that it has a thin walled tube with its the cross-section almost elliptical:

$$I = 2\pi wt^3 h(1/w + 3/t)/4$$

where $2w$ is the width of the bone and h is the wall thickness [16]. Estimates of the wall thickness were obtained from micro CT images and were found to be approximately 0.3 w. A more detailed model for the moment area of inertia would entail using CT image analysis coupled with numerical modelling of the mineral density variation through the rib.

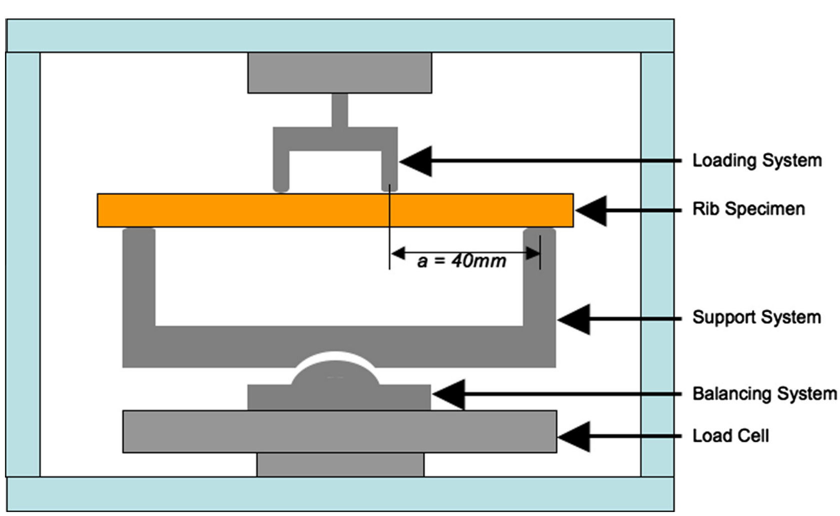

Fig. 1. Schematic diagram of custom rig used for 4-point bending of 5th pig ribs.