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Comportement mécanique du colon humain en situation traumatique

Mechanical behavior of the human colon under trauma

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Résumé

Introduction

Le tube digestif est fréquemment atteint dans les traumatismes fermés de l'abdomen. La connaissance des propriétés mécaniques des différents organes est indispensable à la mise en place d'outils numériques de traumatologie virtuelle. L'objectif de cette étude est de déterminer la réponse mécanique du colon en traction uniaxiale jusqu'à la rupture et quels sont les facteurs la modifiant.

Matériel et méthodes

Nous avons réalisé des essais dynamiques uniaxiaux de spécimens coliques humains. Trois vitesses de sollicitation étaient testées : dynamique (1m/s), intermédiaire (10cm/s) et quasi-statique (1cm/s).

Une étude cinématographique et mécanique était réalisée pour chaque spécimen.

Résultats

Vingt-huit colons humains réfrigérés ont été testés avec un total de 344 spécimens inclus dans l'étude. Le colon présente un comportement mécanique bicouche avec une première rupture de la couche externe comprenant séreuse/musculaire externe puis une seconde rupture de la couche interne composée de la musculaire interne/sous-muqueuse/muqueuse.

Le comportement mécanique est variable en fonction de la localisation sur le cadre colique avec un comportement plus élastique du colon droit et du colon sigmoïde. Le sexe représente également un facteur responsable d'une modification de la réponse mécanique du colon. La durée de conservation des corps et le *tænia coli* ne représentaient pas un facteur influençant le comportement mécanique dynamique du colon.

La réponse mécanique enregistrée est différente en fonction de l'orientation de la sollicitation : les niveaux de contrainte et de déformation étaient statistiquement plus élevés sous sollicitation transversale que longitudinale.

La vitesse de sollicitation modifie la réponse mécanique enregistrée. Le colon est plus élastique en situation quasi-statique et présente des niveaux de rupture plus faibles sous sollicitation dynamique.

Sous sollicitation dynamique, le type de conservation ne modifie pas la raideur du tissu mais modifie la déformation et la force nécessaires pour obtenir des lésions coliques.

Conclusion

Le colon se comporte comme un matériau viscoélastique ductile et bicouche. Son comportement mécanique est dépendant de la localisation sur le cadre colique, du sexe, des méthodes de conservation et des vitesses de sollicitation. Cette étude permettra l'intégration de données biomécaniques dans des modèles de traumatologie virtuelle ou de simulation chirurgicale.

Mots clés : traumatisme, colon, biomécanique

Abstract

Introduction

The digestive tract is frequently affected in blunt abdominal trauma. The knowledge of the mechanical properties of the various organs is essential to the implementation of virtual tools of traumatology. The objective of this study is to determine the mechanical response of the colon in uniaxial traction until rupture and what are the modifying factors.

Material and methods

We performed uniaxial dynamic tests of human colonic specimens. Three loading speeds were tested: dynamic (1m / s), intermediate (10cm / s) and static (1cm / s). A cinematographic and mechanical study was carried out.

Results

Twenty-eight refrigerated human colons were tested with a total of 344 specimens included in the study. The colon exhibits a bi-layered mechanical behavior with a first rupture of the outer layer comprising serosa / external muscle and then a second rupture of the inner layer composed of the internal muscle / submucosa / mucosa.

The mechanical behavior is variable according to the localization on the colonic frame with a more elastic behavior of the right colon and the sigmoid colon. Gender is also a factor responsible for a change in the mechanical response of the colon. The shelf life of the body and *tænia coli* were not a factor influencing the mechanical behavior of the colon under dynamic solicitation.

The recorded mechanical response is different depending on the orientation of the stress: the stress and strain levels were statistically higher under circumferential stress than longitudinal.

The loading speed changes the recorded mechanical response. The colon is more elastic in a quasi-static situation and has lower levels of rupture under dynamic stress. Under dynamic loading, the type of preservation does not modify the stiffness of the tissue but modifies the stress and strain necessary to obtain colonic lesions.

Conclusion

The colon behaves like a ductile and bilayer viscoelastic material. Its mechanical behavior is dependent on the location on the colonic frame, gender, methods of conservation and rates of solicitation. This study will allow the integration of biomechanical data into models of virtual trauma or surgical simulation.

Keywords: trauma, colon, biomechanics

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Valorisation du travail

1. Articles publiés dans des revues indexées

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Surgical Radiological Anatomy (submitted)

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Lecture: #O169, Session: Visceral Trauma

« Analysis of the biomechanical behavior of the digestive tract in abdominal traumatic situation »
D. Massalou, T. Bège, S. Bourguoin, C. Masson, P. Foti, P. Baqué, P.-J. Arnoux, C. Brunet, S.-V. Berdah
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« Traumatismes fermés de l'abdomen : analyse du comportement biomécanique du tube digestif afin de comprendre les lésions.»
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6. Poster

« Dynamic biomechanical characterization of colon tissue according to anatomical factors »
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1. **Introduction**

L'estimation du nombre de patients traumatisés dans le monde s'avère complexe. L'étude *The Global Burden of Disease Study* (GBD) (1), mise en place par l'Organisation Mondiale de la Santé (OMS), représente l'initiative systématique la plus importante à ce jour pour connaître la distribution mondiale des maladies les plus répandues et les traumatismes. Malgré des limites évidentes concernant la difficulté d'établir ces estimations, le GBD est une source épidémiologique solide.

L'impact des traumatismes ne s'évalue pas uniquement à la phase initiale de leur prise en charge mais nécessité également une prise en compte de l'impact des séquelles post-traumatiques et des handicaps qui en découlent. Particulièrement chez les patients traumatisés, qui sont souvent de jeunes individus en bonne santé qui souffrent toute leur vie de handicaps. L'épidémiologie des traumatismes aide à définir les priorités en matière de santé publique, de recherche et contribue à identifier les personnes les plus vulnérables.

Selon le GBD (1), en 2010, les traumatismes représentaient 278,6 millions de personnes soit 11,2% de l'ensemble des personnes considérées comme malades : 29% de ces blessures correspondaient à des accidents de la voie publique, 12,6% de chutes et 9,16% de violence interpersonnelle. Les traumatismes représentent la sixième cause de décès dans le monde (2). Parmi les moins de 35 ans, c'est la principale cause de décès et d'invalidité, principalement dans les pays en voie de développement.

Les patients de plus de 65 ans constituent un groupe de plus en plus affecté (3). Pour des niveaux similaires de blessures, ces patients ont un taux de mortalité deux fois plus élevé que les patients traumatisés jeunes (4). Ceci en raison de l'existence de comorbidités et des traitements associés ; les sujets âgés sont plus susceptibles de mourir de complications médicales tardives au cours de l'hospitalisation.

Il existe plusieurs échelles ou scores pour documenter, rapporter et comparer les données des patients traumatisés sévères. Les scores de traumatisme les plus courants sont le « *Abbreviated Injury Scale* » (AIS), le « *Injury Severity Score* » (ISS) et le score TRISS (*Trauma and Injury Severity Score*).

Bien que rares au cours des traumatismes fermés de l'abdomen (5), les lésions des organes creux intra-abdominaux sont responsables d'une morbi-mortalité de 10 à 30% (6)(7). Au cours des contusions de l'abdomen, les traumatismes du colon représentent 30% des traumatismes du tube digestif (7,8). Des progrès sont nécessaires dans la détection précoce de ces lésions. La compréhension des mécanismes physiopathologiques à l'origine des lésions du tube digestif permettrait d'identifier les facteurs prédictifs qui pourraient être utilisés dans le diagnostic de ces lésions lors de la prise en charge initiale des traumatisés sévères.

Prenant en compte leur gravité potentielle, ces lésions ont été étudiées en biomécanique afin d'en comprendre le processus lésionnel. En effet, les mécanismes à l'origine des lésions du tube digestif sont complexes et impliquent des phénomènes de compression, décélération et écrasement.

Une lésion fréquemment rencontrée est le traumatisme fermé de l'abdomen au cours d'une décélération en automobile. En effet, la décélération va produire une projection du corps vers l'avant, ainsi que des organes « mobiles » (9). Le contact direct de l'abdomen contre la ceinture de sécurité est connu pour être responsable de ces traumatismes du tube digestif. En effet, le traumatisme direct de l'abdomen avec la ceinture de sécurité entraîne une compression et un étirement du jéjunum responsables de perforations du jéjunum. La présence de liquide ou d'air dans le jéjunum semble être nécessaire pour créer des lésions de celui-ci (10,11).

L'évolution informatique a permis la réalisation de modèles numériques de plus en plus sophistiqués. Ces modèles numériques peuvent être utilisés dans de nombreuses applications dont la traumatologie virtuelle en biomécanique avec la réalisation d'accidents automobiles virtuels (12).

L'utilisation de modèles numériques qui décrivent virtuellement la complexité anatomique de la région abdominale permet de comprendre à la fois les conditions et les mécanismes de lésions des viscères (13). La prévention des traumatismes du tube digestif fait appel à ces modèles numériques afin de tester différentes améliorations dans les systèmes de sécurité des véhicules. La performance de ces outils de simulation est intimement liée aux connaissances détaillées du comportement mécanique du tissu viscéral et en particulier du colon, dans des conditions de chargement compatibles avec celles d'un traumatisme.

Le moyen d'étude expérimental le plus adapté à la reproduction des phénomènes lésionnels complexes du tube digestif lors d'un traumatisme correspond aux essais en traction. En effet aussi bien la décélération que l'hyperpression entrainent au niveau local des phénomènes de traction. Dans la littérature, la plupart des vitesses de chargement utilisées sont dites statiques ou quasi-statiques, proche de 0.01m/s (14)(15) avec par exemple 50mm/mn pour Egorov et al. (15). Ces tests ne tiennent pas compte de l'influence des grandes vitesses de déformation sur le comportement mécanique et la rupture, observés lors d'un traumatisme.

Des essais ont été effectués chez le rat (16)(17), le cobaye (18) et le porc (14). Pour le colon humain n'ont été publiés que les résultats de tests de compression, de traction statique (15)(19) et d'aspiration (20). Seuls les organes sous-péritonéaux, impliqués dans les prolapsus, ont fait l'objet de nombreuses études statiques dans le but de mieux appréhender la physiologie de cette pathologie et les échecs des cures chirurgicales(21)(22)(23)(24). Cependant, aucune étude n'a été publiée dans la littérature concernant la caractérisation dynamique du colon humain.

D'un point de vue mécanique, le colon est décrit comme un tissu viscoélastique, contractile et anisotrope (21)(15)(18).

Le comportement mécanique du mésentère a également été étudié dans notre laboratoire afin d'en permettre la modélisation numérique et l'utilisation de cet « organe » en traumatologie virtuelle (25).
L'objectif de cette étude est de déterminer le comportement biomécanique du colon soumis à une sollicitation par traction uniaxiale, en observant son comportement jusqu'à la rupture complète. Notre objectif secondaire est d'étudier les facteurs responsables de variations du comportement mécanique colique.

1.1. Généralités en traumatologie virtuelle

L'élaboration de modèles numériques pour la détermination des mécanismes lésionnels nécessite en premier une description fine de l'anatomie : géométrie tridimensionnelle, variabilité anthropométrique et posturale. Ensuite, les propriétés biomécaniques de l'organe sont intégrées dans le modèle et permettent son utilisation.

L'acquisition de la géométrie tridimensionnelle des différents éléments composant le corps humain nécessite la conception et le développement d'outils spécifiques, qu'ils soient expérimentaux ou informatiques. L'acquisition des données s'appuie sur des techniques d'imagerie médicale, ici un scanner multibarettes.

L'analyse des images obtenues est ensuite réalisée par un médecin radiologue ou chirurgien. La reconstruction 3D fait appel d'une part à des logiciels d'imagerie afin obtenir la géométrie finale tridimensionnelle et d'autre part à des logiciels de maillage.

Le Laboratoire de Biomécanique Appliquée (LBA) étudie le comportement biomécanique de l'ensemble du corps humain, particulièrement en situation traumatique. Le mannequin biofidèle humain « MELBA » est un modèle numérique adapté aux simulations de choc pour des applications en traumatologie virtuelle.

Depuis 2004, le LBA, à travers le projet MELBA, s'est orienté vers une nouvelle génération de modèles éléments finis du corps humain basés sur une représentation biofidèle au plan anatomique, mécanique et physiologique (figure 1). Ce projet a supplanté le mannequin entier « HUMOS ». A ce jour, le modèle « par région anatomique » est opérationnel. Cela concerne la composante abdominale et pelvienne, le thorax, le rachis lombaire et thoracique ; le tube digestif et les mésos n'ont cependant jamais bénéficié d'une étude approfondie en modélisation tridimensionnelle afin d'être intégrés dans ce logiciel.

Le développement d'un modèle du tube digestif s'est arrêté aux difficultés d'acquisition de ces organes et la difficulté d'intégration de modèles tridimensionnels dans le volume imparti au sein de MELBA.

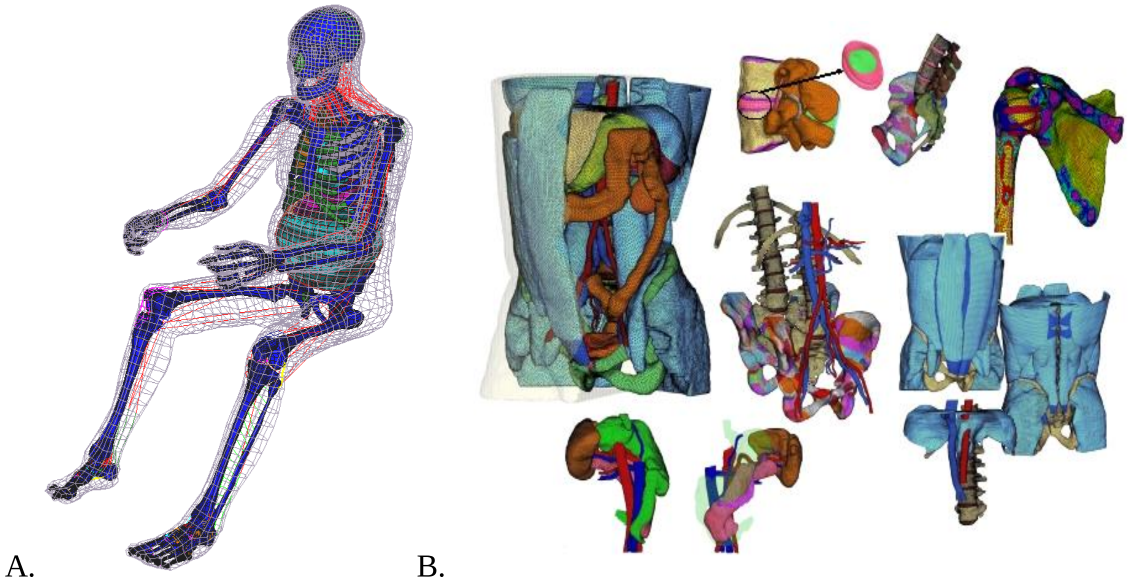


Figure 1 : Modèle complet HUMOS (A) et modèles abdominaux MELBA (B)

L’objectif de notre laboratoire est la création d'un modèle générique complet personnalisable pour la traumatologie virtuelle. Ainsi l’étude de la variabilité inter-individuelle par organe est nécessaire.

L’étude de la variabilité anthropométrique porte sur une étude des caractéristiques géométriques de la population afin de générer différents modèles de morphologie allant de l’enfant à l’adulte (du 5ème percentile femme au 95ème percentile homme – figure 2). Il s’agit de définir les paramètres significatifs pour la création d'un modèle générique personnalisable.

L’ensemble de ces modélisations nous conduit à :

- construire une base de données anthropométriques pour la population adulte
- générer différentes géométries de modèle numérique de l’adulte : femme petite jusqu’à homme grand.

Différents facteurs ont contribué au développement des modèles numériques par éléments finis :

- l’amélioration des moyens de calcul
- un coût inférieur par rapport aux essais sur sujets humains et sur mannequins
- une représentation plus fidèle en terme de géométrie mais également en terme de comportement mécanique

- avoir accès aux déplacements, aux contraintes et aux déformations des structures anatomiques
- pouvoir faire varier les paramètres de l'évaluation une fois que le modèle de base est validé.

Toutefois, l'intestin grêle, le colon et leurs mésos respectifs sont les seuls organes qui n'ont pas été modélisés dans le modèle MELBA. Ainsi, ce travail préliminaire à toute intégration dans MELBA consiste à étudier la variabilité du colon en fonction de critères anthropométriques.

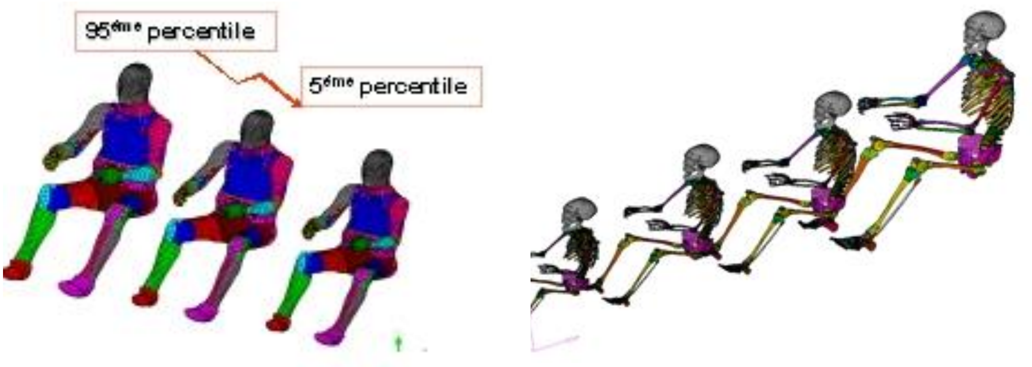


Figure 2 : variabilité inter-individuelle de modèle « éléments finis »

1.2 Bases anatomiques du colon

Le colon est un organe creux unique, abdominal et intra-péritonéal. Il fait partie du tube digestif, fait suite à l'iléon via la valvule iléo-caecale (valvule de Bauhin) et précède le rectum. Il a grossièrement la forme d'un cadre (figure 3). Le rôle du colon est de propulser le chyme alimentaire jusqu'au rectum en déshydratant les matières au fur et à mesure de leur progression, et d'en assurer le stockage dans l'ampoule rectale avant émission par le canal anal. La configuration externe et interne du colon est donc fortement organisée pour cette fonction (26,27)**.**

Le colon possède 4 zones, du proximal vers le distal : colon droit (ou ascendant), colon transverse, colon gauche (ou descendant) et le colon sigmoïde. La partie proximale du colon droit est appelée cæcum. Le cæcum possède à sa base inférieure un « diverticule » appelé appendice vermiforme. Cet appendice possède une fonction lymphoïde et peut présenter une inflammation aiguë ou subaiguë appelée appendicite qui représente, en fréquence, la première urgence chirurgicale digestive en France (28).

Le colon présente des caractéristiques différentes en fonction de la localisation : paroi fine fin et diamètre important dans sa partie proximale, il se rétrécit progressivement jusqu'à devenir épais et de petit calibre au niveau du colon sigmoïde.

La configuration externe du colon est composée de trois bandelettes musculaires longitudinales, dans l'axe de progression du chyme, appelées *tænia coli*, dont l'extrémité proximale commune se situe au niveau de la base appendiculaire (figure 4). Les 3 bandelettes se terminent au niveau de la charnière recto-sigmoïdienne, ce qui constitue un repère chirurgical. La forme « bosselée » du colon est également caractéristique de cet organe et ces formations prennent le nom d'haustrations coliques. Le colon présente également des franges adipeuses (non présentes sur le rectum) appelées franges épiploïques. Des diverticules peuvent également être présents, apparaissant avec l'âge, principalement localisés au niveau du colon gauche et du colon sigmoïde pour les populations occidentales ; les diverticules sont présents chez 50% des plus de 65 ans. Ces diverticules peuvent être le siège de complications hémorragiques et infectieuses.

La jonction recto-sigmoïdienne est une zone difficile à définir, de nombreux critères morphologiques et fonctionnels imposant une localisation différente de celle-ci (29). Ainsi, la jonction recto-sigmoïdienne ne sera pas étudiée dans ce travail.

