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Compressive and tensile mechanical properties of the porcine nasal septum ☆

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ABSTRACT

The expanding nasal septal cartilage is believed to create a force that powers midfacial growth. In addition, the nasal septum is postulated to act as a mechanical strut that prevents the structural collapse of the face under masticatory loads. Both roles imply that the septum is subject to complex biomechanical loads during growth and mastication. The purpose of this study was to measure the mechanical properties of the nasal septum to determine (1) whether the cartilage is mechanically capable of playing an active role in midfacial growth and in maintaining facial structural integrity and (2) if regional variation in mechanical properties is present that could support any of the postulated loading regimens. Porcine septal samples were loaded along the horizontal or vertical axes in compression and tension, using different loading rates that approximate the in vivo situation. Samples were loaded in random order to predefined strain points (2–10%) and strain was held for 30 or 120 seconds while relaxation stress was measured. Subsequently, samples were loaded until failure. Stiffness, relaxation stress and ultimate stress and strain were recorded. Results showed that the septum was stiffer, stronger and displayed a greater drop in relaxation stress in compression compared to tension. Under compression, the septum displayed non-linear behavior with greater stiffness and stress relaxation under faster loading rates and higher strain levels. Under tension, stiffness was not affected by strain level. Although regional variation was present, it did not strongly support any of the suggested loading patterns. Overall, results suggest that the septum might be mechanically capable of playing an active role in midfacial growth as evidenced by increased compressive residual stress with decreased loading rates. However, the low stiffness of the septum compared to surrounding bone does not support a strut role. The relatively low stiffness combined with high stress relaxation under fast loading rates suggests that the nasal septum is a stress dampener, helping to absorb and dissipate loads generated during mastication.

1. Introduction

The nasal septal cartilage is a midline plate extending from the perpendicular plate of the ethmoid bone to the external nose. It is hypothesized that the septal cartilage acts as a primary growth center of the midface, with expansion of the cartilage separating the facial bones at the connecting sutures, resulting in stimulation of bone formation along the sutural edges (Scott, 1953, Kvinnsland, 1974; Sarnat and Wexler, 1966). In addition, it is believed that the nasal septum acts as a vertical strut supporting the face against masticatory loads (Moss et al., 1968; Stenström and Thilander, 1970, Badoux, 1966, 1968). Recently, the vertical strut role was challenged by the finding of anteroposterior compression in the dorsal half of the septum in pigs during mastication (Al Dayeh et al., 2009), however, the septum might still be mechanically necessary as an anteroposterior strut in resisting dorsal flexion of the snout (Fig. 1).

If the septum is a growth center, then it should be able to resist the compressive loads generated by the resistance and recoil of the sutures. If the septum has a mechanical role during chewing, it should show directional and regional adaptations to its loading regime (Fig. 1). Alternatively, the septum may act as a stress dampener, absorbing and dissipating loads generated during mastication. Furthermore, finite element analysis of trauma to the human nose also suggests a significant role of the septum in stress absorption (Lee et al., 2010).

Cartilage is an almost avascular tissue that includes type II collagen and aggrecans. This complex composition gives rise to a well documented viscoelastic mechanical behavior (Langelier and

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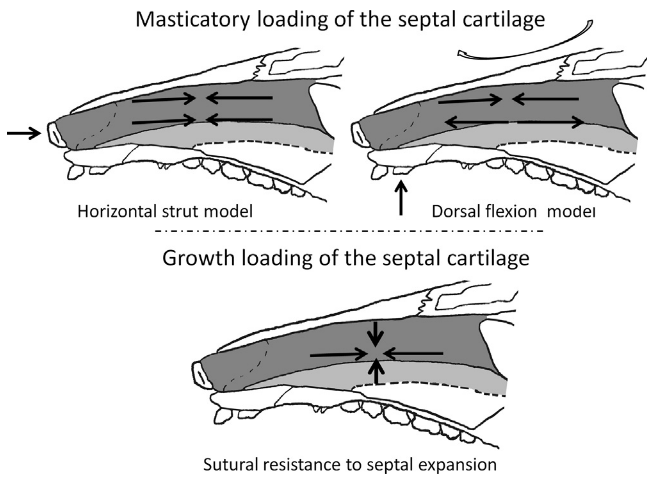

