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Shear mechanical properties of the porcine pancreas: Experiment and analytical modelling

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ABSTRACT

We provide the first account of the shear mechanical properties of porcine pancreas using a rheometer both in linear oscillatory tests and in constant strain-rate tests reaching the non-linear sub-failure regime. Our results show that pancreas has a low and weakly frequency-dependent dynamic modulus and experiences a noticeable strain-hardening beyond 20% strain. In both linear and non-linear regime, the viscoelastic behaviour of porcine pancreas follows a four-parameter bi-power model that has been validated on kidney, liver and spleen. Among the four solid organs of the abdomen, pancreas proves to be the most compliant and the most viscous one.

1. Introduction

Studies of the mechanical behaviour of pancreas are still wanting, probably due to the low incidence of pancreatic trauma. Indeed, due to its anatomical localisation, pancreas is less vulnerable than other organs, being protected by the bony structure of the rib cage and partly protected by the stomach (Shinkawa et al., 2004).

Pancreatic injuries are primarily caused by motor vehicle collisions but remain infrequent with regard to all body blunt (0.2%) and penetrating wounds (1.1%), other solid organs such as liver and spleen being significantly more often injured (Kao et al., 2003). An in-depth study of 372 car occupants who sustained AIS 3+ abdominal injuries revealed 4.6% of ruptured pancreas while kidneys, liver and spleen failed in 5.6, 27 and 37.9% of cases, respectively, regardless of the use or not of a restraint system, of the occupant position and age (Lamielle et al., 2006). Yoganandan et al. (2000) reported that the abdominal AIS 3+ injuries due to car interior contact points (e.g. steering wheel) in frontal crash mainly affected the spleen (63.6%), the diaphragm (15%), the liver (14.4%) and the digestive organs (4.6%), kidney and pancreas accounting for less than 1% of the injuries; overall, pancreas was found to sustain little or no injuries in all AIS scores.

Regardless of the cause of trauma, Nance et al. (1997) noticed from a study of nearly three thousand adult patients sustaining a blunt abdominal trauma that pancreas injuries were observed in only 1.3% of cases whilst spleen, liver and kidneys were injured in 35, 25 and 17% of cases, respectively. In particular, they noted that pancreatic injuries were strongly associated with injuries of other organs. In addition, Miller et al., 2002 showed that the injuries of pancreas were mostly associated with primary liver injuries, whatever the severity of the latter. According to Kao et al. (2003), pancreas injuries never were directly responsible for the victim's death, which was caused by injury in other organs or vascular networks. From an epidemiological standpoint, pancreatic trauma appears thus chiefly as secondary to a more serious trauma

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in other thoraco-abdominal organs. In this sense, pancreatic injuries turn out to be a good predictor of the impact severity.

Besides, another possible cause for the scarcity of reported pancreatic injuries is the fact that these injuries often go undetected on CT scans, in contrast to liver, spleen and kidney injuries. For instance, Phelan et al. (2009) found that at least 40% pancreatic injuries were missed when using abdominal CT scan, and Holmes et al. (2012) found five patients with pancreatic injuries among eight patients with an apparent normal abdominal CT scan.

This low (apparent?) exposure of pancreas in impact situations then results in a poorly documented mechanical response to external dynamical loading, whereas the mechanical properties of spleen, liver and kidney tissues have been actively studied for decades.