L'organisation de la paroi du colon obéit à une organisation circulaire composée de couches concentriques, avec de l'extérieur vers l'intérieur (figure 5) :

- séreuse
- musculaire longitudinale externe, incomplète, épaisse en regard des bandelettes
- musculeuse circulaire interne
- sous-muqueuse
- muqueuse

Entre couches sous-muqueuse et muqueuse existe la *muscularis mucosæ* qui constitue une fine couche musculaire lisse. L'épithélium muqueux est un épithélium glandulaire dit lieberkhünien.

Sa vascularisation est assurée par l'artère mésentérique supérieure pour le colon droit et les 2/3 proximaux du colon transverse, le reste du colon étant vascularisé par l'artère mésentérique inférieure.

Les rameaux vasculaires et nerveux à destinée colique cheminent de la séreuse vers la sous-muqueuse. La muqueuse ne dispose pas de vaisseau et sa vascularisation est assurée par le passage extra-vasculaire d'éléments sanguins, via un tissu conjonctif.

L'innervation est assurée par l'innervation autonome, via les systèmes sympathique et parasympathique. Cinq plexus de l'innervation autonome sont donc mis en jeu : plexus cœliaque, plexus mésentérique supérieur, plexus mésentérique inférieur, plexus hypogastrique supérieur et plexus hypogastrique inférieur. Les métamères impliqués vont de T5 à S4.

Vascularisation et innervation cheminent dans un méso appelé mésocolon. Le mésocolon droit est le prolongement du mésentère.

Il existe des zones fixes, accolées au péritoine pariétal postérieur, tel que le colon droit, le colon gauche, les angles coliques droit et gauche, ainsi que la jonction colo-sigmoïdienne et la charnière recto-sigmoïdienne.

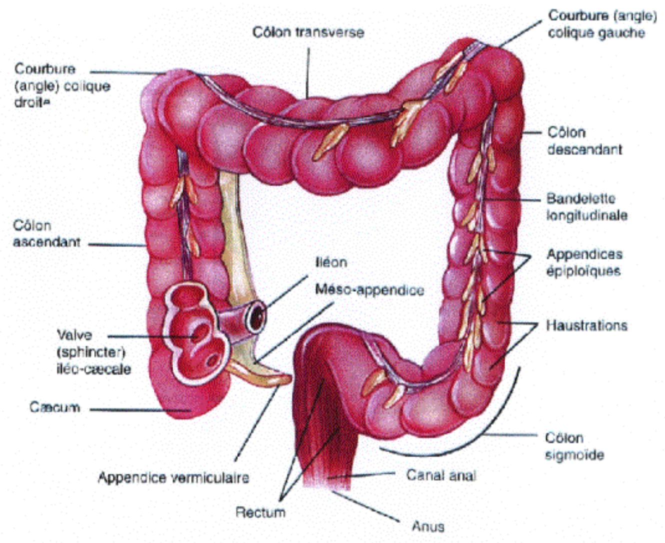
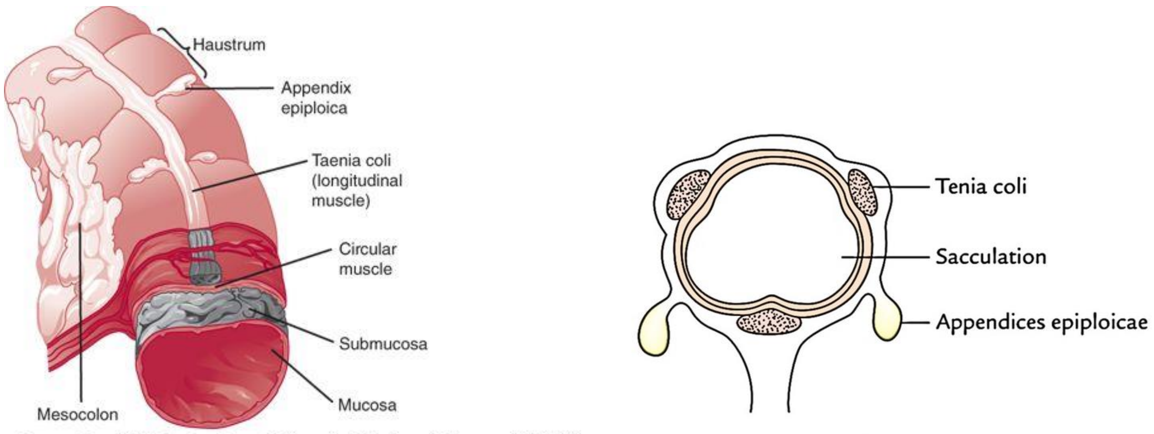


Figure 3 : anatomie générale du colon humain



Source: Gerard M. Doherty: Current Diagnosis & Treatment: Surgery, 14th Edition
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Cross-sectional View

Figure 4 : présence des bandelettes longitudinales musculaires du colon, appelées *taenia coli*

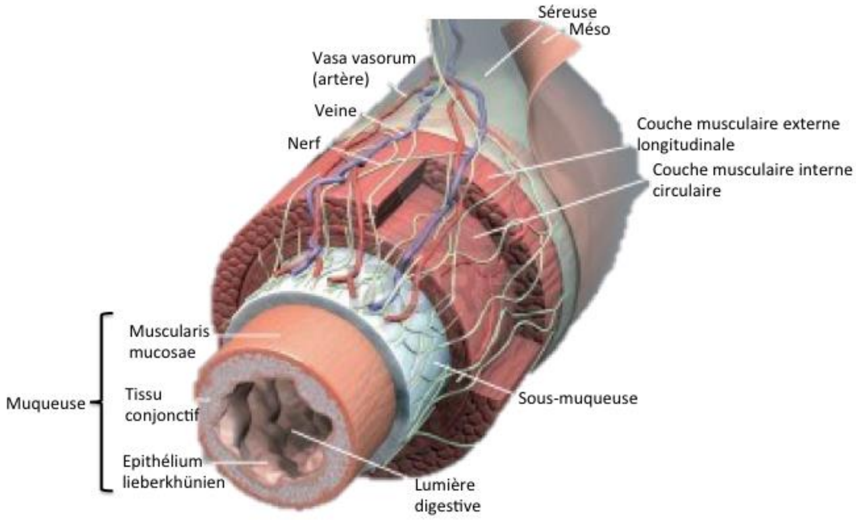

Figure 5 : anatomie des différentes tuniques composant la paroi colique

2. Etude numérique de la variabilité inter-individuelle

2.1. Variabilité inter-individuelle de l’anatomie digestive

La notion de variabilité inter-individuelle permet d’expliquer la différence de phénotypes présentés par une population. Cette variabilité s’applique autant aux caractères morphologiques « externes » qu’à l’anatomie viscérale. Le tube digestif est une structure tridimensionnelle complexe décrite en embryologie et en anatomie humaine.

La particularité des viscères abdominaux est de posséder une partie fixe qui permet le passage des éléments vasculo-nerveux, les méso, et le tube digestif lui-même, portion plus ou moins mobile.

Ainsi, la variabilité inter-individuelle du tube digestif comprend la variabilité du tube digestif lui-même et celle de ses moyens de fixité.

Notre laboratoire étudie la variabilité inter-individuelle des organes digestifs par des études radiologiques, à partir de scanner abdomino-pelviens chez des patients sains.

2.2. Variabilité inter-individuelle des méso du tube digestif

L’étude des variations anatomiques des méso du tube digestif a été étudiée. En effet, son intérêt clinique est limité, mais devient capital en traumatologie virtuelle avec utilisation de modèles personnalisables.

C’est dans cette optique que nous avons étudié la morphologie tridimensionnelle du mésentère humain à travers une étude radiologique. Cette étape anatomique descriptive permet d’appréhender les difficultés rencontrées au cours de la modélisation et du maillage numérique, mais également d’intégration du calque 3D dans un modèle déjà défini tel que MELBA ou HUMOS.

Le comportement mécanique du mésentère a également été étudié dans notre laboratoire afin d’en permettre la modélisation numérique et l’utilisation de cet « organe » en traumatologie virtuelle (25).

2.3. Variabilité inter-individuelle des moyens de fixité du colon

L'importance de la variabilité de la longueur du côlon et de ses différents segments en fonction de l'âge, du sexe et de la corpulence ont été démontrés dans différentes études (30,31).

Cependant, ces études n'ont pas fourni une disposition précise du côlon dans la cavité abdominale. En outre, la plupart des études ont été réalisées dans des conditions non physiologiques, au cours de procédures chirurgicales, de dissections cadavériques (32) ou avec des colons préparés et insufflés au cours de coloscopies.

Or, la connaissance de la disposition du côlon et de la variabilité anatomique dans la population générale en condition physiologique sont critiques pour la modélisation de l'abdomen. Il s’agit d’une étape dans la création de modèles personnalisés pour le tractus gastro-intestinal utilisé pour des simulations chirurgicales ou dans les études de traumatisme virtuel.

Une étude tomodensitométrique de la variabilité de la position intra-abdominale du côlon a été réalisée dans notre laboratoire (figure 6) (33). La longueur des segments digestifs et leur position par rapport à la cavité abdominale ont été étudiés et varient en fonction du genre, de l’âge des sujets et de leur corpulence (figure 7).

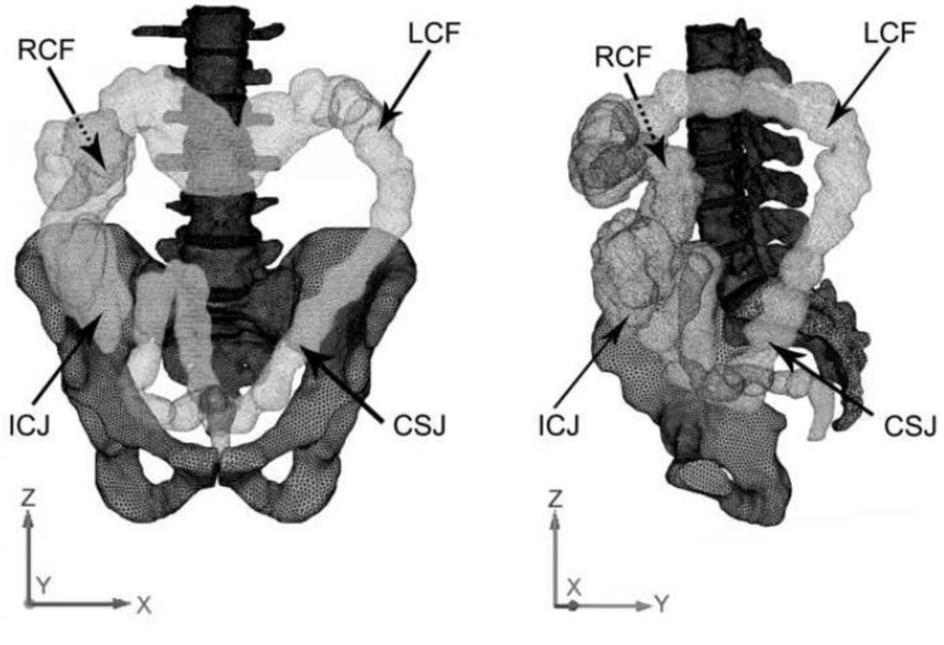

Figure 6 : modélisation tridimensionnelle du colon humain (selon Bourgouin et al.)

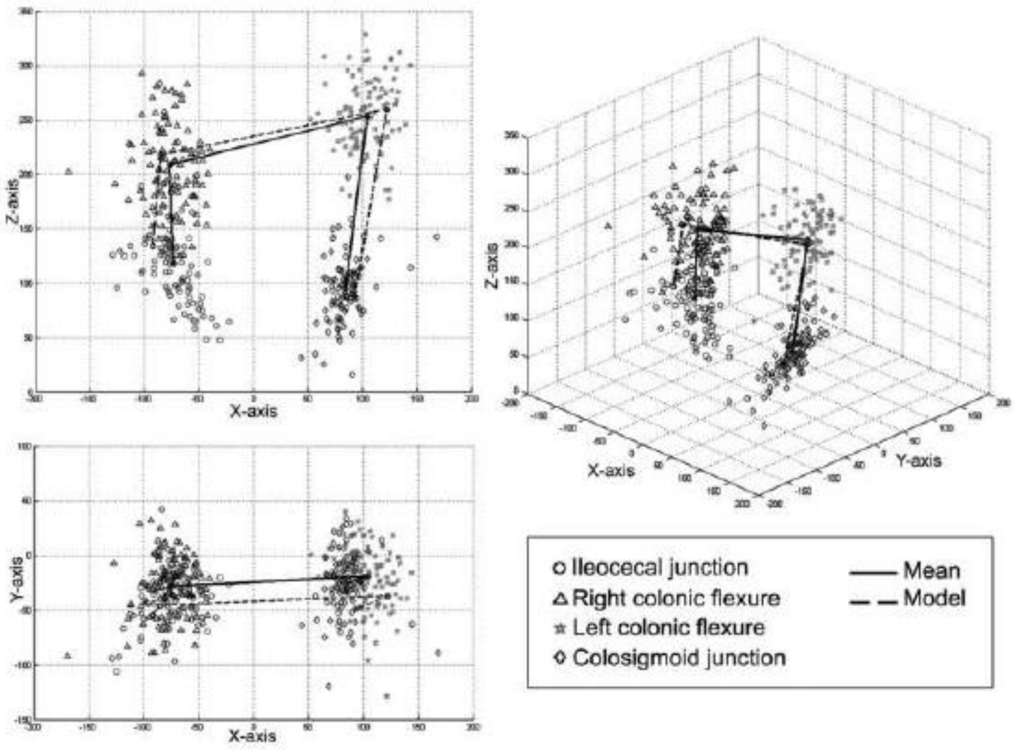

Figure 7 : variabilité inter-individuelle du colon (selon Bourgouin et al.)

2.4. Article sur la modélisation du mésentère humain

Surg Radiol Anat
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ANATOMIC VARIATIONS

Three-dimensional variability of the mesentery and the superior mesenteric artery: application to virtual trauma modeling

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Abstract

Introduction Trauma is a major cause of death worldwide, mainly affecting a young male population. Blunt trauma of the abdomen can cause a trauma of the mesentery in 5 % of cases. Rapid decelerations and injuries by seat belts are the most common pathophysiological mechanisms. Three-dimensional anatomical scanning of the mesentery and gastrointestinal tract is the first essential step in modeling abdominal trauma in an attempt to understand the pathophysiology of mesenteric lesions and to improve the safety features of vehicles.

Objective of the study To analyze the individual variability of the mesentery and the superior mesenteric artery (SMA) from medical imaging and to develop a three-dimensional customizable finite element model.

Materials and methods In this retrospective study, one hundred abdominopelvic injected CT scans were analyzed from healthy patients. The evaluation criteria of the mesentery were its volume (total and the distribution of adipose tissue/non adipose tissue), the length of the SMA and the distance between duodenojejunal angle (DJA) and the ileocecal junction (ICJ). The variability of these measures has been studied by demographic (age and gender) and morphologic (height evaluated by the T11–L4 distance, the waist circumference and the thickness of the subcutaneous adipose tissue).

Results Mean mesenteric volume was 644 cm^3 (ranges from 89 to 1,869 cm^3), and the mean length of the SMA was 224.9 mm (ranges from 138.4 to 312.3). There was a statistically significant association between waist circumference and the total volume of the mesentery, its fat component and non fat component ($p < 0.001$). Waist circumference was the only morphological parameter associated with the length of the superior mesenteric artery and the length of the DJA to ICJ ($p < 0.001$). Subcutaneous adipose tissue and female sex were statistically

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associated with total mesentery volume (respectively, $p = 0.005$ and $p = 0.001$). Age was an independent predictor of the increased volume of the mesentery and the length of the SMA. The height of the subject changes the length of the SMA ($p = 0.001$).
Conclusion The assessment of the mesenteric variability highlighted three factors associated with its size and length: age, sex, and waist circumference. These parameters have to be taken into account to personalize numerical model in the area of virtual trauma.

Keywords Mesentery · Superior mesenteric artery · Variability · CT · Virtual trauma modeling

Introduction

The mesentery supports the blood vessels of the jejunum and ileum. This organ is injured in 5 % of blunt abdominal trauma [39], during rapid decelerations or when the abdomen is crushed. Its weight, combined with that of the small intestine (especially if the latter is full) makes a moving mass that may be projected against the anterolateral wall of the abdomen and thus cause potentially lethal lesions due to the mesenteric root being torn from the abdominal wall.

The arterial vascularization of the small intestine is provided by the superior mesenteric artery (SMA), branching from the aorta. The SMA is located in the mesentery. A study by Asensio et al. [2], which was based on the segmentation of the mesenteric arteries [17], suggests that a lesion of the SMA is associated with a 25 % higher risk of death. The injury may be fatal in up to 100 % of cases, if the proximal portion of the artery is injured.

Injuries are a major cause of death worldwide, mainly affecting a young male population. This has led the World Health Organization to issue an international alert [40]. An adequate understanding of the mechanisms of blunt trauma requires a good understanding of the anatomy of the viscera. The three-dimensional geometry of the various components of the human body necessitates the design and development of tools for virtual traumatology with acquisition of morphological data by abdominal CT scan.

These digital models are more and more accurate and tend to become customizable templates for each individual based on different anthropometric criteria such as age, sex, height, etc.

Our institution has developed digital models of trauma affecting many abdominal organs [6–8, 10, 12, 13, 33]. To integrate the mesentery and SMA in HUMOS, our finite element model of virtual trauma [6], we conducted a study on the anatomical variability of the mesentery and the SMA, according to various anthropometric parameters.

Materials and methods

A retrospective study was conducted from a series of medical imaging data from abdominal and pelvic CT scans performed consecutively in 2011. The scanner used was a Siemens sensation 64 cardio (Erlangen, Germany). The protocol was identical for all patients. Exposure resulted in a dose of radiation of 120 kV, 400–500 mAS according to the patient's weight. Slice thickness was 0.7 mm. Acquisition was performed 80 s after an injection of 120 ml of a contrast medium iodized to 350 mg/ml.

Progressive abdominal pathology, severe spinal curvature and previous abdominal surgery constituted the criteria for exclusion.

All the CT scans were studied by the same operator (DM) using the imaging software Mimics 12.1 (Materialise, Leuven, Belgium). Four parameters of interest allowed us to describe the mesentery: the study of its volume, the distribution of fat and non-fat components within it, the length of the SMA (and its segments, in keeping with Fullen et al. [17] and the length of the duodenojejunal angle (DJA) to the ileocaecal junction (ICJ).