Fig. 1. Medial view of the pig nasal septum (gray; the light gray part sits within the vomer bone) illustrating possible patterns of loading during mastication (top row) and during growth (bottom). Both the horizontal strut model and the dorsal flexion model are consistent with in vivo data indicating that the dorsal region of the septum and snout are compressed anteroposteriorly during mastication (Al Dayeh et al., 2009; Rafferty et al., 2003). Mechanical adaptation to a horizontal strut model would suggest a relatively high anteroposterior compressive stiffness and strength with vertical adaptation to resist tensile strain. Dorsal flexion of the snout predicts horizontal adaptation to compression dorsally and to tension ventrally. Because growth expands the snout both horizontally and vertically, the resistance would be to compression in both axes, but at a very slow loading rate.

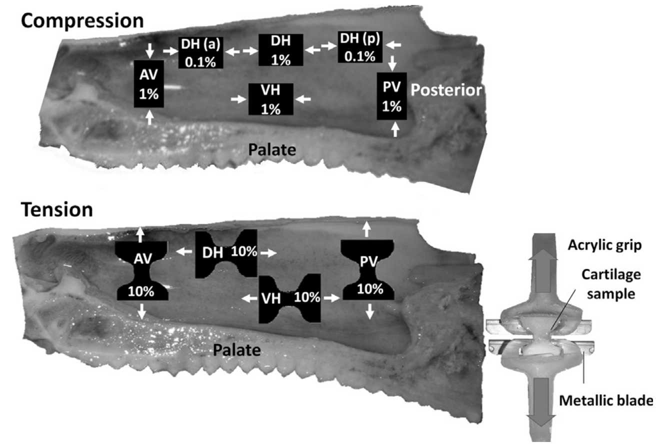

Fig. 2. Medial view of the septum illustrating the location of the tested samples in compression (top) and in tension (bottom). Loading direction is designated by arrows. Numbers indicate loading speed in %length/s. AV: anterior vertical, VH: ventral horizontal, DH: dorsal horizontal, PV: posterior vertical. DH (a): dorsal horizontal (anterior), DH (p): dorsal horizontal (posterior). Right: During tension experiments the cartilage samples were placed in acrylic grips and kept aligned by metallic blades.

Buschmann, 2003, Huang et al., 2001). The compressive properties are dictated by the aggrecans and water content while the tensile properties are dictated by the collagen content. Thus, direction of loading, loading rate (DiSilvestro et al., 2001; Langelier and Buschmann, 2003; Li and Herzog, 2004), loading time and hydration (Race et al., 2000) are important determinants of the mechanical properties of cartilage. Loading rate is especially important in considering the possible roles of the septal cartilage in growth (slow loading) and mastication (fast loading). Although the septum, including the porcine septum, is often used as a source for the measurement of the mechanical properties of cartilage (Chao et al., 2003; Gaon et al., 2003; Grellmann et al., 2006; Naumann et al., 2002; Richmon et al., 2005a, 2006; Rotter et al., 2002; Westreich et al., 2007; Wong et al., 2001; Xia et al., 2012; Zemek et al., 2012), these studies have not been systematically investigated directional and regional differences in relation to function. Additionally, the perichondrium was excised in most cases, a procedure that results in a 50% decrease in the elastic modulus of auricular cartilage (Roy et al., 2004).

The overall aim of this study was to measure the mechanical properties of the composite structure of the septal cartilage and the covering perichondrium in compression and tension, with particular attention to regional variation and loading rate. The perichondrium was left intact to approximate the mechanical properties of the nasal septum as it exists in vivo. The ultimate goal is to shed light on whether the mechanical properties of the nasal septum support an active role in facial growth and in supporting the face during dynamic loading.