Nevertheless, assessing the mechanical properties of pancreas is interesting for several reasons. First, this will help to improve the level of details in the human body finite element models used in the automotive community in order to understand and predict the injury/protective mechanisms within the abdomen in crash situations. Currently, apart from spleen, liver and kidneys, the rest of the abdomen including stomach, pancreas, small and large intestine, gallbladder, bile ducts, ureters, rectum and adrenal glands are usually modelled as a whole using one or several bags under pressure (Lee and Yang, 2001) or an interstitial continuous solid mesh (Ruan et al., 2005), thus ignoring the interactions between organs. Second, collecting material properties of pancreas has a great interest for biomedical sciences since this should help to calibrate new tools such US or MR elastography (Janssen et al., 2007; Yin et al., 2008) developed to make quickly non-invasive diagnostics and to differentiate pathologies resulting in different tissue stiffness, such as diffuse and focal diseases, chronic pancreatitis or tumors. Third, from a fundamental point of view, pancreas is a parenchymal organ like kidney, liver and spleen, which the mechanical behaviour was found to be slightly frequency-dependent (at low frequencies) and strain-hardening, following a bi-power nonlinear law validated in constant strain-rate as well as oscillatory tests (Nicolle et al., 2010, 2012). The questions we address in this study are as follows: Does the pancreas follow the same type of constitutive law as other abdominal solid organs, as regards the frequency-dependent as well as the non-linear response? What are the similarities and differences between the mechanical behaviours of the four solid soft organs of the abdomen?

2. Materials and methods

The instrument of choice for shear experiments is the rotational rheometer and the practical sample geometry is the parallel-plate device, in which a thin disc-shaped sample is sandwiched between two circular plates and sheared through rotation of one plate. Thirty-three samples were excised from eight fresh pancreases of 6-month pigs collected from a slaughterhouse. The shortest time between animal's sacrifice and testing was 3 to 4 h but some samples were tested one or two days after death. After receipt, pancreases were stored in hypothermic conditions during transportation to the laboratory. Immediately after arrival, the disc-shaped samples were prepared using a 15 mm diameter punch and home-made double-bladed scalpels with various gaps to obtain samples of thickness ranging from 1.9 to 3.5 mm (mean: 2.67 mm ± standard deviation: 0.44 mm) (Fig. 1). The specimens were removed from the head and the body of pancreas on either side of the main duct (Wirsung's duct), where the tissue composed of acinar cells, islets of Langerhans, interlobular and intralobular ducts is most homogeneous and continuous. During storage the samples were immersed into an isotonic solution at 4 °C until the test.

The samples were glued to the plates of a rotating rheometer (Bohlin C-VOR 150) and surrounded with a saline solution to prevent tissue dehydration, as recommended in Nicolle and Palierne (2010, 2012). To ensure a full contact between the sample and the plates, a small precompression was applied, generating a normal force less than few milli-Newtons. The test temperature was 37 °C and a heated cover enclosed the sample/plates system in order to reduce thermal convection and water loss.

For the sake of comparison, shear experiments similar to those performed on kidney, liver and spleen (Nicolle et al., 2010, 2012) were carried out, namely, a linear and a nonlinear test performed in quick succession. First, the linear viscoelastic properties of pancreas were probed in oscillatory tests at small strains ($\gamma_0 = 1\%$ at the edge of the sample), at frequency swept up and down from 0.1 to 10 Hz. This test was repeated until obtaining a steady response ("preconditioning"). Second, the non-linear properties of pancreas were assessed up to 150% strain by submitting 7, 10 and 6 samples to the respective constant strain rates of 0.0151, 0.133 and 0.66 s^{-1}, calculated at the outer edge of the sample. These strain rates lie in the range of those experienced by the samples during the small-strain oscillatory tests between 0.1 and 10 Hz causing a maximal strain rate included between 0.006 and 0.63 s^{-1} according to the formula $\dot{\gamma}_0 = 2\pi f \gamma_0$. Ten samples were not retained in the non-linear test because of adhesion failure. The benefit of the constant strain rate experiments is to gradually explore the transition to non-linearity in the strain-dependent behaviour of the tissue. The nonlinear viscoelastic model we propose is a fractional model including a power-law strain-dependent kernel (Nicolle et al., 2010). Briefly, the linear behaviour, pertaining to the small strain limit, is that of a fractional element (Schiessel et al., 1995) relating the stress σ to the strain γ according to the rheological constitutive equation

Fig. 1 – Punch used to cut a cylindrical shaped specimen (left) and home-made double-blade scalpel used to prepare from the cylindrical specimen a sample of homogeneous thickness (right).