These parameters were calculated as follows:

- The mesentery was seen as an object with a full volume, without taking into account the different folds that compose it, given that they are not distinguishable on a CT scan. A model of the volume of the mesentery was made by manually following the axial plane for every three slices (every 21 mm—Fig. 1). The contours of the three-dimensional model were checked in frontal and sagittal planes, and adjustments were made if necessary (Fig. 1). The volume between the slices was interpolated to obtain a three-dimensional model (Fig. 2). Software deducted the volume of the object (in mm^3) thus obtained, which corresponded to the mesentery in its entirety (Fig. 2).
- The fat content of the mesentery was obtained by thresholding method. A model specifically focused on fat densities (between −205 and −31 Hounsfield units) was built. A three-dimensional model corresponding to the volume of non-fat mesentery was obtained by removing the model of the fat content from the total volume of the mesentery. The volume of this object was subtracted from the total volume to determine the mesenteric adipose volume.
- A three-dimensional model of the SMA was made from the aorta to its distal extremity. The model was made by manually following the axial plane, every two slices (Figs. 1, 2). The tool "center-line" imaging software allowed us then to know the size of different segments composing the SMA. The two first segments of the SMA were measured taking into account the Fullen

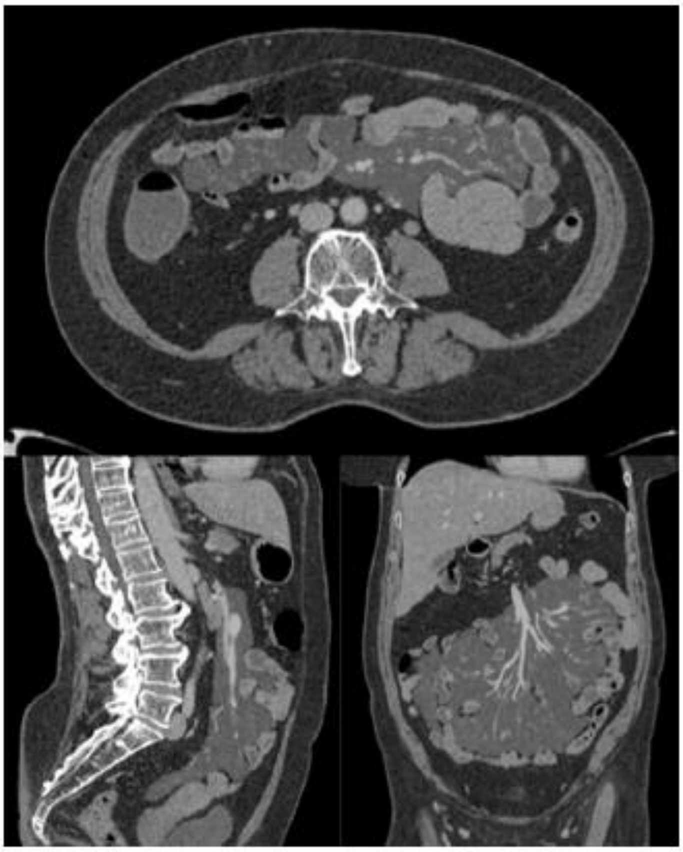

Fig. 1 Creation of the layer of the mesentery axial section (the mesentery is manually contoured every three CT slices) and check in the frontal and sagittal planes

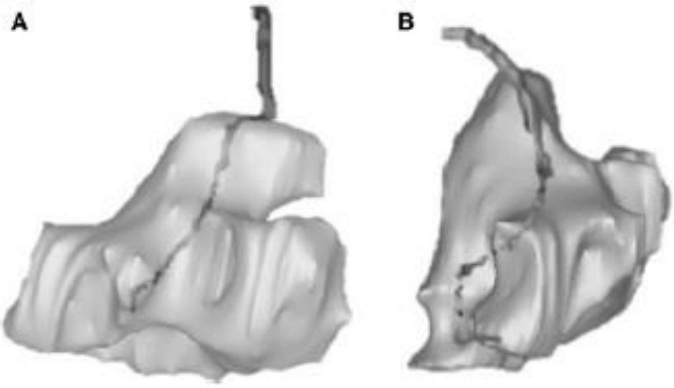

Fig. 2 Dimensional layers of the mesentery and the total SMA. **a** Frontal view, **b** side view

classification [17], that is between the aorta and the inferior pancreaticoduodenal artery for segment 1; between the inferior pancreaticoduodenal artery and the middle colic artery for segment 2. Segments 3 and 4 could not be individualized on CT.

- DJA–ICJ length corresponded to the distance between these two points (in mm) in the frontal plane.

The study of the factors explaining the variability of the mesentery focused on the influence of gender, age, and the following morphological parameters as identified by the CT scan:

- The thickness of the subcutaneous adipose tissue: on an axial section passing through the navel, the measurement was made in the sagittal plane, parallel to the axis of the umbilical cone 1 cm from the umbilicus (Fig. 3).
- Waist circumference at the umbilicus (Fig. 3) on an axial section through the navel, the measurement was

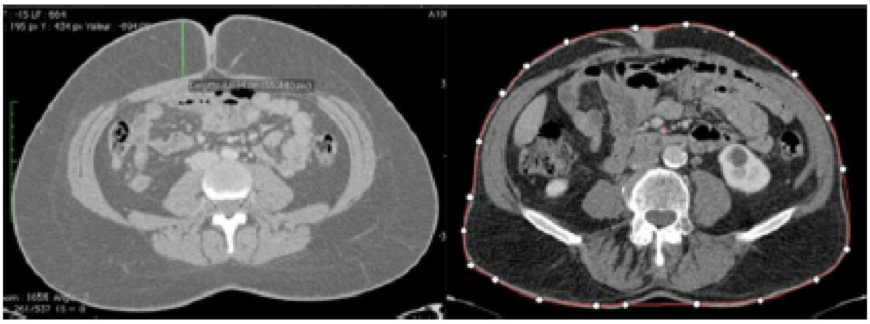

Fig. 3 Measurement of the thickness of subcutaneous adipose tissue, to 1 cm from the umbilicus, in an axial section passing through the navel. Measurement of waist circumference at the umbilicus

performed by manually following the waist circumference.
- The distance T11–L4 to obtain an approximation of the height of the patient.
- The length of the colon: the measurement corresponded to the sum of the distances between the fixed points of the colon, as used in a previous publication [8].

We considered patients to be obese if they had an abdominal circumference greater than 88 cm for women and 102 cm for men [8, 20].

Statistical analysis

The statistical analysis was performed with the program SPSS version 17.0 (SPSS Inc., Chicago, IL, USA). Quantitative data are presented as a mean (minimum–maximum).

We performed univariate analysis using Student's t test to compare quantitative values within subgroups and the Pearson correlation to examine the link between quantitative values. The coefficient of variation is the ratio between the standard deviation σ and the average μ.

We considered a value of $p < 0.05$ as statistically significant for all two-tailed tests used.

Results

One hundred patients were included, with an equal distribution between men and women. The general description of this population is shown in Table 1.

Variability of the volume of the mesentery

Adipose tissue accounted for 58 % of the volume of the mesentery and was the most variable parameter: the coefficient of variation of intra-mesenteric adipose tissue was 82 % while it was only 35.4 % for the non volume adipose. This adipose component was therefore the main parameter that changed the volume of the mesentery.

Variability of the length of the SMA

This was the least variable parameter in our population. The coefficient of variation was the lowest of the various criteria that we studied. The average length of segment 1 of the SMA (according to Fullen et al. [17]) was 38.61 mm (min 16.27–max 62.23) and in segment 2 was 16.2 mm (min 2.03–max 35.65).

Influence of waist circumference

Waist circumference was correlated with four parameters of our evaluation of the mesentery: total volume, adipose tissue, length of SMA and DJA–ICJ distance. Waist circumference showed a strong statistical correlation with the total volume of the mesentery, both fat and non-fat volumes ($p < 0.001$) (Table 2). The increase in abdominal circumference was the main anthropometric factor in increasing the volume of the mesentery and had the highest Pearson correlation coefficient ($r = 0.705$, $p < 0.001$) (Table 2; Fig. 4).

Waist circumference was the only morphological parameter associated with both the length of the SMA and the length of the DJA to ICJ ($p < 0.001$).

Influence of subcutaneous abdominal adipose tissue

Subcutaneous adipose tissue was statistically associated with both the total volume and the adipose volume of the mesentery, respectively, $p = 0.005$ and $p = 0.003$ (Table 2; Fig. 5).

Table 1 Descriptive statistics involving 100 patients

	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
Age (years)	16	87	58	14.14	24.4
Length of SMA (mm)	138.4	312.3	224.9	30.3	13.5
Length of DJA–ICJ (mm)	102.2	264.8	166.6	28.1	16.9
Total volume of mesentery (cm^3)	89.5	1,869.6	644.5	418	64.9
Volume of adipose mesentery (cm^3)	1.1	1,432.1	451	369.7	82.0
Volume of non-adipose mesentery (cm^3)	85.2	449	193.4	68.5	35.4
Percentage of intra-mesenteric adipose tissue (%)	1.3	87.3	58.4	23.5	40.3
Waist circumference (mm)	617.4	1,340.9	921.9	146.9	15.9
Thickness of subcutaneous adipose tissue (mm)	18.1	63.8	20.9	10.7	52.2
Length of the colon (mm)	275.7	626.3	452.1	69.5	15.37

SMA superior mesenteric artery, *DJA* duodenojejunal angle, *ICJ* ileocecal junction

Table 2 Results of univariate analyses by the Pearson correlation test (only statistically significant correlations are shown)

	Age	Length of the colon (mm)	Waist circumference (mm)	Subcutaneous adipose tissue (mm)	Distance T11–L4 (mm)
Total volume of mesentery (cm^3)	0.292 ($p = 0.003$)		0.705 ($p < 0.001$)	0.278 ($p = 0.005$)	
Volume of adipose mesentery (cm^3)	0.273 ($p = 0.006$)		0.696 ($p < 0.001$)	0.297 ($p = 0.003$)	
Volume of non-adipose mesentery (cm^3)	0.307 ($p = 0.002$)	0.23 ($p = 0.021$)	0.543 ($p < 0.001$)		
Length of SMA (mm)	0.316 ($p = 0.001$)		0.324 ($p < 0.001$)		0.458 ($p < 0.001$)
Length of DJA–ICJ (mm)			0.458 ($p < 0.001$)		

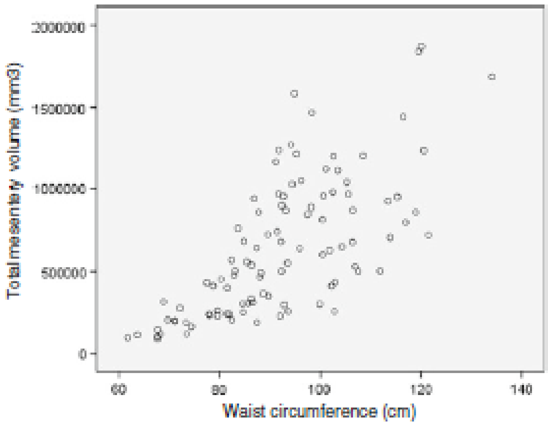

Fig. 4 Correlation between waist circumference and total volume of the mesentery ($r = 0.71$; $p < 0.001$)

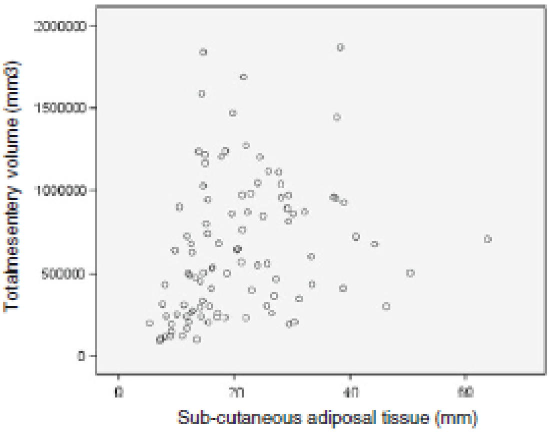

Fig. 5 Correlation between subcutaneous adipose tissue and total volume of the mesentery ($r = 0.28$; $p = 0.005$)

Influence of age

Age was a factor in increased volume of the mesentery and the length of the SMA (Table 2). For subgroups of age over or less than 60 years, only the group "age over 60" was a factor in changing the volume of the mesentery ($p < 0.001$).

Influence of sex

Sex was statistically correlated to the total volume of the mesentery ($p = 0.012$), to the adipose tissue and non-adipose tissue of the mesentery (respectively $p = 0.024$ and $p = 0.014$).

These three volumes were particularly related to female ($p < 0.001$ for each volume). Sex was not a factor statistically associated with the length of the SMA and the DJA–ICJ distance.

Other factors

The height of the subject was positively correlated with the length of the SMA ($p < 0.001$) (Table 2). Variability in the length of segments 1 and 2 of the SMA was also correlated with the height of the subject (respectively, $p = 0.028$ and $p = 0.05$). The length of the colon was also correlated to the distance T11–L4 ($p = 0.001$) (Table 2).

Discussion

The main anthropometric factors responsible for morphological changes of the mesentery are abdominal circumference, age and gender.

The variability of the human mesentery between individuals had never been investigated either during studies of cadavers or in clinical trials, unlike the length of the small bowel [18, 21, 35] or the colon [8, 15, 31, 32]. As for the peritoneum covering the mesentery, it represents nearly 26 % of the total peritoneum but has been the object of few studies [1]. Besides the classic study of anatomical variations, the appearance of surgical simulation and digital models of virtual trauma also require a precise knowledge of the variability of each organ.

Knowledge of the variability of the mesentery is crucial to create for each individual a virtual trauma model, which will predict the likelihood of particular lesions. However, the length of the small bowel, measured either intraoperatively or during cadaveric dissections, does not seem to be affected by gender (male or female), weight, height or age [18, 21].

Functional nuclear medicine imaging has demonstrated a decrease in metabolic activity for all abdominal organs, including the gastrointestinal tract, with increasing age [26].

The measurement of waist circumference is a good indication of the quantity of abdominal fat and of the associated cardiovascular risks [23, 24, 42]. This is also true for the volume of the mesentery, which is strongly linked to waist circumference ($p < 0.001$).

Studies have shown that there is an increase in visceral adipose tissue with increasing age and decreased subcutaneous adipose tissue, with no difference between the sexes [38]. In our study, male gender, age (especially over 60 years), increased abdominal girth or an increase in the thickness of subcutaneous adipose tissue are all factors in the increase in total mesenteric volume as well as the increase in adipose and non-adipose volumes of the mesentery. We have also demonstrated an association between colon length and the non-adipose volume of the mesentery.

A study published in 2007 [29] reported that the length of the proximal part of the SMA varies according to the body mass index (BMI) of the patient, as does the angle between the aorta and the root of the SMA. Indeed, the more the BMI increases, the more this angle increases and the greater the length of the root of the SMA (no difference was seen between male and female groups). These results have since been confirmed by a Turkish team [28] and by the present study.

We have also found an association among age, waist circumference, height of the individual and the length of the SMA. Our hypothesis is that a person with a large and therefore heavier mesentery, associated with a longer mesentery root will be at greater risk of suffering a lesion. New experimental protocols will be necessary to support this hypothesis.

Indeed, the digestive tract and mesentery are involved in 10 % of blunt abdominal trauma [39], especially due to decelerations during road accidents. Its weight makes it a moving mass that may be projected against the anterolateral wall of the abdomen and thus cause potentially fatal lesions involving the tearing out of the root of the mesentery. Thus, given that the energy transmitted during deceleration is equal to $\frac{1}{2}mv^2$, a more massive mesentery would have greater kinetic energy during a deceleration. BMI has already been described as a risk factor in injuries resulting from traffic accidents [16, 37].

When the passenger is belted, this seat belt can play the role of an obstacle and an energy transmitter. One of the most dangerous effects is sub-marining, i.e., the slip of the seat belt under the abdominal strap at the time of the impact, whereas, the belt was correctly positioned before the shock. This phenomenon of belt slipping will cause a compression of the abdomen [7].

The presence of the seat belt sign, which is the mark of the seat belt on the casualty, is correlated with an increasing risk of hollow viscous and solid abdominal organ injuries [4, 27, 34].

A dearth of data explains the practitioner's ignorance regarding the degree of morbidity and mortality of lesions resulting from the tearing out of the mesentery [14, 39], and underscores the potential interest of elaborating morphological prognostic data.

The severity of lesions is correlated with the location of lesions of the SMA: the closer the lesion is to the SMA, the greater the mortality, in cases of a tear at the inception of the SMA (segment 1), the mortality rate is higher than 75 % [2, 3]. The literature does not offer a therapeutic standard: possibility of arterial ligation or revascularization, the latter solution would guarantee a better chance of digestive conservation [9].

Anthropometric factors that may be associated with increased morbidity and mortality, and which thus should be looked for in case of closed trauma of the abdomen are: masculine gender, age over 60 years, an increased waist circumference (88 cm for women, 102 cm for men), an increase of subcutaneous adipose tissue and tall height. However, trauma victims are mostly young men.

Other applications of our work are also possible, such as the inclusion of obesity in surgical simulation. Indeed, during laparoscopic surgery, obesity increases the risk of a longer operative time and conversion to open procedure [5, 25, 41]. During surgical simulation, operating on virtually obese patients would complicate the realization of a laparoscopy and thus add to the level of technical difficulty.

The results of our study has some limitations. The study population was older than the general population with an average age of 58 years in our study, against an average age of 40 years in France; however, this distribution is closer to the distribution of the adult "standard" population. However, the aim of our study was to create "patterns measure" used in three-dimensional models, rather than reflect the representativeness of the morphological variability.

As for waist circumference, our population is close to the population studied in the literature with an average waist circumference of 92 cm [24, 42].

The choice of our CT measures should be explained. The measurement of subcutaneous adipose tissue has already been reported in the literature, either as a measure of volume or as in our study via a measurement of sagittal axial section through the umbilicus [19, 22, 30].

The CT measurement of waist circumference has a correlation of 85 % with a clinical measurement of this parameter ($p = 0.001$) [19]. Waist circumference is correlated with BMI and as such represents a good cardiovascular prognostic factor [36]. There is a statistically significant difference in the distribution of visceral adipose mass, BMI and waist circumference between different ethnic backgrounds [11], but we have not taken account of this criterion for patients in this study.

There was less classical approximation of the root of the mesentery by measuring DJA–ICJ. However, the length of the root of the mesentery is a major surgical data. Difficulties of exposure are more frequent, especially in laparoscopy when the mesentery is short. Integrating this concept into a 3D model can therefore have an interest in future applications of numerical models abdomen.

Conclusion

The mesentery is a complex anatomical structure that has considerable variability. The three factors explaining this variability include: age, gender, and weight.

The mesentery has significant variability, due to age over 60 years, female gender, subcutaneous adipose tissue and waist circumference greater than 88 cm for women and 102 cm for men. The length of the SMA is correlated with age, waist circumference and the height of the individual.

This anatomical variability should allow customization of virtual digital models whose main applications are virtual trauma and surgical simulation.

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Conflict of interest The authors declare that they have no conflict of interest.

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2.5. Etude mécanique du mésentère

Comme nous l’avons vu, les organes doivent être étudiés d’un point de vue morphologique et mécanique afin d’obtenir un modèle tridimensionnel générique et personnalisable. Ainsi notre laboratoire a étudié les propriétés mécaniques du mésentère (25) et de l’intestin grêle (34).

L’étude mécanique du colon humain vient compléter les données sur le comportement du tube digestif réalisée par notre laboratoire.

3. Variations du comportement mécanique du colon en fonction des conditions d’examen

3.1 Introduction

La modification de la vitesse de sollicitation sera responsable d’une modification de la réponse mécanique lors d’un test conduit jusqu’à la rupture.
Le tube digestif est composé de structures viscoélastiques (34,35) dont les variations de conditions de chargement pourraient modifier la relation contrainte-déformation.
Dans d’autres tissus viscoélastiques comme le tendon, une vitesse accrue de la déformation tendineuse, liée au développement d’une force musculaire plus rapide, augmente la rigidité des tendons et réduit ainsi la déformation à un niveau de force donné (36,37).

Une rupture peut survenir quand les sollicitations ont lieu dans les circonstances suivantes :

- Basses températures,
- Grandes vitesses de chargement, et
- Défauts préexistants ou créés pendant la sollicitation.

Les ruptures brutales dont il s'agit peuvent être classées en deux catégories :

- Les ruptures fragiles liées à l'absence de ductilité du matériau sollicité sous une certaine température, et
- Les ruptures ductiles sans prévenir, c'est-à-dire à très faible déformation plastique. Ce peut être le cas pour des matériaux à haute limite d'élasticité où il n'existe pas de dépendance très nette entre la ténacité et la température c'est-à-dire où la rupture en charge est liée à la propagation quasi instantanée d'une fissure à partir d'un défaut préexistant (38).

Dans le cadre thermodynamique général des milieux continus, les aspects mécaniques et thermiques sont « naturellement » couplés. Ceci met clairement en évidence l’importance de la température du spécimen lors de la réalisation d’un essai, et le couplage de cette influence avec la vitesse de déformation. Le régime thermique d’un essai peut être modifié en fonction de la vitesse de déformation mise en jeu. La puissance de déformation plastique est essentiellement dissipée en chaleur dans l’élément de volume considéré. Cette chaleur doit donc être évacuée par conduction thermique. Lors d’essais « lents » (chargements quasi-statiques), la chaleur a le temps de se dissiper, de sorte que l'on peut considérer que l'essai est isotherme. Dans un régime intermédiaire ou d'impact, l'éprouvette s'échauffe vite, et la chaleur produite n'a pas le temps de se dissiper. Ceci a une conséquence sur le comportement du matériau, et sur l'évolution de sa structure (39).