2. Materials and methods

2.1. Compression tests

Pig heads ($n=18$) were obtained from an abattoir (Kapowsin Meat, Graham, WA), age, sex and breed unknown. Nasal septa were extracted and stored frozen in 4% phosphate buffered saline (PBS).

On the day of measurement, septa were thawed and six 9–10 by 9 mm rectangular samples were cut (Fig. 2): 2 vertical (anterior and posterior) and 4 horizontal (three dorsal and one ventral). Natural thickness with the perichondrium in place was preserved and measured. The thickness of the porcine septum was relatively uniform, averaging 5.4 ± 0.8 mm; thus, samples were rectangular in section. Samples were compressed in the sagittal plane in the long-axis orientation (arrows in Fig. 2). The 2 vertical and 2 of the horizontal samples (dorsal middle and ventral) were loaded at 1%/s ($\sim$0.1 mm/s) while the remaining 2 horizontal (dorsal anterior and posterior) samples were loaded at 0.1%/s ($\sim$0.01 mm/s). The faster strain rate was chosen to mimic the low end of masticatory loading in pigs (Al Dayeh et al., 2009), while the slower rate was the closest approximation to the growth rate of the cartilage (approximately 2×10^{-5}%/s, calculated from Al Dayeh et al., 2013) that could be achieved with our testing machine (MTS/Sintech 2, Raleigh, NC). Sandpaper was glued to the compression platens in order to keep samples in place, and samples were immersed in saline during preloading and testing.

Samples were preloaded to 1.5 or 2.5 N, a process that was completed within 1 s for the 1%/s samples and 7 s for the 0.1%/s samples. The resultant deformation was defined as 0% strain. Subsequently, samples were loaded to strain points 2, 4, 6, 8 and 10% in random order, and the strain was held for a relaxation time of 120 s. The l ow strain point of 2% approximates the strains generated on the septum during mastication (0.1–1%, calculated from Al Dayeh et al., 2009). Growth strains are much lower (Al Dayeh et al., 2013), but were impossible to approximate experimentally. The high strain point of 10% approximates some traumatic loads and is a typical lower end of values used by other workers (Richmon et al., 2005b, 2006; Zemek et al., 2012). The varying strain levels provide a comparison to the literature and illustrate general patterns of septal mechanical behavior. A two-minute rest period separated each loading to allow rehydration. Finally, samples were loaded until failure.

Deformation was converted to strain by dividing by the length of the sample between compression platens before loading. Load was converted to stress by dividing by the sample cross-sectional area perpendicular to the compression axis, calculated from the thickness and width before the test. Throughout each test, stress and strain were continuously recorded at 50 Hz. Stress–strain and stress–time graphs were plotted. Samples that showed buckling or instability were discarded.

For each test, the stress–strain curve (Fig. 3) was plotted, and stiffness was calculated as the slope of the least-squares linear regression line (line of best fit) through the data points. Relaxation stress was measured at 0, 10, 30 and 120 s (Fig. 3). The percentage drop in the relaxation stress between each time interval was calculated as an indication of stress absorption by the cartilage. The final failure test was used to measure the ultimate stress and strain of the septum.

The effect of loading rate was tested by comparing dorsal samples loaded at 1 and 0.1%/s (Fig. 2), using repeated measures ANOVA (RM-ANOVA). To assess whether the septum is adapted as a vertical or anteroposterior strut (Fig. 1), stiffness and strength (ultimate stress) of vertically and horizontally loaded samples (Fig. 2) were compared using RM-ANOVA followed by post-hoc paired t-tests to identify the source of significance. Statistical tests were performed using SPSS v13.0.

2.2. Tension tests

Pig heads ($n=22$) were obtained as before; nasal septa were extracted and stored in saline at 4 °C. On the day of testing, four hourglass-shaped samples