Dans notre étude sur spécimen colique, la température de l'échantillon n'était pas mesurée. La température des essais était contrôlée aux alentours de 23°C. Néanmoins, compte-tenu de la masse des spécimens coliques, de la température extérieure et les vitesses de sollicitation utilisées, nous considèrerons ces essais comme isothermes.

3.2. Article sur le comportement mécanique du colon en fonction de la vitesse de sollicitation (en cours de finalisation avant soumission au *Journal of Biomechanics*)

What are the mechanical effects of the solicitation speed for the human colon?

Abstract

Introduction

The colon is an organ of the digestive tract that can be reached in abdominal trauma as well as non-traumatic pathological phenomena.

The aim of this study was to determine the mechanical behaviour of the colon using tensile tests under different loading speeds.

Material and methods

Specimens were taken from refrigerated cadavers from different locations of the colonic frame: ascending, transverse, descending and sigmoid colon. Specimens were submitted to tensile tests, after preconditioning, to dynamic load (1m/s), intermediate load (10cm/s) and quasi-static load (1cm/s).

Results

A total of 336 specimens were tested, taken from 18 refrigerated colons.

Stress-strain analyse indicated, for longitudinal specimens, indicated a Young's modulus in the first quasi linear phase, for each loading speed, respectively 3.17 ± 2.05 MPa under dynamic loading (1 m/s), 1.74 ± 1.15 MPa under intermediate loading (10 cm/s) and 1.76 ± 1.21 MPa under quasi-static loading (1 cm/s) with $p<0.001$.

For circumferential specimen, stress-strain curves indicated a Young modulus in the first quasi linear phase, for each loading speed, respectively 3.15±1.73 MPa under dynamic loading (1 m/s), 2.14 ± 1.3 MPa under intermediate loading (10 cm/s) and 0.63 ± 1.25 MPa under quasi-static loading (1 cm/s) with $p<0.001$.

The appearance of the curves reveals two types of behaviour of the colon: fast break behaviour at high speed traction (dynamic protocol to 1m/s) and a different type of behaviour for lower speeds (intermediate protocols to 10cm/s and quasi-static 1cm/s). Changes in loading speed were responsible for modification of the profile curves of the colon but did not change the Young modulus.

The orientation of the specimen was also responsible for a change in the mechanical response of the colon: the circumferential orientation required greater levels of stress and strain in order to obtain lesions, indicating a more elastic behavior than longitudinal stress.

The presence of *taenia coli* was responsible for a change in the mechanical response during low speed loading.

Conclusion

Colon behaves as a viscoelastic material. Colonic mechanical behaviour varies with loading speeds for which it is submitted with two different types of mechanical behavior: more fragile dynamic stress and more elastic for quasi-static solicitations, close to physiological stresses.

This work will be used to develop numerical models in the context of trauma and the use of virtual surgical simulators.

Introduction

Knowledge of the mechanical properties of the digestive tract is essential. Indeed, this allows both to understand the physiological phenomena through quasi-static tests (Egorov, Schastlivtsev, Prut, Baranov, & Turusov, 2002), but also the understanding of traumatic phenomena using dynamic tests (Crandall et al., 2011). Quasi-static tests can also be used to put in place materials allowing digestive sutures or surgical simulation. Realistic modelling of soft tissue biomechanics and mechanical interactions between tissues have been shown to be very suitable for simulation of soft tissue biomechanics and successfully used in a number of image-guidance systems (Johnsen et al., 2015).

Experimental biomechanical characterization of the colon is poorly described compare to other abdominal organs : it is an anisotropic viscoelastic material (Higa et al., 2007)(Carter, Frank, Davies, McLean, & Cuschieri, 2001)(Egorov et al., 2002)(Watters et al., 1985)(Kauer, Vuskovic, Dual, Szekely, & Bajka, 2002; Yamada, 1970)(Y.-C. Fung, 1993)(Rubod et al., 2012). The morphology of the colon varies depending on its location: large diameter and thin wall for the ascending colon, gradually tapering to a small diameter and thick wall for the sigmoid colon. Its wall is functionally divided into two layers (from inner to outer): mucosa, submucosa, inner circular muscular layer and then the outer layer with outer longitudinal muscular layers and serosa.

Only a few tensile tests have been performed on human tissue, including Egorov under quasi-static solicitation (Egorov et al., 2002), Howes with high-rate equibiaxial elongation tests (Howes & Hardy, 2012) and our team with dynamic tensile tests at 1 m/s (Massalou et al., 2016).

Dynamic tests are characterized by loading speeds in the order of m/s, whereas tests are considered static when they are of the order of cm/s or mm/s (Rosen, Brown, De, Sinanan, & Hannaford, 2008)(Rubod et al., 2012)(Egorov et al., 2002). No studies have been published concerning the mechanical variability of the human colon subjected to various speeds under uniaxial stress.

Our main objective is to determine the mechanical variability of the human colon subjected to various speeds under uniaxial stress by observing its behavior until the complete rupture.

Matériel et méthodes

1. Origin of the tissue

The colonic specimens which were tested were samples taken from human subjects stored at 1 ° C without preservative solution.

The use of cadaveric human tissue was made as part of a protocol approved by the ethics committee of the Medical school of Nice concerning the donation of bodies to science.

The study included only adult subjects whose colon showed no signs of pathology (cancer, inflammation). The presence of diverticula was not a reason for exclusion of the organ given its high prevalence in the adult human population. However, the colonic samples did not contain colonic diverticula. Samples were taken from a total of 18 different colons: 12 from females and 6 from males. The average age was 87.2 years ± 8.4 years and the bodies had been conserved an average of 21.3 days ± 11.5 days (Table 1).

2. Preparation of the specimens

The specimens were colon segments taken from the antimesenteric border after performing a longitudinal opening, following a standardized format using a rectangular punch with the following dimensions: 25 x 100mm.

For each anatomical subject and each direction (longitudinal and circumferential), 2 specimens were taken according to their location on the colonic segment (ascending, transverse, descending, sigmoid colon). The longitudinal specimens with taenia coli (muscle strips) were made parallel to the axis of the strip and included the strip. The circumferential specimens were made perpendicular to the axis of the muscle strip (taenia coli), with the strip situated in the middle of the specimen.

The full description of the specimen preparation protocol has been described in one of our previous articles (Massalou et al., 2016).

3. Dynamic tensile tests

The initial length (L_0) of the specimens was thus 40 mm. The experimental characterization of the mechanical behavior of the colon was made from uniaxial tensile tests under: dynamic load (1m/s), intermediate load (10cm/s) or static load (1cm/s). The test was performed using a hydraulic test system MTS 370.10 Landmark® (USA) under displacement control.

The tests were tensile tests and we confirm there was some ramp-up of the test system during the initial stretch of the sample. We chose to adjust all load responses to 2N at t=0.

Because the colon is viscoelastic, a pre-conditioning test phase of the specimen was performed with test parameters chosen to avoid the occurrence of lesions. Preconditioning 10 sinusoidal cycles with an amplitude of 6 mm at a speed of 0.5 m / s was carried out (as described in a previous publication for the small intestine (Bourgouin et al., 2012)). The preconditioning phase was immediately followed by a tensile load of 1 m/s, 10 cm/s or 1 cm/s up to a 10 cm distance.

4. Data acquisition and post-processing of results

Data were not filtered, the stress-strain curves were then zeroed (a 2N reset was applied) to remove a possible initial load in the set up of the samples and a response corridor was generated (mean ±standard deviation (SD)). The strain was calculated from the initial length (L_0) using the following equation: strain (%) = final length (mm) / initial length L_0 (40mm). The stress was calculated using this equation: stress (MPa) = force (N) / surface (mm). We measured only global displacement because our objective was to determine a global behavior for biomechanical characterization.

Young’s modulus was calculated for only the linear region of the stress-strain curves.

Statistics were performed using Statistica software for Windows.

Since the normality condition of the variables is rejected by the Shapiro test (p-value <1%), we use the nonparametric Kruskal-Wallis test. This one allows to test if the independent samples come from the same population. The results were considered statistically significant if p-value <0.05.

Results

A total of 336 specimens, obtained from 18 human subjects, were submitted to tensile tests, after preconditioning. The tests were based on:

- 80 longitudinal and 40 circumferential specimens under quasi-static load (1cm/s),
- 64 longitudinal and 32 circumferential specimens under intermediate load (10cm/s),
- 80 longitudinal and 40 circumferential specimens under dynamic load (1m/s).

1. Mechanical behavior for quasi-static solicitation

Uniaxial tensile tests were performed under quasi-static solicitation at 1 cm / s, with the specimens being oriented in the colon axis (longitudinal) or perpendicular to the axis (circumferential). The results are shown in Table 2 and figure 1.

The change in the orientation of the specimen is responsible for a change in the mechanical response of the colon. The circumferential stress requires higher levels of stress and strain in order to obtain lesions.

	LS	**CS**	**p-value**
Modulus of the elastic phase (MPa)	1.76 ± 1.21	0.63 ± 1.25	0.93
Strain at 1st inflexion (%)	40.45 ± 25.49	61.31 ± 21.96	**<0.001**
Stress at 1st inflexion (MPa)	0.36 ± 0.21	0.64 ± 0.38	**<0.001**
Strain at 2nd inflexion (%)	78.75 ± 45.15	81.24 ± 37.54	0.35
Stress at 2nd inflexion (MPa)	0.46 ± 0.22	0.7 ± 0.35	**<0.001**

Table 2: Influence of orientation on the mechanical response of the quasi-static solicitation. LS: longitudinal static ; CS: circumferential static. Bold p-values are statistically significant.

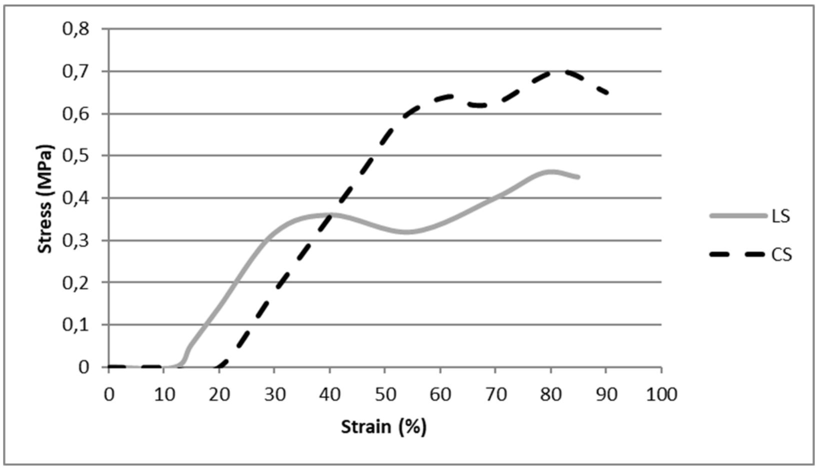

Figure 1: stress-strain curves for uniaxial dynamic test under static solicitation at 1cm/s. LI: longitudinal static ; CI: circumferential static

2. Behavior for intermadiate solicitation

Uniaxial tensile tests were performed under intermediate solicitation at 10 cm / s, with the specimens being oriented in the colon axis (longitudinal) or perpendicular to the axis (circumferential). The results are shown in Table 3.

The circumferential stress requires higher levels of stress and strain in order to obtain lesions.

	LI	**CI**	**p-value**
Modulus of the elastic phase (MPa)	**1.74 ± 1.15**	**2.14 ± 1.3**	**0.1**
Strain at 1st inflexion (%)	**36.72 ± 19.84**	**64.63 ± 24.23**	**<0.001**
Stress at 1st inflexion (MPa)	**0.35 ± 0.21**	**0.76 ± 0.38**	**<0.001**
Strain at 2nd inflexion (%)	**87.76 ± 51.63**	**80.76 ± 33.43**	**0.74**
Stress at 2nd inflexion (MPa)	**0.48 ± 0.22**	**0.84 ± 0.39**	**<0.001**

Table 3: Influence of orientation on the mechanical response of the intermediate solicitation. LI: longitudinal intermediate ; CI: circumferential intermediate

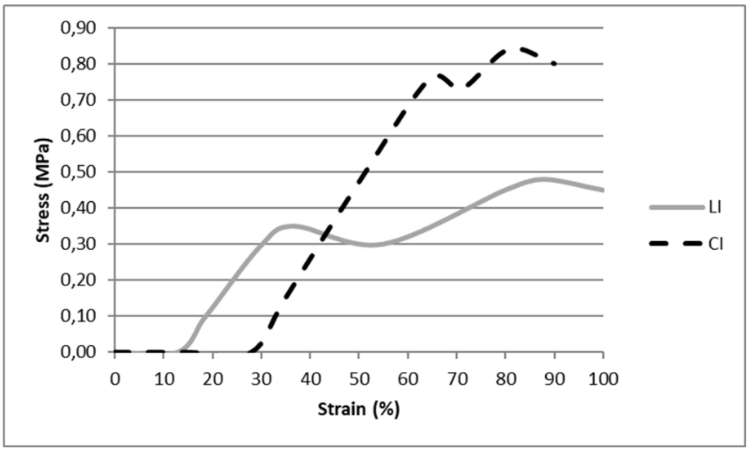

Figure II: stress-strain curves for uniaxial dynamic test under intermediate solicitation at 10cm/s. LI: longitudinal intermediate ; CI: circumferential intermediate

3. Behavior for dynamic solicitation

Uniaxial tensile tests were performed under dynamic solicitation at 1 m / s, with the specimens being oriented in the colon axis (longitudinal) or perpendicular to the axis (circumferential). The results are shown in Table 4.

The circumferential stress requires higher levels of stress and strain in order to obtain lesions. The Young's modulus is never modified by the orientation of the specimen.

	LD	**CD**	**p-value**
Modulus of the elastic phase (MPa)	3.17 ± 2.05	3.15 ± 1.73	0.88
Strain at 1st inflexion (%)	27.61 ± 14.44	56.06 ± 15.04	**<0.001**
Stress at 1st inflexion (MPa)	0.42 ± 0.29	0.93 ± 0.52	**<0.001**
Strain at 2nd inflexion (%)	55.41 ± 31.66	68.6 ± 21.72	**<0.001**
Stress at 2nd inflexion (MPa)	0.7 ± 0.34	1.02 ± 0.5	**<0.001**

Table 4: Influence of orientation on the mechanical response of the intermediate solicitation. LD: longitudinal dynamic ; CD: circumferential dynamic

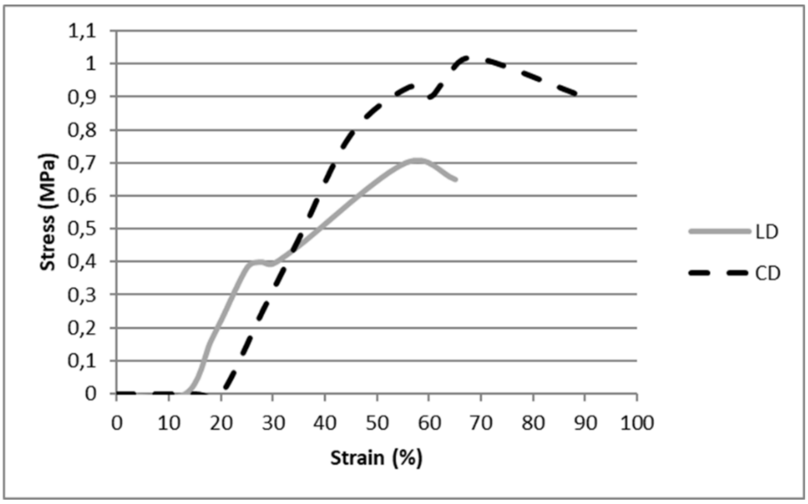

Figure 3: stress-strain curves for uniaxial dynamic test under dynamic solicitation at 1m/s. LD: longitudinal dynamic ; CD: circumferential dynamic

4. Mechanical behavior as a function of the solicitation

4.1. Mechanical behavior as a function of the solicitation – longitudinal specimen

The mechanical response differed depending on the speed of the solicitation. There was a significant statistical difference in the modulus (Table 5).
Stress-strain curves indicated a Young modulus in the first quasi linear phase, for each loading speed, respectively 3.17 ± 2.05 MPa under dynamic loading (1 m/s), 1.74 ± 1.15 MPa under intermediate loading (10 cm/s) and 1.76 ± 1.21 MPa under quasi-static loading (1 cm/s) with $p<0.001$ (figure 4).
The appearance of the curves reveals two types of behaviour of the colon according to the loading speed: fast break behaviour at high speed traction (dynamic protocol 1m/s) and a different type of behaviour for lower speeds (intermediate protocols 10cm/s and quasi-static 1cm/s). Changes in loading speed were responsible for modification of the profile curves of the colon.

The velocity varies all the coordinates of the points and the Young's modulus except for the stress necessary for the first point of rupture.

	LS	**LI**	**LD**	**p-value**
Modulus of the elastic phase (MPa)	1.76 ± 1.21	1.74 ± 1.15	3.17 ± 2.05	**<0.001**
Strain at 1st inflexion (%)	40.45 ± 25.49	36.72 ± 19.84	27.61 ± 14.44	**<0.001**
Stress at 1st inflexion (MPa)	0.36 ± 0.21	0.35 ± 0.21	0.42 ± 0.29	0.31
Strain at 2nd inflexion (%)	78.75 ± 45.15	87.76 ± 51.63	55.41 ± 31.66	**<0.001**
Stress at 2nd inflexion (MPa)	0.46 ± 0.22	0.48 ± 0.22	0.7 ± 0.34	**<0.001**

Table 5: Influence of solicitation on the mechanical response of the longitudinal specimen.
LS: longitudinal static; LI: longitudinal intermediate; LD: longitudinal dynamic

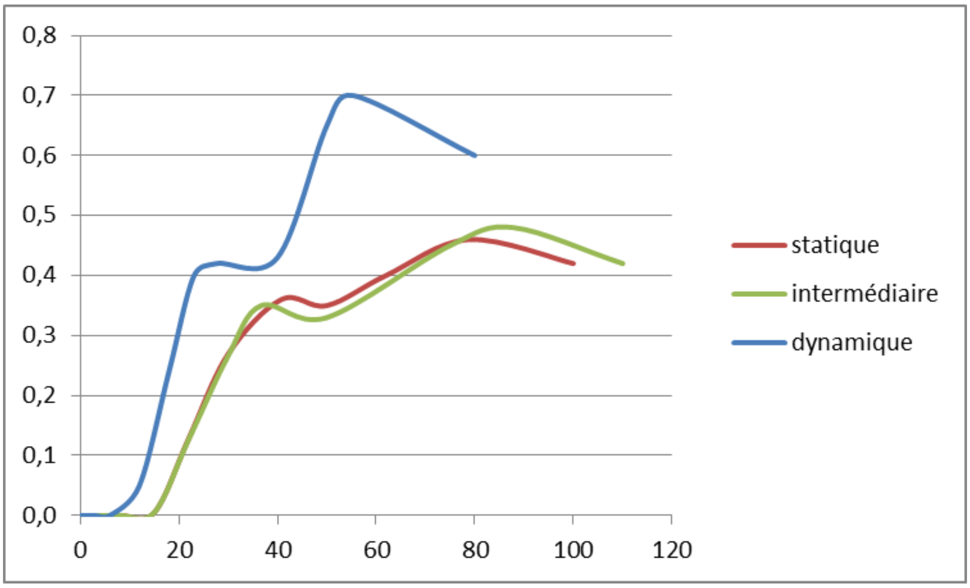

Figure 4: stress-strain curves for the 3 protocols under longitudinal solicitation.

4.2. Mechanical behavior as a function of the solicitation – circumferential specimen

The mechanical response differed depending on the speed of the solicitation. There was a significant statistical difference in the Young modulus (Table 6).

Stress-strain curves indicated a Young modulus in the first quasi linear phase, for each loading speed, respectively 3.15 ± 1.73 MPa under dynamic loading (1 m/s), 2.14 ± 1.3 MPa under intermediate loading (10 cm/s) and 0.63 ± 1.25 MPa under quasi-static loading (1 cm/s) with $p<0.001$ (figure 5).

Dynamic loading has a more fragile mechanical behavior than slower loads.

	CS	**CI**	**CD**	**p-value**
Modulus of the elastic phase (MPa)	0.63 ± 1.25	2.14 ± 1.3	3.15 ± 1.73	**<0.001**
Strain at 1st inflexion (%)	61.31 ± 21.96	64.63 ± 24.23	56.06 ± 15.04	0.45
Stress at 1st inflexion (MPa)	0.64 ± 0.38	0.76 ± 0.38	0.93 ± 0.52	**0.005**
Strain at 2nd inflexion (%)	81.24 ± 37.54	80.76 ± 33.43	68.6 ± 21.72	0.18
Stress at 2nd inflexion (MPa)	0.7 ± 0.35	0.84 ± 0.39	1.02 ± 0.5	**0.001**

Table 6: Influence of solicitation on the mechanical response of the circumferential specimen. CS: circumferential static; CI: circumferential intermediate; CD: circumferential dynamic

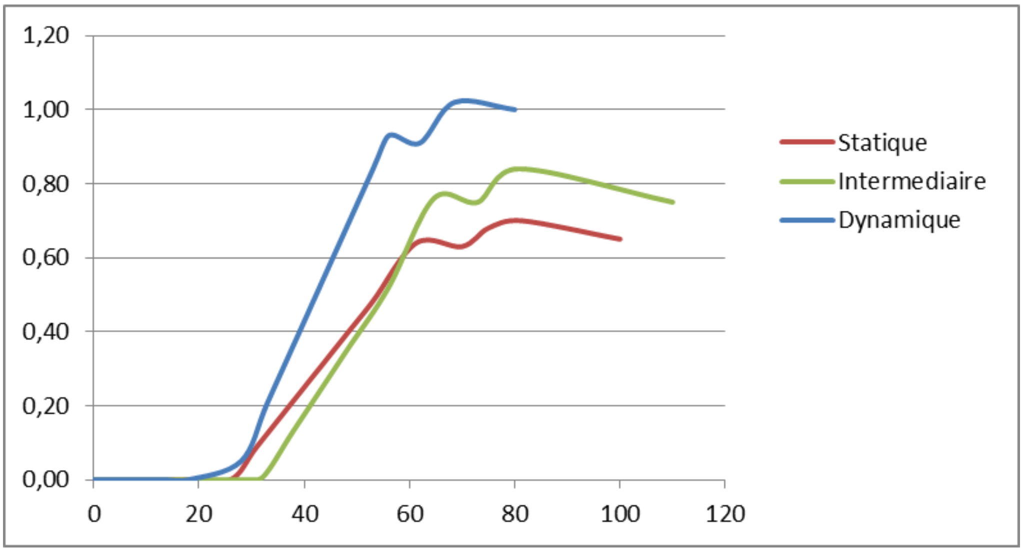

Figure 5: stress-strain curves for the 3 protocols under circumferential solicitation.

5. Mechanical behavior as a function of the *taenia coli* – longitudinal specimen

For longitudinal specimens, we performed tests with the presence or not of the *taenia coli*, for the three different speed loadings. The mechanical response with or without *taenia coli* differed depending on the speed of the solicitation: there was no effect for dynamic solicitation but the *taenia coli* modified the mechanical behavior of the specimens for lower speed solicitation (Table 7 – figures 6, 7 and 8).

For specimen with *taenia coli*, the analysis indicated a Young modulus in the first quasi linear phase, for each loading speed, respectively 3.15±1.58 MPa under dynamic loading (1 m/s), 1.76 ± 0.87 MPa under intermediate loading (10 cm/s) and 1.77 ± 0.95 MPa under quasi-static loading (1 cm/s).

For specimen without *taenia coli*, the analysis indicated a Young modulus in the first quasi linear phase, for each loading speed, respectively 3.17 ± 1.59 MPa under dynamic loading (1 m/s), 1.72 ± 0.86 MPa under intermediate loading (10 cm/s) and 1.76 ± 0.95 MPa under quasi-static loading (1 cm/s).

The presence of *taenia coli* makes the colonic tissue more rigid; this results in lower levels of stress and deformation at break than in the absence of *taenia coli*.

	LS	**LI**	**LD**
Modulus of the elastic phase (MPa)	0.07	**0.02**	0.26
Strain at 1st inflexion (%)	**< 0.001**	**< 0.001**	0.19
Stress at 1st inflexion (MPa)	**0.04**	0.21	0.75
Strain at 2nd inflexion (%)	**0.04**	0.95	0.78
Stress at 2nd inflexion (MPa)	0.78	0.5	0.14

Table 7: statistical analysis about the influence of speed loading on the mechanical behavior with or without *taenia coli*, for the longitudinal specimen. LS: longitudinal static; LI: longitudinal intermediate; LD: longitudinal dynamic. Bold p-values are statistically significant

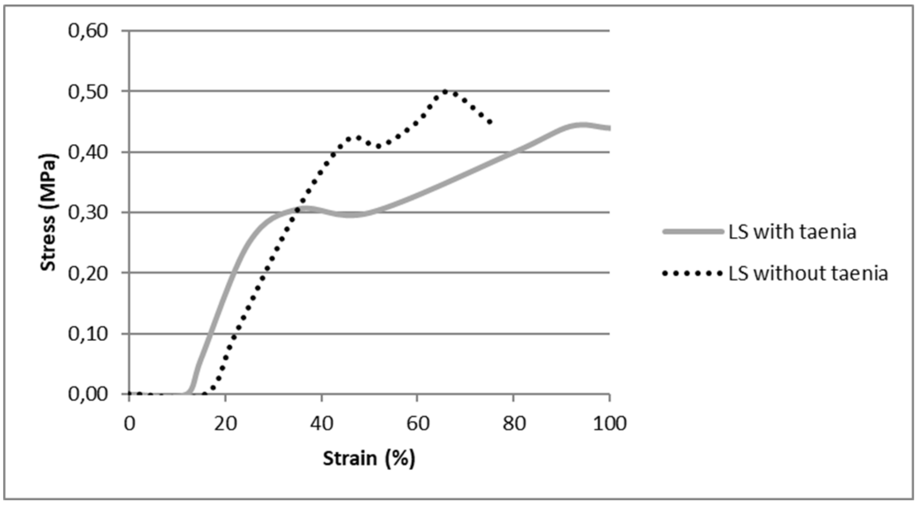

Figure 6: stress-strain curves with or without *taenia coli* for longitudinal uniaxial test under static solicitation at 1cm/s. LS: longitudinal static ; CS: circumferential static

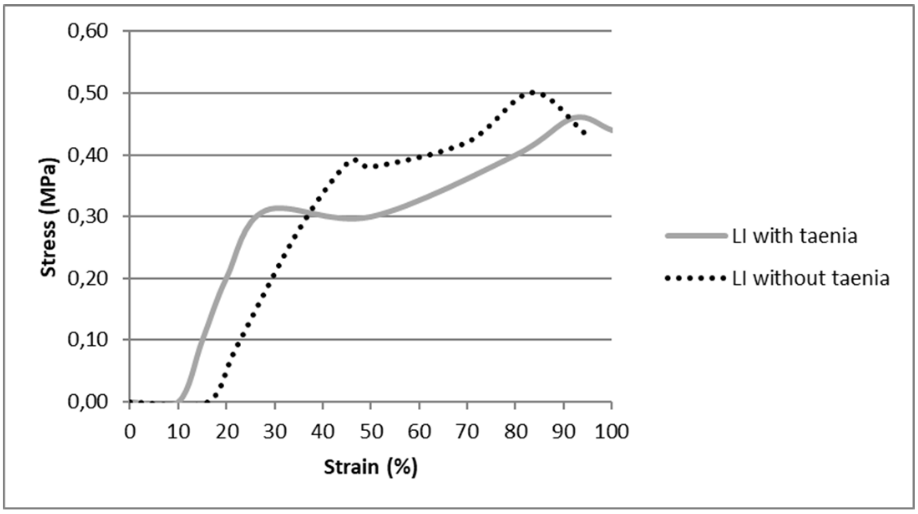

Figure 7: stress-strain curves with or without *taenia coli* for longitudinal uniaxial test under intermediate solicitation at 10cm/s. LI: longitudinal intermediate ; CI: circumferential intermediate

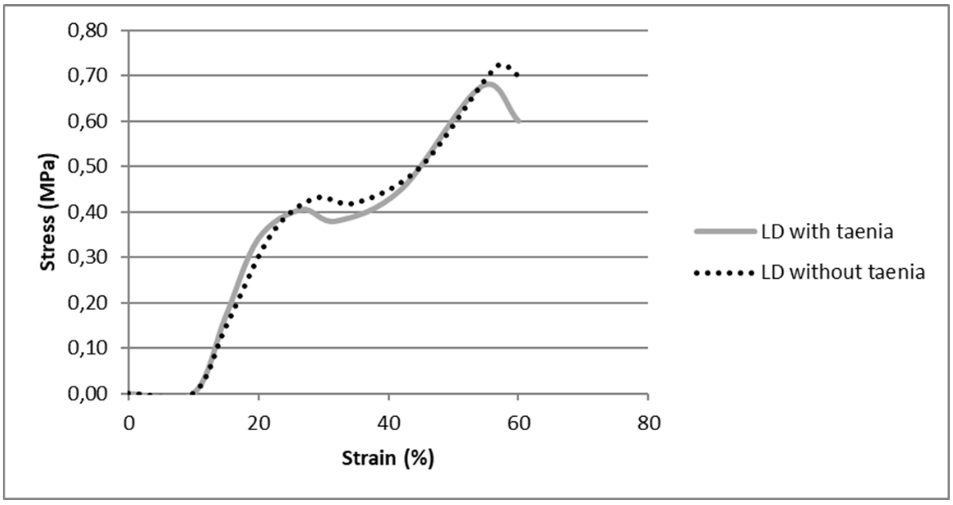

Figure 8: stress-strain curves with or without *taenia coli* for longitudinal uniaxial test under dynamic solicitation at 1m/s. LD: longitudinal dynamic ; CD: circumferential dynamic

Discussion

This study on the human colon completes Yamada's earlier work (Yamada, 1970), Fung (Y.-C. Fung, 1993), Egorov (Egorov et al., 2002) and those of our laboratory (Massalou et al., 2016). From a mechanical point of view, the colon is described as a viscoelastic tissue, contractile and anisotropic (Rubod et al., 2012)(Egorov et al., 2002)(Y.-C. Fung, 1993).

The knowledge of the passive properties obtained for the colon are crucial for understanding colonic functioning (Y. C. Fung, 1991). Gregersen demonstrated a better reflection of passive mechanical behavior with circular segments of a hollow organ rather than uniaxial tensile samples (Gregersen & Kassab, 1996). However, the digestive tract is an anisotropic material (Rubod et al., 2012)(Yamada, 1970)(Fan, Gregersen, & Kassab, 2004)(Gao & Gregersen, 2000)(Liao, Zhao, Fan, & Gregersen, 2004), the use of longitudinal samples allows a more precise characterization of the longitudinal fibers (Gao & Gregersen, 2000).

The objective of this study was to describe the differences in mechanical behavior of the refrigerated human colon subjected to different rates of uniaxial tensile stress. In our study, the colon behaved as a viscoelastic material with a different mechanical response depending on the speed of loading: the dynamic stress is responsible for an earlier rupture of the specimen.

The appearance of the typical curves of quasi-static and intermediate tests carried out in our study is very close to the curves published by Egorov during transverse tests of static traction on transverse colon (Egorov et al., 2002). In his static study, Egorov demonstrates a modification of the colonic mechanical response by *taenia coli* (longitudinal muscle strip of the colon). Under static and intermediate stress, we also find, in our study, the mechanical impact of *taenia coli*. However in dynamic traction we had not demonstrated effect of *taenia coli*, even if the levels of deformation seem identical between the study of Egorov and ours (Massalou et al., 2016). We did not study in this study the impact of taenia coli separately.

Other anisotropic and viscoelastic materials appear to behave in the same way.

For the striated muscular fibers, the increase of the speed of stress decreases the force necessary to the rupture, whether in a static or dynamic situation (Roberts, 2016; Rosario, Sutton, Patek, & Sawicki, 2016). As in our study, there is a fragile behavior under dynamic stressing and for slower stresses, the results are then superimposable and more elastic. The elastic mechanisms identified are mainly based on the presence of tendons in series with the striated muscle, to allow for example the extension: the loading time of a muscle will produce a quantity of energy proportional to the loading time. But many structures within the muscles intervene in this reaction: actomyosin bypasses, actin and myosin filaments, titin, and the scaffolding of the connective tissue of the extracellular matrix; all have the potential to store and recover elastic energy during muscle contraction (Fallqvist & Kroon, 2013; Fallqvist, Kulachenko, & Kroon, 2014; Kroon, 2011; Roberts, 2016).

During an isotonic contraction, the variation of the speed of solicitation also modifies the mechanical behavior of the smooth muscle fibers (Kroon, 2010).

Regarding bone tissue, the adult human skull has also been tested under different dynamic stresses. Different dynamic load speeds had a significant effect on the resulting values for maximum breaking force, elastic modulus and stress. The cranial bone was significantly stiffer with increased dynamic test speeds. In addition, important correlations were found between the strain rate and the maximum breaking force, the maximum stress and the energy absorbed to failure. (Motherway, Verschueren, Van der Perre, Vander Sloten, & Gilchrist, 2009).

The colon, anisotropic material, has different mechanical properties between longitudinal and circumferential uniaxial stress tests (Massalou et al., 2016; Merlo & Cohen, 1988). Howes had also highlighted this property in uni and then bi-axial dynamic tests (Howes & Hardy, 2012) ; we confirm this property for dynamic speeds as well as for slower solicitations. Indeed, the mechanical response of the colon subjected to circumferential traction is more elastic, requiring higher levels of stress and strain in order to obtain lesions of the specimens.

Other factors may also modify the experimental results with respect to the in vivo behavior of the colon:

- Active properties of muscle cells responsible for the propulsion of the digestive contents (Kroon, 2010)
- Modification of digestive tonicity: intestinal mechanoreceptors are sensitive to the stress stimulus and a linear association between stress relaxation and afferent discharge adaptation has been found (Liao et al., 2012)
- Modification of the composition of the inter or intracellular fluid: the presence of certain neuropeptides or the concentration of calcium will modify the recorded mechanical response (La et al., 2005; Merlo & Cohen, 1988; Middleton, Cuthbert, Shorthouse, & Hunter, 1993; Washabau & Sammarco, 1996)
- Pathological phenomena: Inflammatory bowel diseases or the deletion of certain genes can lead to a modification of the mechanical behavior of the colon (Onori et al., 2005; Sung, La, Kang, Kim, & Yang, 2015).

It is therefore difficult to apprehend, including in our tests, the mechanical behavior of the human colon in a physiological situation. The completion of bi-axial tests would describe more complete colon behavior. Being a tissue with a muscular layer, the synchronous realization of contraction tests would also approach the behavior of the human colon in vivo (Murtada, Humphrey, & Holzapfel, 2017).

This experimental study has made it possible to obtain reference values for the colon subjected to different stresses. These values can be used for finite element models of virtual trauma and quasi-static simulation, as in the case of surgical simulation or improvement of colonic stent deployments.

Conclusion

The mechanical behavior of the refrigerated human colon was evaluated by uniaxial tensile tests on tissue specimens. There is variability in the mechanical behavior of the colon as a function of the rate of loading: the colonic tissue behaves in the same way under static and intermediate stress, and then its behavior becomes more fragile under dynamic stress. Whatever the study speed, the mechanical response of the colon is different depending on the orientation of the specimens (longitudinal vs circumferential). In the case of quasi-static stress, taenia coli modifies the mechanical response of the colon.

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4. Variations du comportement mécanique intrinsèque du colon

4.1. Introduction

Comme nous l'avons précédemment vu, la réalisation de modèles numériques personnalisables impose la connaissance des variabilités inter-individuelles pour chaque organe. Cette variabilité inclue l'anatomie descriptive de l'organe et de ses variations, mais également le comportement mécanique de l'organe lui-même.

Nous voulions connaitre le comportement mécanique du colon et les facteurs anatomiques modifiant cette réponse. Deux paramètres nous ont semblé relevant : la localisation sur le cadre colique et l'orientation du colon lui-même.

Comme nous l'avons vu, le colon possède des portions fixes et d'autres plus mobiles. Au-delà de ses moyens de fixité, la morphologie extrinsèque du colon est variable : angles coliques droit et gauche de hauteur différente, colon ascendant large et peu épais pour terminer par le colon sigmoïde, de petit diamètre et épais.

De plus, la musculature intrinsèque du colon possède plusieurs couches, l'une circulaire, l'autre longitudinale. Cette dernière possède un renforcement musculaire visible à la surface du colon, appelée *taenia coli*.

Nous avons souhaité étudier le comportement mécanique du colon en situation de traumatisme. Des tests de traction uniaxiale sous sollicitation dynamique à 1m/s ont été réalisés.

L'analyse a porté sur le comportement colique sous sollicitation dynamique en fonction de la localisation sur le cadre colique, l'orientation de la sollicitation et la présence du *taenia coli* dans les spécimens longitudinaux.

4.2. Article sur le comportement mécanique du colon sous sollicitation dynamique en fonction de la localisation sur le cadre colique, la présence du *taenia coli* et l'orientation de la sollicitation

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Dynamic biomechanical characterization of colon tissue according to anatomical factors

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ABSTRACT

Introduction: The aim of this study was to determine the mechanical response of colonic specimens retrieved from the entire human colon and placed under dynamic solicitation until the tissue ruptured.
Material and methods: Specimens were taken from 20 refrigerated cadavers from different locations of the colonic frame (ascending, transverse, descending and sigmoid colon) in two different directions (longitudinal and circumferential), with or without muscle strips (taenia coli). A total of 120 specimens were subjected to tensile tests, after preconditioning, at the speed of 1 m/s.
Results: High-speed video analysis showed a bilayer injury process with an initial rupture of the serosa / external muscular layer followed by a second rupture of the inner layer consisting of the internal muscle / submucosa / mucosa.

The mechanical response was biphasic, with a first point of initial damage followed by a complete rupture. The levels of stress and strain at the failure site were statistically greater in terms of circumferential stress (respectively 69 ± 22% and 1.02 ± 0.50 MPa) than for longitudinal stress (respectively 55 ± 32% and 0.70 ± 0.34 MPa). The difference between longitudinal and circumferential stress was not statistically significant (3.17 ± 2.05 MPa for longitudinal stress and 3.15 ± 1.73 MPa for circumferential stress). The location on colic frame significantly modified the mechanical response both longitudinally and circumferentially, whereas longitudinal taenia coli showed no mechanical influence.
Conclusion: The mechanical response of the colon specimen under dynamic uniaxial solicitation showed a bilayer and biphasic injury process depending on the direction of solicitation and colic localization. Furthermore these results could be integrated into a numeric model reproducing abdominal trauma to better understand and prevent intestinal injuries.

1. Introduction

Traumatic lesions of the colon often occur during traffic accidents, with seat belts paradoxically worsening the injuries (Frampton et al., 2012; Anderson et al., 1991). The occurrence of these lesions justifies ongoing research in an effort to prevent them. Despite this, there have been only two studies to date devoted specifically to the mechanical characterization of the human colon under dynamic load (Yamada, 1970; Howes and Hardy, 2012).

The digestive tract is injured in 3% of blunt traumas to the abdomen (Watts and Fakhry, 2003). These are mainly high kinetic injuries occurring during traffic accidents. The severest of these injuries is the perforation of the bowel wall, causing peritonitis. These injuries are the cause of significant morbidity and mortality due to the difficulty of diagnosing early perforations and the resulting delay in medical treatment (Fakhry et al., 2003; Williams et al., 2003). Among the lesions of the digestive tract, the two most frequent are lesions of the small intestine and colon. The latter represent 30% of all injuries of the digestive tract (Williams et al., 2003). Some predictive factors of injury have been identified like the use of seat belt and the rear position of the passenger (Bège et al., 2016) but the pathophysiological mechanisms at the origin of colon lesions are not known. The use of numerical models that give a virtual representation of the anatomical complexity of the abdominal region allow an understanding of both the conditions and the mechanisms of visceral lesions (Crandall et al., 2011). These tools will certainly be used to improve safety devices, and perhaps will highlight situations especially likely to cause injury.

The mechanisms at the origin of digestive tract lesions are complex and involve simultaneously phenomena of compression,

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tensile test and bursting. Tensile test is the most appropriate mechanism to model complex lesional phenomena observed in gastrointestinal-tract trauma. Indeed, both deceleration and hypertension result in traction on the abdomen. There are two examples of research involving tensile tests of the behavior of the small intestine (Bourgouin et al., 2012) and the mesentery (Bège et al., 2015). The small intestine and the colon do not have the same morphology, which justifies a separate study of each organ. Experimental biomechanical characterization of the colon was carried out for tests of compression (Higa et al., 2007), indentation (Carter et al., 2001) tensile test (Egorov et al., 2002; Watters et al., 1985) and suction (Kauer et al., 2002). These tests were performed mainly on rats (Ekmektzoglou et al., 2006), rabbits (Tucker et al., 1979), guinea pigs (Fung, 1993) and pigs (Rosen et al., 2008). The colon is described in these studies as a tissue which is viscoelastic, contractile and anisotropic (Egorov et al., 2002; Fung, 1993; Rubod et al., 2012). The morphology of the colon varies depending on its location: large diameter and thin wall for the ascending colon, gradually tapering to a small diameter and thick wall for the sigmoid colon. Its wall is divided into four layers (from inner to outer): mucosa, submucosa, muscularis (inner circular and outer longitudinal layers) and serosa.

Only a few tensile tests have been performed on human tissue, including Egorov et al. (2002) and more recently Howes and Hardy (2012), but to the best of our knowledge none has characterized the biomechanical response of the colon under uniaxial dynamic tensile load up rupture.

Our main objective was to determine the mechanical behavior of the human colon by providing mechanical data for the development of constitutive models. The colon samples were subjected to uniaxial dynamic tensile load up failure. Our secondary objective was to investigate the influence of the direction of colonic samples, the influence of the presence of taenia coli (longitudinal muscle strips) and the mechanical response of the tissue depending on the origin of the sample within the colon.

2. Material and methods

2.1. *Origin of the tissue*

The colonic specimens which were tested were from samples taken from human subjects stored at 1 °C without preservative solution.

The use of cadaveric human tissue was made as part of a protocol approved by the ethics committee of the Faculty of Medicine of Nice concerning the donation of bodies to science.

The study included only adult subjects whose colon showed no signs of pathology (cancer, inflammation). The presence of diverticula was not a reason for exclusion of the organ given its high prevalence in the adult human population. However, the colonic samples did not contain colonic diverticula. Samples were taken from a total of 20 different colons: 11 from females and 9 from males. The average age was 84 years ± 11 years and the bodies had been conserved an average of 21 days ± 9 days.

2.2. *Preparation of the specimens*

The specimens were colon segments taken from the antimesenteric border after performing a longitudinal opening, following a standardized format using a rectangular punch with the following dimensions: 25 × 100 mm.

For each anatomical subject, different specimens were taken according to their location on the colonic segment (ascending, transverse, descending, sigmoid colon), and their direction (longitudinal and circumferential). The longitudinal specimens with taenia coli (muscle strips) were made parallel to the axis of the strip and included the strip. The circumferential specimens were made perpendicular to the axis of the muscle strip (taenia coli), with the strip situated in the middle of the specimen.

2.3. *Dynamic tensile tests*

The initial length (L_0) of the specimens was thus 40 mm. The experimental characterization of the mechanical behavior of the colon was made from uniaxial tensile tests under a dynamic load of 1 m/s. The test was performed using a hydraulic test system MTS 370.10 Landmark® (USA) under displacement control. The sampling of data collection was 10.24 kHz. The force sensor (Kistler 9327A. 0–500N) was at the bottom of the assembly. The MTS operates in displacement control. The displacement rate was constant ($\varepsilon = 1118$ mm/s). The control loop of the MTS is of PID type (Proportional, Integral and Derivative). The parameters of the PID were defined before the test to get optimal response. Rise time, overshoot and steady-state error were optimized to have a constant displacement rate near 1 m/s.

The tests were tensile tests and we confirm there was some ramp-up of the test system during the initial stretch of the sample. Furthermore one difficulty with these soft tissues during the setting-up was the initial stress of the specimen. We chose to adjust all load responses to 2N at $t=0$.

Uniaxial tension to failure tests was performed in displacement-controlled mode with a nominal strain rate of 0.3%/s. Samples were slack after clamping, and therefore, the postprocessing was based on a specified force threshold value of 2N (reference state). This value roughly represents the point where substantial axial tension starts. The calculation of tensions and nominal strains is based on the defined reference state. The nominal strain e in load direction as where L_0 is the initial length is the reference state.

The nominal membrane tension was calculated as $\sigma = F/S$, where F is the measured force and S is the measured width in the reference state.

Because the colon is viscoelastic, a pre-conditioning test phase of the specimen was performed with test parameters chosen to avoid the occurrence of lesions. Preconditioning 10 sinusoidal cycles with an amplitude of 6 mm at a speed of 0.5 m/s was carried out (as described in a previous publication for the small intestine (Bourgouin et al., 2012)). The preconditioning phase was immediately followed by a dynamic tensile load of 1 m/s up to a 10 cm distance.

2.4. *Data acquisition and post-processing of results*

Data were not filtered, the stress–strain curves were then zeroed (a 2N reset was applied) to remove a possible initial load in the set up of the samples and a response corridor was generated (mean ± standard deviation (SD)). The strain was calculated from the initial length (L_0) using the following equation: strain (%) = final length (mm) / initial length L_0 (40 mm). The stress was calculated using this equation: stress (MPa) = force (N) / surface (mm). We measured only global displacement because our objective was to determine a global behavior for biomechanical characterization.

The stress–strain curves were calculated using displacement of the initial length because the objective was to determine the global mechanical behavior of the colon. Young's modulus was calculated for only the linear region of the stress–strain curves.

Statistics were performed using Statistica software for Windows. The non-parametric Mann–Whitney test and ANOVA were performed. The results were considered significant if p-value < 0.05.

3. Results

In all, 122 tests were conducted of which 120 were valid (2 specimens having slipped out of the vice). The tests were based on 40 circumferential samples and 80 longitudinal samples (Table 1) obtained from twenty human subjects. No pathology was found macroscopically or microscopically.

3.1. *Behavior of the colon under longitudinal stress*

3.1.1. *High-speed video analysis*

The location of the initial damage, the type of damage, the number of lacerations and the damage propagation were analyzed using the video recordings.

The initial damage was a partial failure of the outer layer of the specimen. The damage occurred suddenly and was always located on the serous side. It was most often concentrated in the central region of the specimen, both on the longitudinal axis (59% of cases) and on the circumferential axis (47% of cases). Therefore the damage process is a progressive laceration of the different layers until complete failure (Fig. 1).

Table 1
Distribution of the specimens according to their longitudinal and circumferential direction, the location on the colon and the presence of taenia coli: None for the absence of taenia coli and With for the presence of taenia coli.

	Location on the colon								
	Ascending		**Transverse**		**Descending**		**Sigmoid**		**Total**
Taenia coli	**None**	**With**	**None**	**With**	**None**	**With**	**None**	**With**	
Longitudinal	10	10	10	10	10	10	10	10	**80**
Circumferential	10		10		10		10		**40**

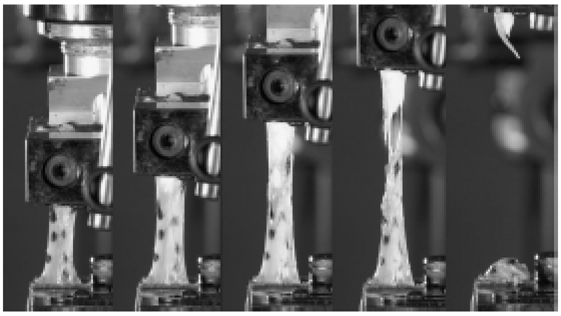

Fig. 1. Photographs of successive damage during a uniaxial dynamic tensile load of a human colon.

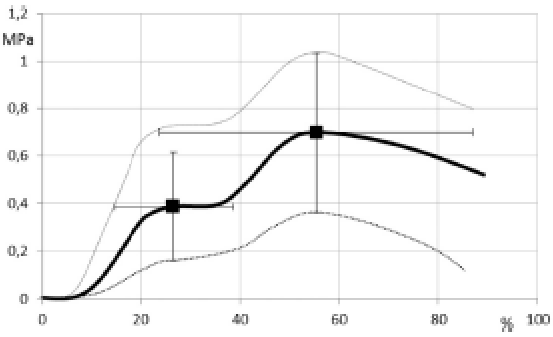

Fig. 2. Typical stress–strain curve for longitudinal specimens. The *x*-axis corresponds to the strain (%) and the *y*-axis corresponds to the stress (MPa). The solid line represents the average of all trials; the two curves formed by dotted lines represent a corridor created by the mean plus or minus the standard deviation.

The number of lesions was on average 1.9 per specimen. In 32% of cases, a sole lesion was observed on the serosal surface. In the other cases several lesions were observed on the serosal surface: 2 lesions in 40% of cases and 3 lesions in 28% of cases. One specimen did not tear apart.

3.1.2. Mechanical behavior of longitudinal specimens

The analysis of the stress–strain curves shows a global behavior in several phases: the first phase is linear elastic, the slope of this phase constitutes the modulus of the specimen (Fig. 2). The modulus was calculated including only the linear region on the stress/strain curves. It is on average 3.17 ± 2.05 MPa. The end of the elastic phase corresponds to the first inflection point. The inflection point appears on average for a strain of 27 ± 12% and a stress of 0.39 ± 0.23 MPa. It is followed by a second quasi-linear phase before the complete rupture of the specimen, which occurs for a strain of 55 ± 32% and a stress of 0.70 ± 0.34 MPa.

3.1.3. Behavior of the colon as a function of the location

The mechanical response differed depending on the location of the colonic segment: ascending, transverse, descending or sigmoid colon. There was a significant statistical difference in the modulus (Table 2).

The stress values at initial damage and the modulus were equivalent for the ascending and sigmoid colons. The values were greater than those for the transverse and descending colon.

3.1.4. Behavior of the colon depending on the presence of taenia coli

The presence of taenia coli on the specimen did not significantly affect the mechanical response of the sample (Table 3 and Fig. 3).

3.2. Behavior of the colon under circumferential stress

3.2.1. High-speed video analysis

The initial damage was a partial failure of the outer layer of the specimen and was always located on the serous side. It was most often concentrated in the central region of the specimen, both on the longitudinal axis (56% of cases) and on the circumferential axis (31%). Therefore the damage process is a progressive laceration of the different layers until complete failure.

The number of lesions was on average 1.4 per specimen. In 64% of cases, a sole lesion was observed on the serosal surface. In the other cases several lesions were observed on the serosal surface: 2 lesions in 23% of cases and 3 lesions in 13% of cases. A single specimen did not tear apart.

3.2.2. Mechanical behavior of circumferential specimens

The analysis of the stress–strain curves reveals a general behavior in several phases: the first phase is linear elastic (Fig. 4). The average modulus was 3.15 ± 1.73 MPa. The end of the elastic phase corresponds to the first inflection point. The inflection point appears on average for a strain of 56 ± 15% and a stress of 0.93 ± 0.52 MPa. It is followed by a second quasi-linear phase before the complete rupture of the specimen, which occurs for a strain of 69 ± 22% and a stress of 1.02 ± 0.50 MPa.

3.2.3. Behavior of the colon as a function of the location

The mechanical response differs depending on the colonic segment location: ascending, transverse, descending or sigmoid colon. Table 4 shows significant differences for the modulus and the strain at the point of complete failure of the specimen). From the proximal to the distal colon, the modulus decreases progressively while strain at the second inflection point increases.

3.3. Mechanical response versus load direction

3.3.1. High-speed video analysis

Whatever the direction of the load, the initial damage was therefore a partial tear on the serosal surface which did not reach the mucosal surface. On the other hand, the number of serosal

Table 2
Influence of location on the mechanical response of the longitudinal specimen.

	Location on the colon				
	Ascending	Transverse	Descending	Sigmoid	p-Value
Modulus of the elastic phase (MPa)	4.27 ± 2.62	2.84 ± 1.68	2.21 ± 1.84	3.41 ± 1.48	**0.01**
Strain at 1st inflexion (%)	24.11 ± 9.09	28.47 ± 15	28.65 ± 14.99	24.9 ± 7.47	0.68
Stress at 1st inflexion (MPa)	0.53 ± 0.25	0.30 ± 0.14	0.35 ± 0.24	0.4 ± 0.22	0.07
Strain at 2nd inflexion (%)	59.1 ± 52.34	57.12 ± 20.54	55.94 ± 24.92	49.6 ± 20.6	0.81
Stress at 2nd inflexion (MPa)	0.71 ± 0.33	0.77 ± 0.35	0.6 ± 0.23	0.72 ± 0.42	0.48

Table 3
Influence of taenia coli on the mechanical response of the longitudinal specimen.

	Taenia coli	*No taenia coli*	*p*-Value
Modulus of the elastic phase (MPa)	3.41 ± 2.30	2.92 ± 1.75	0.29
Strain at 1st inflexion (%)	25.44 ± 12.70	28.39 ± 11.03	0.37
Stress at 1st inflexion (MPa)	0.37 ± 0.19	0.42 ± 0.27	0.37
Strain at 2nd inflexion (%)	54.30 ± 35.67	56.56 ± 27.37	0.75
Stress at 2nd inflexion (MPa)	0.68 ± 0.39	0.72 ± 0.28	0.55

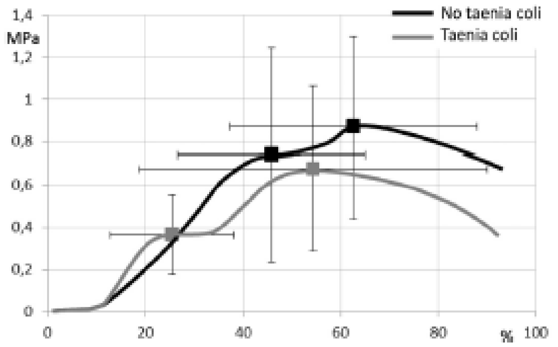

Fig. 3. Standard stress–strain curve for longitudinal specimens with or without longitudinal muscle strip (*taenia coli*). The *x*-axis corresponds to the strain (%) and the *y*-axis to the stress (MPa).

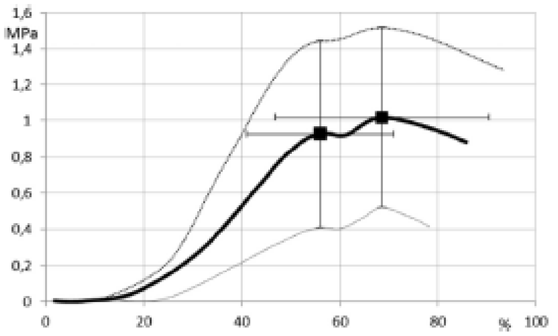

Fig. 4. Standard stress–strain curve of the circumferential protocol. The *x*-axis corresponds to the stress (%) and the *y*-axis to the strain (MPa). The solid line represents the average of all the trials; the two curves formed by dotted lines represent a corridor created by the mean plus or minus the standard deviation.

lesions was significantly higher for longitudinal specimens than for circumferential specimens (p-value < 0.01).

3.3.2. Mechanical behavior as a function of direction of the load

The mechanical response differs between all longitudinal (with and without teniae coli) and circumferential specimens (Fig. 5).

Taking into account all the specimens, there is a statistically significant difference in the levels of stress and strain required to induce damage in the specimens (first and second inflection points). A circumferential sample requires a greater level of strain ($p < 0.01$ and $p = 0.02$ for the first and second inflection points, respectively) and stress ($p < 0.01$) to obtain equivalent damage. Nevertheless the orientation of the specimen does not affect the modulus ($p = 0.96$).

3.3.3. Mechanical behavior as a function of the location and orientation

We found a marked difference in the mechanical behavior of the colon depending on the location and the orientation of the specimen (Table 5).

Whatever the origin of the specimen on the colon, the stress and strain were significantly greater at the first inflection point for circumferential stress than for longitudinal stress.

4. Discussion

The mechanism of deceleration in a blunt abdominal trauma leads to tensile load in the intestinal tissue. The chosen methodology has been to study the mechanical response of colonic specimens subjected to uniaxial dynamic tensile loading until complete failure of the specimen.

In the present study, the stress–strain curves were determined for 120 samples which underwent longitudinal tensile tests (80) and circumferential tensile tests (40). The tests revealed a global behavior of the specimens with a first linear elastic phase leading to initial damage followed by a second phase of plastic deformation until complete rupture occurred.

This behavior has already been shown by Egorov et al. (2002) under quasi-static loading (for circumferential and longitudinal specimens) and Bourgouin et al. (2012) during longitudinal dynamic loading tests on the small intestine. Our results showed that the colonic mechanical response is ductile and bilayer for both quasi-static and dynamic and for both longitudinal and circumferential tensile loading conditions.

Clinical observation of blunt intestinal trauma shows partial lesions (described as serous) and complete lesions (described as transfixing) (Watts and Fakhry, 2003; Williams et al., 2003) with a predominance of serous wounds. This observation can be explained by the bilayer behavior of colonic tissue as described experimentally.

The high-speed video analysis coupled with an additional histological analysis showed that the first phase corresponded to a sero-muscular injury while the second phase corresponded to a mucosal lesion.

This failure pattern is very similar to small intestine under dynamic tensile loading. Indeed Bourgouin et al. (2012) showed a first clear break corresponding to a detachment of an outer layer (serosa and muscularis externa) from the rest of the intestinal

Table 5
Statistical relationship of the 1st and 2nd inflection points of the colon as a function of the direction of the tensile load (longitudinal and circumferential) and the precise origin of the colonic sample.

	Location on the colon **Comparison of circumferential and longitudinal stress**			
	Ascending **p-Value**	**Transverse** **p-Value**	**Descending** **p-Value**	**Sigmoid** **p-Value**
Modulus of the elastic phase (MPa)	0.95	0.31	0.39	**0.01**
Strain at 1st inflexion (%)	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
Stress at 1st inflexion (MPa)	**< 0.01**	**< 0.01**	**< 0.01**	**0.02**
Strain at 2nd inflexion (%)	0.91	0.26	0.14	**< 0.01**
Stress at 2nd inflexion (MPa)	**< 0.01**	**0.04**	**0.02**	0.81

longitudinal circular) and probably have their own mechanical behaviors. However, as it is not technically possible to separate these two muscle layers in humans, characterization of each layer cannot be obtained.

Our study shows that the modulus is statistically different as a function of the location on the colonic segment. Whatever the type of tensile loading, the value of the modulus decreases from the ascending colon to the descending colon. This tendency was shown by Yamada (1970) only for circumferential loading. For Gao and Gregersen (2000), the transverse colon was the stiffest part of the colon. It can be explained by the anatomy of the colon, whose morphology varies depending on its location: large diameter and thin wall for the ascending colon, gradually tapering to a small diameter and thick wall for the sigmoid colon. In the present study all samples had the same size, with the wall thickness being the main fluctuating parameter. So although the changes may seem minimal, this parameter plays an important role in the biomechanical response of colic tissue and should not be neglected.

However, in clinical studies, there is no difference in terms of the localization of traumatic lesions of the colon (Williams et al., 2003). Thus it appears necessary to include the means by which the colon is held in place in order to reproduce the pathophysiological mechanisms at the origin of these lesions.

One limitation of this study concerns the high age of the cadavers from which the samples were collected. Age clearly influences the mechanical properties of many soft tissues (Lu et al., 2005; Chantereau et al., 2014). However, the colons showed no morphological abnormality (selection of anatomical subjects who have given their bodies to science by a medical doctor). So, it seems reasonable to postulate that the samples used in the present study were more suitable than those retrieved from animal or pathological tissues (eg post-surgery samples). As in most studies on biological tissue, especially soft tissue, a scatter in the results was expected. This scatter can be explained by intra-individual and inter-individual differences, but also by the high sensitivity of the specimens to their mode of conservation (Rubod et al., 2007; Meghezi et al., 2012; Gilchrist et al., 2010; Ocal et al., 2010). It was therefore essential to perform the tests on a large number of specimens (120) in order to be able to carry out a satisfactory statistical analysis.

A second limitation is the fact that uniaxial test do not match multi-axial loading expected in vivo. The protocol proposed in this study allow to characterize the mechanical behavior of the colon in 2 independently directions, longitudinal and circumferential. These uniaxial tensile tests do not reproduce multi-axial loading conditions observed in vivo. Nevertheless these data are a first step for the evaluation of numerical model of this complex organ. One perspective of our study is to perform extension–inflation tests in order to characterize the colon behavior in realistic conditions.

Conflict of interest

All the authors declare they have no conflict of interest.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2016.10.023.

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5. Variations du comportement mécanique du colon en fonction de facteurs anatomiques et expérimentaux

5.1. Introduction

L’étude de la variabilité intrinsèque du comportement mécanique est fonction de la localisation sur le cadre colique et de l’orientation de la sollicitation.

Afin de permettre la réalisation de modèles personnalisés et personnalisables en traumatologie virtuelle, l’étude de la variabilité inter-individuelle est nécessaire. S’agissant le plus souvent de matériel cadavérique, les conditions de conservation peuvent entrainer une modification de la réponse mécanique (40,41).

Ainsi, le genre des individus, leur âge, leurs caractéristiques morphologiques, etc. devraient être renseignés dans chaque étude.

L’obésité modifierait la réponse mécanique de certains tissus. Cette description a été faite pour d’autres organes, particulièrement au niveau ostéo-articulaire, cardio-vasculaire et pulmonaire (42–46), mais n’a jamais été décrite pour le tube digestif. Néanmoins, ce paramètre n’a pu être étudié dans cette étude. Le poids et la taille n’étaient pas connus pour la moitié des sujets dont sont issus les spécimens ; de plus, l’absence d’examen scannographique ne permettait pas non plus une étude morphométrique du périmètre abdominal, ni l’analyse de la répartition entre graisse viscérale et graisse pariétale abdominale.

5.2. Article sur la variabilité du comportement mécanique du colon en fonction de l'âge, du genre, du type de conservation des sujets et la durée de conservation

(soumis à : Surgical Radiological Anatomy)

Influence of gender, age, shelf-life, and conservative method on the biomechanical behavior of colon tissue under dynamic solicitation

D. Massalou, C. Masson, S. Afquir, P. Baqué, S-V. Berdah, P-J Arnoux, T. Bège

Abstract

The aim of this study was to determine factors that modify the mechanical response of human colonic specimens.
We performed uniaxial dynamic tests. Specimens were taken according to three different protocols: refrigerated cadavers without embalming, embalmed cadavers, and fresh colonic tissue. A total of 143 specimens were tested, at a speed of 1 m s^{-1}.
The type of preservation modifies the stress and the strain required to obtain lesions of the colonic specimens. Gender is also a factor responsible for a change in the mechanical response of the colon. The age of the subjects and the shelf-life of the bodies did not represent factors influencing the mechanical behavior of the colon.

Keywords: colonic mechanical response, human colon, biomechanics, dynamic solicitation

Introduction

The digestive tract is injured in 3% of blunt abdominal trauma (Watts & Fakhry, 2003). These are mainly lesions occurring during high kinetic road accidents. Numerical modeling reproducing the conditions of trauma allows the introduction of effective means of prevention (Whyte, Gibson, Eager, & Milthorpe, 2017).

Among the lesions of the digestive tract, the two most frequent are lesions of the small intestine and the colon. The latter accounts for 30% of all lesions of the digestive tract (Nash et al., 2016; Williams, Watts, & Fakhry, 2003). Traumatic rupture of the colon can lead to serious injuries, with a high risk of complications, including peritonitis due to bowel perforation, which can cause death.

Because of their potential seriousness, these lesions have been studied in biomechanics in order to understand the lesion process. The mechanisms at the origin of digestive tract lesions are complex and can involve simultaneously phenomena of compression, deceleration, and bursting.

Since the historical work of Yamada (Yamada, 1970) and Fung (Fung, 1993), several publications have described the mechanical properties of the colonic frame using tensile tests, which can describe local lesional phenomena observed in gastrointestinal-tract trauma. Egorov determined the biomechanical properties from static uniaxial traction tests in humans and highlighted that the mechanical strength of the bowel wall is determined by the different layers of its wall (Egorov, Schastlivtsev, Prut, Baranov, & Turusov, 2002). From static uniaxial tests on pig intestinal tissue, Carniel (Carniel et al., 2014) shows anisotropic and non-linear behavior of colonic tissues.

In a previous study, we highlighted the influence of localization on the mechanical response of the colon under uniaxial traction until rupture (Massalou et al., 2016). This result was also shown in Howes' dynamic bi-axial colon tests (Howes & Hardy, 2012).

The values of the mechanical behavior presented in these publications show great variability. The heterogeneity of the experimental protocols can explain these differences; the mechanical properties can be modified by the type of solicitation, animal or human model, preservation method (fresh, refrigerated or embalmed), and anthropometric factors (such as sex, age, and obesity of the subjects studied). Nevertheless, it is important to know the influence of each factor on the mechanical behavior, especially for the development of personalized digital models.

Our objective was to determine the influences of four parameters (gender, age, shelf-life, and conservative method) on the mechanical behavior of the human colon based.

Materials and Methods

Origin of the tissue

The colon samples used were generated from three different protocols. The first protocol generated the "fresh" group. The colon samples came from people in a state of encephalic death; sub-total colectomy was performed during multi-organ harvesting for organ transplantation by a visceral surgeon at the end of the procedure. Therefore, the shelf-life is 0 days. The use of fresh tissue was incorporated as part of the protocol approved by l'Agence de la Biomédecine et l'Etablissement Français des Greffes of the university hospital of Marseille. The second and third protocols used cadaveric human tissue after approbation by the ethics committees of the medical schools of Medicine of Nice and Marseille concerning the donation of bodies to science. The shelf-life of the bodies was systematically recorded.

Samples generated from the second protocol are referred to as the "embalmed" group: patients were transferred after their death to the thanatopraxy laboratory. The subjects were embalmed with Winkler's liquid (Winkler, 1974) then kept at 4°C until the colon is removed and the tests are carried out at room temperature.

The third protocol is the "refrigerated" group; the patients were transferred after their death to the anatomy laboratory and then stored at 1°C without preservatives. The study included only adult subjects whose colon showed no sign of pathology (cancer, chronic inflammation). Colonic diverticulosis was not a cause of exclusion given its high prevalence in the adult human population. However, colonic specimens did not contain colic diverticula.

Population studied

Eighteen subjects (six men and 12 women) were studied. The protocol of "fresh" subjects included one man and three women, with an average age of 40 years (range: 20–53 years). The "embalmed" protocol consisted of one man and three women, with an average age of 89 years (range: 82–93 years) and average shelf-life of 42 days. The protocol for "refrigerated" subjects consisted of four men and six women, with an average age of 86 years (range: 73–100 years) and an average shelf-life of 19 days.

The distribution of subjects by gender, age, protocol, and shelf-life is presented in Table 1.

Preparation of the specimens

The specimens were colon segments taken from the antimesenteric border after performing a longitudinal opening, following a standardized format using a rectangular punch with the following dimensions: 25 × 100 mm.

For each anatomical subject, eight longitudinal specimens were spread across all segments of the colon: ascending, transverse, descending, and sigmoid colon.

The samples were taken in the middle of the colic segment concerned. The tests were based on 32 fresh specimens, 32 embalmed specimens, and 80 refrigerated specimens obtained from 18 human subjects.

Experimental conditions

The samples were then stored between wet compresses of the isotonic saline solution to prevent desiccation. The tests were conducted at room temperature with a delay of fewer than 24 h after collection. We did not do hygrometric readings. The experimental characterization of the mechanical behavior of the colon was made from uniaxial tensile tests under a dynamic load of 1 m s^{-1}. The modalities of the traction protocol and preconditioning have already been published by our team (Massalou et al., 2016).

Data acquisition and post-processing of results

Data were not filtered. The strain-strength curves were then zeroed (a 2N reset was applied) to remove a possible initial load in the set-up of the samples. The Young's modulus was calculated from the linear region during the elastic phase of the stress-strain curves.

All the tests were filmed by two VITCam® digital cameras with a recording rate of 1000 frames per second: a camera for the anterior surface of the sample and a second for the posterior surface. The definition of the image was 1260 × 960. The location of the initial damage, the type of damage, the number of lacerations, and the damage propagation were analyzed using the video recordings.

Statistical analysis

Statistics were performed using SPSS for Windows version 11.0 (SPSS Inc., Chicago, IL). Regarding film analysis, the non-parametric Mann-Whitney test and Kruskal-Wallis were performed for univariate analysis.

For the statistical analysis of the mechanical behavior, the number of specimens was different depending on the subject. Therefore, to have the same number of samples per subject, we chose to create a weighting variable based on the number of test specimens per individual.

To avoid any variability of the results related to a difference of distribution of the samples on the colonic framework according to the groups, we carried out an ANOVA test to verify that the distribution of the samples by subject studied here allowed a statistical analysis independently of location.

To explain the influence of each of the explanatory variables, univariate analyzes (ANOVA) were performed. The significant variables were then included in multivariate analyzes by multiple linear regression. The results were considered statistically significant if the p-value was < 0.05.

Results

In all, 144 tests were conducted of which 143 were valid (one specimen having slipped out of the vice). The ANOVA test shows that the data are homogeneous concerning the location on the colonic frame (> F: 0.314).

Mechanical behavior according to the method of conservation

High-speed video analysis – For the three groups, the initial damage was a partial failure of the outer layer of the specimen. The damage occurred suddenly and was always located on the serous side (Fig. 1). Therefore, the damage process is a progressive laceration of the different layers until complete failure (Fig. 1).

We found that the central region is a privileged area for the appearance of the first lesion for all specimens. This is particularly pronounced in the case of embalmed or refrigerated specimens (42% and 43% of cases) compared to fresh specimens (14%). There were one to three ruptures per specimen, with no statistically significant difference between the three groups ($p = 0.87$).

Mechanical behavior as a function of the conservation method – The analysis of the stress-strain curves in the three groups shows a global elastic behavior (Fig. 2). The Young's modulus, as well as the strain and stress values at the point of the 1st damage and the point at rupture, are given in Table 4. The stress and strain levels show a statistically significant difference in the points of stress, depending on the method of preservation. Only the elastic modulus of the elastic phase is not modified by the preservation method ($p = 0.718$ - Table 2).

The fresh colon works in large deformations with deformation at break of 206% against 55% for the refrigerated colon and 105% for the embalmed colon.

The stress at the elasticity limit (1st point of damage) was significantly higher for the embalmed colon than for the other two protocols (0.8 vs. 0.4 MPa, $p < 0.001$).

The stress at the point of rupture is lower for the refrigerated colon (0.7 MPa) than for the other two protocols (0.8 MPa), but this result is not statistically significant ($p = 0.718$).

Mechanical behavior according to the shelf-life

High-speed video analysis – The impact of shelf-life was assessed for all specimens. The average retention period of the bodies was 16 days (range: 0–76 days). We formed two groups of identical size ($N = 9$): body conservation for more or less than 16 days. The serosal lesion was most often concentrated in the central region of the specimen. There is, however, a difference between specimens less than 16-days-old (51.8% of cases) and specimens over 16-days-old (41.2% of cases); the specimens with the shortest shelf-life tear significantly more often in the core area than specimens with a longer shelf-life (p-value = 0.04).

Mechanical behavior depending on preservation duration – The behavior of colonic specimens as a function of the shelf-life is presented in Figure 3.

Statistical analysis of the values of the stresses and deformations at the points of inflection as a function of the shelf-life reveals a statistically significant difference as a function of the shelf-life of the fresh specimens, particularly at rupture, with a deformation at the point of rupture rate of 138% of the colon samples kept for less than 16 days and 55% for those kept for more than 16 days (Table 3). Subjects retained for more than 16 days have fewer deformities than subjects kept for less than 16 days ($p < 0.001$).

The behavior of the colon depending on gender

High-speed video analysis – For the "refrigerated" protocol, male- and female-derived samples had the same number of serosal lesions (1.94 for the male and 1.91 for the female, $p = 0.91$). The serosal lesion was most concentrated in the central region of the specimen for male (48.4% of cases), and this trend was less for the female samples (42.9% of cases). This difference was not statistically significant ($p = 0.97$).

Mechanical behavior depending on gender – The behavior of colonic specimens as a function of the gender is presented in Figure 4. A statistically significant difference between men and women was found in the behavior of refrigerated specimens for all parameters (Table 4). The Young's modulus, the stress at the first point of damage, and the stress at rupture were higher for the female- than men-derived samples ($p = 0.002$, $p < 0.001$, and $p < 0.001$, respectively).

The behavior of the colon depending on age

High-speed video analysis – The average age of all subjects in our study is 76-years-old. We divided the subjects into two identical groups ($N = 9$): more or less than 76-years-old on the day of death. Regarding the cinematographic analysis of the specimens, there was no statistically significant difference related to the age of the individuals ($p = 0.11$).

Mechanical behavior depending on age – The mechanical behavior of colonic specimens as a function of age is presented in Figure 5. A statistically significant difference as a function of age is observed in the behavior of fresh specimens, particularly at rupture with 1st deformation point at 66% for the oldest patients and 186% for the youngest (Table 5; $p = 0.03$ for the 1st inflection point and $p < 0.001$ for the 2nd inflection point).

Relative influence of each factor on the mechanical response of the colon

In our statistical analysis, we analyzed all the data acquired during this study and did not make a subgroup analysis. The parameters that could explain a change in the recorded mechanical response were analyzed for all subjects: the average age of the sample donors was 76 years and the average retention period was 16 days.

Univariate analysis was performed to identify statistically significant factors. The results are given in Table 6.

A multivariate analysis was then performed using linear regression. Since this is a multiple linear regression, only the first point of inflection has been studied, the second point of inflection being dependent on the first. The type profile studied is female, the type of preservation is embalming, the age is less than 76-years-old, and the shelf-life is less than 16 days. The results are shown in Table 7.

The type of conservation strongly modifies the mechanical response. In linear regression, the intercept is modified by about 30% by the type of conservation for the 1st point of inflection, with an embalmed colon that accepts more deformation than the other types of conservation; nevertheless, the Young's modulus is not modified by the type of conservation. The Young's modulus is modified by gender: men have a lower Young's modulus than women by about 30%. The gender also modifies the mechanical stress of the colon. Age significantly modifies the deformation, but linear regression indicates that this change is quantitatively small.

Shelf-life does not change the mechanical response in our multivariate linear regression model.

Discussion

This study on the human colon is a continuation of earlier works, including the studies of Yamada (Yamada, 1970), Fung (Fung, 1993), Egorov (Egorov et al., 2002) ,and Christensen (Christensen, Oberg, & Wolchok, 2015). The tests revealed a global behavior of the specimens with a first linear elastic phase leading to initial damage, followed by a second phase of plastic deformation until complete rupture occurred. Our results show that the colonic mechanical response is ductile and bilayer for dynamic longitudinal tensile loading conditions.

Being a biological tissue, the mechanical behavior could be influenced by the methods of preservation (Christensen et al., 2015). Although studies show that in quasi-static tests, the differences between fresh and cadaverous digestive tissue are negligible (Egorov et al., 2002), no work had yet evaluated possible differences for the human colon under dynamic stress. This protocol has demonstrated the impact of preservation methods on the mechanical response of this viscoelastic tissue: there is a statistically significant difference in the mechanical response between fresh human tissue and tissue preserved by embalming or refrigeration at 1°C. Specimens from fresh subjects require greater deformation to achieve a rupture. These results are consistent with our team's previous work on the small intestine (Bourgouin et al., 2012) and other teams that have shown that different preservation methods alter the collagen and elastin fiber structure of the fabric, the alteration of which modifies the mechanical response (Zhou et al., n.d.),(Brüel & Oxlund, 1996),(Xia, Kong, Xiong, & Ren, 2010).

Several studies confirm the impact of storage temperature as a factor that modifies the mechanical response: freezing at -10°C or -20°C decreases the stress and strain levels required for failure compared to fresh samples (Xia et al., 2010),(Quirinia & Viidik, 1991),(Huang, Zhang, Sun, Zhang, & Tian, 2011). The use of other preservatives has also been studied, with the use of salt crystals (Watters et al., 1985) or vasilated solutions, but these did not change the mechanical response (Rubod, Boukerrou, Brieu, Dubois, & Cosson, 2007).

The temperature of the tests was constant at about 22°C. Some authors perform their tests at body temperature (37°C). We suspect that the temperature of the tests would not change the mechanical behavior of the specimen, so long as avoiding extreme temperatures (Rubod et al., 2007; Wex, Stoll, Fröhlich, Arndt, & Lippert, 2014). However, a study on the behavior of a collagen matrix showed a decrease of the Young's modulus of the structure if the temperature of the test was increased from 23°C to 37°C (Meghezi, Couet, Chevallier, & Mantovani, 2012).

The use of fresh or non-embalmed colon should be preferred. Sampling was always done with repeated application of saline; drying may be responsible for a change in the mechanical behavior of the tissue (Rubod et al., 2007),(Lacoste-Ferré et al., 2011),(Meghezi et al., 2012).

In our study, the shelf-life of refrigerated tissue did not significantly alter the mechanical response. This is in contradiction with Ocala's work (Ocal, Ozcan, Basdogan, & Basdogan, 2010), which showed an increase in the stiffness of the material with an increase in the shelf-life of the samples. Nevertheless, because the experimental protocols used differ greatly, other factors (e.g., type of tests and the speed of stress) can explain this difference. In our study, we have demonstrated the modification of the mechanical behavior of the colon related to gender, particularly for Young's modulus and stress. Specimens from female subjects require greater strain for lesions.

It has already been demonstrated that female sex is an independent predictor of smooth muscle cells stiffening. This pro-rigidity effect represents an important element (Dinardo et al., 2015; Sokolis & Iliopoulos, 2014), but did not change with age (Vermeersch et al., 2008).

Only one publication previously studied the influence of gender on colonic mechanical behavior, which used a manometric catheter. These authors detected no significant differences (Viebig, Pontes, & Michelsohn, 1994).

Nevertheless, our protocol is different from that of Viebig (Viebig et al., 1994): we performed dynamic uniaxial tests conducted to rupture, while Viebig performed quasi-static circular measurements under physiological filling conditions of the colon and rectum. Regarding the influence of age on the mechanical response of the human colon, our results show a small change in the mechanical response between subjects aged over 76 years. Two other studies also did not find this association between age and mechanical response: not for the human vagina (Gilchrist, Gupta, Eberhart, & Zimmern, 2010) or human colon (Watters et al., 1985). Nevertheless, age greater than 65 years has been described as being able to reduce tissue rupture thresholds (Brüel & Oxlund, 1996)(Koeller, Muehlhaus, Meier, & Hartmann, 1986).

This study has several limitations, among which is the low number of specimens tested, particularly for the embalmed and fresh protocol-derived samples. We did detect an inter-individual variation, but this was considered as not significant in ANOVA; however, it is difficult to obtain a larger number of tests.

Uniaxial studies do not consider the three-dimensional behavior of the digestive tract, but they do allow an accurate study of the behavior of the colonic wall. The influence of loading speed will need to be addressed in order to appreciate the differences of biomechanical behaviors between a colon in a traumatic situation (dynamic tests) and a colon in the physiological or surgical situation (quasi-static tests). Other fields of application seem to benefit from our study, such as the development of computer simulations in road accidentology.

Conclusion

The mechanical behavior of the colon in a traumatic situation was evaluated by dynamic traction tests. The dynamic study of the colon under uniaxial traction at 1 m s^{-1} revealed its viscoelastic behavior. There is a change in the mechanical behavior of the colon depending on the gender and the method of body conservation. Whereas the age of the subjects and their duration of conservation do not modify the mechanical behavior of the human colon. The use of fresh or non-embalmed human tissue is preferred. The future realization of static tests would complete the mechanical study of the human colon.

Disclosure statement

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Figure 1 (chap 5.2): outer layer damage during an uniaxial dynamic tensile load of a human colon.

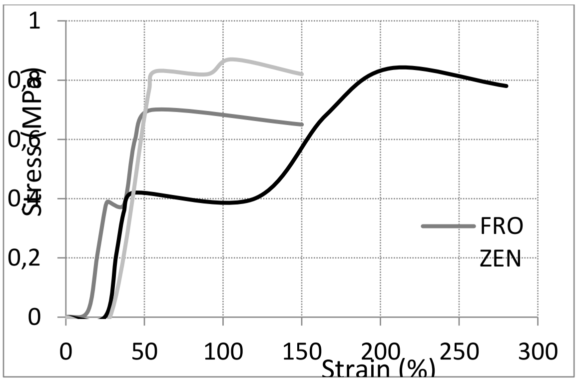


Figure 2 (chap 5.2): Standard stress- strain curves for longitudinal specimens under dynamic solicitation depending on the method of preservation. The x-axis corresponds to the strain (%) and the y-axis to the stress (MPa).

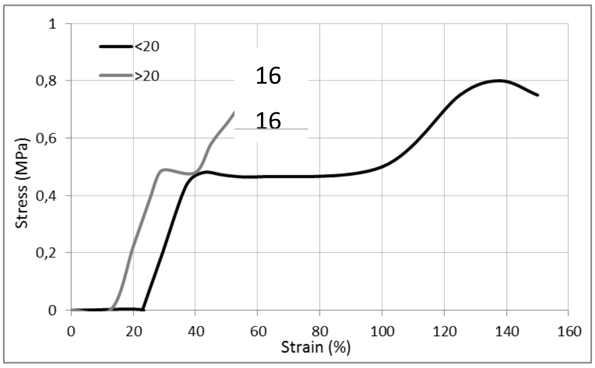


Figure 3 (chap 5.2): Standard stress-strain curves for longitudinal specimens under dynamic solicitation depending on the duration of preservation. The x-axis corresponds to the strain (%) and the y-axis to the stress (MPa). <16 means that the colon was taken from a subject who died less than sixteen days ago; > 16 means that the colon was taken from a subject who has been dead for more than 16 days.

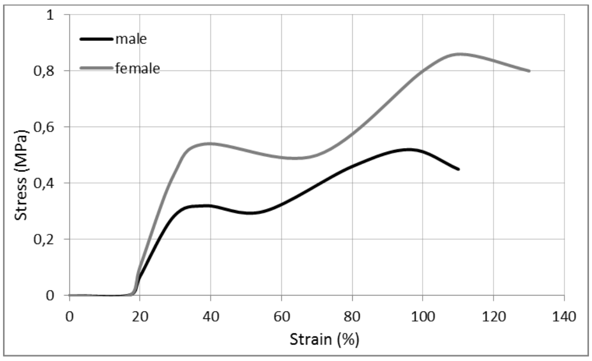


Figure 4 (chap 5.2): stress-strain curves for longitudinal dynamic specimens depending on the gender. The x-axis corresponds to the strain (%) and the y-axis corresponds to the stress (MPa).

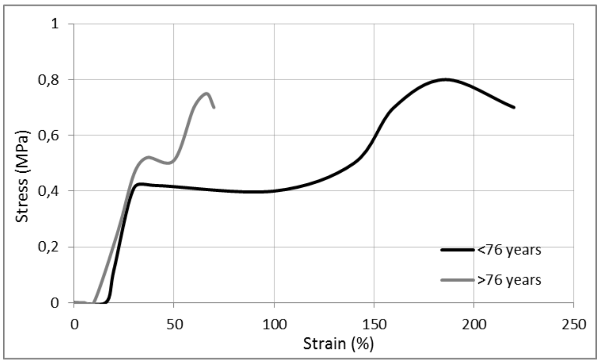


Figure 5 (chap 5.2): stress-strain curves for longitudinal dynamic specimens depending on the age. The x-axis corresponds to the strain (%) and the y-axis corresponds to the stress (MPa).

Patient	Gender	Age (y)	Protocol	Shelf life(d)
124-10	F	91	E	76
129-10	M	82	E	46
39-11	F	93	E	28
44-11	F	91	E	17
Average		89 ± 5		42 ± 26
SF1	M	20	F	0
SF2	F	38	F	0
SF3	F	49	F	0
SF4	F	53	F	0
Average		40 ± 15		-
1	F	100	R	21
2	F	84	R	2
3	F	81	R	33
4	M	84	R	34
5	F	86	R	12
6	M	88	R	25
7	M	73	R	9
8	M	96	R	23
9	F	82	R	13
10	F	89	R	16
Average		86 ± 8		19 ± 10

Table 1 (chap 5.2): Specimen matrix. For gender: M for male and F for female. For conservative method : F for « fresh », E for « embamed » and R for « refrigerated ».

	Embalmed	**Fresh**	**Refrigerated**
Modulus of the elastic phase (MPa)	3.1 ± 2	3 ± 2.6	32 ± 2.1
Strain at 1st inflexion (%)	57.3 ± 47.5	43.3 ± 29.8	26.7 ± 12
Stress at 1st inflexion (MPa)	0.8 ± 0.4	0.4 ± 0.3	0.4 ± 0.2
Strain at 2nd inflexion (%)	105.3 ± 78.4	206.4 ± 135.8	55.4 ± 31.7
Stress at 2nd inflexion (MPa)	0.9 ± 0.4	0.8 ± 0.4	0.7 ± 0.3

Table 2 (chap 5.2): Influence of method of preservation on the mechanical response of the longitudinal specimen

	<16 (d)	**> 16 (d)**
Modulus of the elastic phase (MPa)	3.1 ± 2.2	3.1 ± 2.2
Strain at 1st inflexion (%)	42.4 ± 35.8	30.4 ± 15.4
Stress at 1st inflexion (MPa)	0.5 ± 0.3	0.5 ± 0.4
Strain at 2nd inflexion (%)	138.1 ± 121.2	55.4 ± 26.4
Stress at 2nd inflexion (MPa)	0.8 ± 0.4	0.7 ± 0.4

Table 3 (chap 5.2): Influence of preservation duration on the mechanical response of the refrigerated specimens. <16 meanss that the colon was taken from a subject who died less than sixteen days ago; > 16 means that the colon was taken from a subject who has been dead for less than 16 days ; >16 means that the colon was taken from a subject who died more than sixteen days ago

	Male	**Female**
Modulus of the elastic phase (MPa)	2.2 ± 2	3.4 ± 2.2
Strain at 1st inflexion (%)	38.5 ± 24	38.3 ± 32.9
Stress at 1st inflexion (MPa)	0.3 ± 0.2	0.5 ± 0.3
Strain at 2nd inflexion (%)	96.5 ± 84	110.6 ± 111.7
Stress at 2nd inflexion (MPa)	0.5 ± 0.2	0.9 ± 0.4

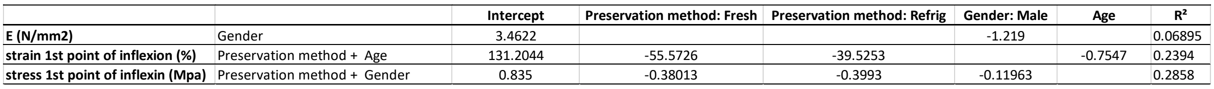
Table 4 (chap 5.2): Influence of gender on the mechanical response of the refrigerated specimens.

	<76 (y)	**> 76 (y)**
Modulus of the elastic phase (MPa)	2.9 ± 2.5	3.2 ± 2
Strain at 1st inflexion (%)	411.7 ± 28.4	36.5 ± 32.2
Stress at 1st inflexion (MPa)	0.4 ± 0.3	0.5 ± 0.3
Strain at 2nd inflexion (%)	185.9 ± 134.9	66.3 ± 50.3
Stress at 2nd inflexion (MPa)	0.8 ± 0.4	0.8 ± 0.4

Table 5 (chap 5.2): Influence of preservation duration on the mechanical response of the refrigerated specimens. <76 means that the subject was under the age of 76 ; >76 means that the subject was above the age of 76.

	Conservative method	Preservation duration	Gender	Age
Modulus of the elastic phase (MPa)	0.718	0.356	**0.002**	0.146
Strain at 1st inflexion (%)	**<0.001**	0.148	0.822	**0.03**
Stress at 1st inflexion (MPa)	**<0.001**	0.361	**0.001**	0.16
Strain at 2nd inflexion (%)	**<0.001**	**<0.001**	0.637	**<0.001**
Stress at 2nd inflexion (MPa)	0.0919	0.431	**<0.001**	0.517

Table 6 (chap 5.2): univariate analysis ; bold p-values are statistically significant and included in multivariate analysis



		Intercept	Preservation method: Fresh	Preservation method: Refrig	Gender: Male	Age	R^2
E (N/mm2)	Gender	3.4622			-1.219		0.06895
strain 1st point of inflexion (%)	Preservation method + Age	131.2044	-55.5726	-39.5253		-0.7547	0.2394
stress 1st point of inflexin (Mpa)	Preservation method + Gender	0.835	-0.38013	-0.3993	-0.11963		0.2858

Table 7 (chap 5.2): multivariate analysis - only statistically relevant regressions are presented in this table. Profile type: Woman, embalmed type of conservation, <76 years, shelf life <16 days

6. Discussion

Nous avons pu établir des valeurs mécaniques de référence pour le colon humain sous sollicitation uniaxiale. Plusieurs facteurs sont responsables d'une modification de la réponse mécanique :

- facteurs anatomiques : localisation des spécimens sur le cadre colique, orientation longitudinale ou transversale du prélèvement, sexe ;
- facteurs expérimentaux : type de conservation et vitesse de sollicitation.

D'autres études ont également cherché à caractériser le comportement mécanique du colon. Il est néanmoins difficile de comparer nos résultats et ceux d'autres équipes eu égard des différences de protocoles expérimentaux (tableau 1).

Authors	**Humain / Animal**	**Conservation**	**Vitesse de sollicitation**	**Orientation**	**Localisation colique**
Watters (1985)	Humain	Réfrigéré 4°C + sel	50mm/min	Circonférentielle	D/T/G/S
Merlo (1988)	Félin	Frais 37°C	Statique	L et T	D / S
Fung (1993)	Porcin	Frais 37°C	0.2 Hz / 20 Hz	Longitudinale	*Taenia coli*
Egorov (2002)	Humain	Réfrigéré 4°C	50mm/min	L & T	T
Howes (2012)	Humain	?	100/s	Bi-axiale	?
Christensen (2014)	Humain et porcin	Congelé -20°C	10mm/s	L & T	S (+ rectum)
Carniel (2014-2015)	Porcin	Réfrigéré puis 39°C	25mm/s	Circonférentielle	Pas de *taenia*
Massalou (2016)	Humain	Réfrigéré 1°C	1m/s	L & T	D/T/G/S

Tableau 1 : comparaison des différentes études mécaniques sur le colon sous différentes conditions expérimentales. L & T : sollicitation longitudinale et transversale. D : colon droit ; T : colon transverse ; G : colon gauche ; S : colon sigmoïde.

La diversité des protocoles expérimentaux fait appel à différentes espèces de mammifères : porc, cochon d'Inde ou bien humain. Ensuite, il existe peu de tissus frais ou à défaut réfrigéré sans utilisation d'éléments pouvant modifier la réponse mécanique comme les cristaux de sel, l'embaumement ou la congélation. Les publications font rarement état des conditions de température, d'hygrométrie et de réhydratation éventuelle des spécimens au cours des essais. Or ces paramètres peuvent chacun modifier la réponse mécanique enregistrée (19,24,40,47–49).

Dans la littérature, la plupart des études ont été réalisées en condition quasi-statique, c'est-à-dire en situation quasi-physiologique. Notre étude a la particularité d'étudier également le colon sous sollicitation dynamique afin d'appréhender la réponse mécanique rencontrée à haute vélocité comme dans l'accidentologie routière. Voici les principaux résultats des publications de biomécanique sur le colon :

- Watters (19) : il existe peu de changement après conservation du colon dans le sel pour une durée allant jusqu'à cinq semaines. Les niveaux de force restent inchangés le long du côlon. La résistance à la traction diminue distalement, lorsque l'épaisseur de la paroi colique augmente. Le comportement visco-élastique des contraintes était constante dans toutes les régions du cadre colique.
- Merlo (51) : chez le colon frais de félin, dans des conditions qui reproduisent l'homéostasie, il existait une différence mécanique entre colon proximal et colon distal, mais surtout une différence entre sollicitation longitudinale et transversale. De plus, les modifications des concentrations ioniques et en neuropeptides du liquide d'essais, modifiaient la réponse mécanique enregistrée.
- Fung (18) : sollicitation à type de traction uniaxiale de colon porcin mettant en évidence une différence de réponse mécanique en fonction de la déformation du segment prélevé et en fonction de la fréquence de sollicitation : tissu élastique à basse fréquence et rupture à fréquence élevée.
- Egorov (15) : mise en évidence d'un comportement mécanique rigide du *taenia coli* en condition quasi-statique par rapport aux spécimens sans *taenia coli*. Description du caractère bicouche du colon transverse avec mise en charge progressive des couches externe puis interne.
- Howes (52) : publication complète non disponible
- Christensen (40) : les tissus humains nécessitaient plus de force à la rupture que leurs homologues porcins. De plus, la localisation du site de prélèvement sur le cadre colique ainsi que l'orientation des essais ont considérablement modifié les propriétés mécaniques dans les tissus porcins, mais très peu dans les tissus humains. Les données suggèrent que le tissu colorectal porcin ne reproduit pas correctement les propriétés mécaniques du tissu colorectal humain.

Comme nous l'avons vu, la caractérisation colique dépend de nombreux facteurs anatomiques, anthropométriques mais aussi du protocole expérimental. Le tissu frais, ou à défaut non embaumé doit être préféré, afin de limiter la modification de la réponse mécanique. Concernant la modélisation numérique en traumatologie routière virtuelle, la sollicitation dynamique est à privilégier. La simulation informatique doit également prendre en compte le caractère anisotrope du colon dans l'orientation du traumatisme.

D'autres conditions expérimentales permettraient d'approfondir la connaissance du comportement mécanique du colon : sollicitation bi-axiale, sollicitation cylindrique par insufflation d'air (ou d'eau).

Par rapport aux tests uniaxiaux dans deux directions orthogonales, les tests multiaxiaux (comme les tests biaxiaux ou d'extension-gonflage) présentent plusieurs avantages. Les tests biaxiaux conduisent à un couplage du comportement transversal et axial, entraînant une déformation plus proche des conditions physiologiques ou traumatiques lors de ces tests tout en évitant les rotations non physiologiques des fibres qui pourraient se produire lors des essais uniaxiaux (53). En sollicitation biaxiale chez le cochon d'inde, le colon ne dispose pas des mêmes propriétés biomécaniques que sous sollicitation uniaxiale, qu'elle soit longitudinale ou transversale : des charges longitudinales croissantes entraînent une diminution de la déformation transversale ; l'augmentation de la charge transversale, est responsable d'une augmentation de la déformation transversale (54). Dans notre étude, le colon possède un comportement plus élastique transversalement que longitudinalement : les valeurs de contrainte et déformation sont environ 30% plus élevées pour l'obtention de la rupture du spécimen ; le module d'Young n'est quant à lui pas modifié par l'orientation de la sollicitation (cf tableau 2, 3 et 4 de la publication dans le chapitre 3). D'autres segments du tube digestif ont également un comportement mécanique différent entre sollicitation uniaxiale et biaxiale :

- Pour l'œsophage ovin frais, les essais de traction biaxiale ont mis en évidence un comportement non linéaire, mais, contrairement au comportement de traction uniaxiale, les phénomènes d'anisotropie sont peu marqués pour de faibles vitesses de sollicitation mais s'accentuent si on augmente celles-ci (55) ;
- Pour le tube digestif porcin, des tests de traction uniaxiale et biaxiale ont été réalisés ; dans ces deux sollicitations, l'intestin grêle se comportait de façon anisotropique et la sollicitation transversale était moins raide que la direction axiale (56–58) ;
- Pour l'estomac porcin, les mêmes conclusions sont retrouvées par Aydin (59).

Pour le colon porcin, des tests de gonflement à l'air ont montré un comportement élastique anisotrope des spécimens, avec une réponse variable en fonction de la vitesse de remplissage et la durée de celui-ci (60)(61). Il a été démontré que des phénomènes pathologiques lents (comme l'occlusion intestinale), modifiaient la réponse mécanique de l'intestin grêle lors d'essais de gonflement-étirement : les lésions apparaissaient pour des niveaux de contrainte et de déformation augmentés (62). Le comportement mécanique du tube digestif au cours des traumatismes fermés de l'abdomen présente probablement des niveaux de rupture différents de ceux présentés dans les études *in vitro* quasi-statiques.

L'interprétation des résultats de certaines publications peut être délicate. En effet, plusieurs publications présentent des résultats mécaniques du tube digestif, couche par couche, par exemple dans un modèle bi-couche d'œsophage (53,55,63). Or, le comportement de l'œsophage intact n'est pas le même que le comportement par couche : la couche interne composée de la muqueuse et sous-muqueuse est la plus rigide (61). Ainsi la réalisation d'essais avec paroi totale est à privilégier et évite des microlésions lors de la dissection des deux couches, qui peuvent endommager le matériau et le rendre fragile. Dans notre étude, nous avons fait le choix d'étudier le colon en paroi totale et en prenant garde de ne pas réaliser de micro-lésions lors de la réalisation des spécimens.

De plus, l'étude séparée du tube digestif et de ses mésos ne reflète pas complètement la réalité mécanique du tube digestif. Dans la publication de Bège et al., la réponse mécanique était différente si l'on étudiait ensemble intestin grêle et mésentère, par rapport à l'étude de chaque « organe » pris séparément : l'association mésentère et intestin grêle nécessitait plus de force pour obtenir des lésions que ces éléments pris séparément (25). Cette différence était statistiquement significative en condition dynamique et statique. Dans notre étude sur le colon humain, nous n'avons étudié que le tissu colique, sans étudier le mésocolon. Afin de compléter ce point, il conviendrait d'étudier le comportement mécanique des mésos et du tube digestif en prenant en compte leur insertion rétropéritonéale ; des difficultés techniques concernant le modèle expérimental rendraient peut-être les manipulations difficiles et/ou non reproductibles.

Si notre étude permet de proposer des valeurs pour les paramètres mécaniques du colon en chacun de ses segments et en fonction de différentes vitesses de sollicitation, néanmoins d'autres paramètres devront pris en compte pour la réalisation de modèles numériques.
En particulier le volume de remplissage du tube digestif (et donc sa masse) est à prendre en compte. Cette masse fécale est modifiée par l'alimentation des individus, l'hydratation, la prise médicamenteuse et le temps de transit colique. Cela peut entraîner des phénomènes locaux lors des traumatismes fermés de l'abdomen mais également modifier la masse du tube digestif que

doit supporter le méso (mésocolon ou mésentère). La réalisation de modèles numériques de traumatologie virtuelle devra prendre en compte ces paramètres.

Enfin, le choix du modèle animal ou humain doit être réfléchi. Le modèle animal présente certains avantages : disponibilité, possibilité de procédures expérimentales non réalisables chez l'humain, létalité acceptable, contraintes administratives moindres, etc. Dans de nombreuses expériences, le modèle animal est un prérequis voire le seul modèle expérimental réalisable.
Les similitudes potentielles et l'existence de données biomécaniques pourraient faire du tissu porcin un modèle expérimental idéal. Cependant, bien qu'anatomiquement proche de l'humain, il n'est pas certain que les similitudes s'étendent aux propriétés mécaniques : en effet, le comportement mécanique tu tube digestif est différent entre l'être humain et les animaux comme le porc ou le cochon d'Inde (40,64). D'autres tissus présenteraient des différences de comportement mécaniques entre espèces animales et humains : valves aortique et cardiaque (65,66), cerveau (67).

Nous l'avons vu, le choix du modèle expérimental est capital. Celui-ci doit s'attacher à reproduire *in vitro* les phénomènes à étudier *in vivo*.
Ainsi, l'étude expérimentale idéale du colon humain en situation traumatique, devrait être réalisée de la façon suivante :

- Tissu humain frais ou à défaut non embaumé,
- Réalisation de tests uniaxiaux en traction longitudinale et transversale, biaxiaux, cylindriques par gonflement et de compression,
- Sollicitation dynamique proche des conditions des traumatismes abdominaux fermés,
- Réaliser ces tests avec le mésocolon
- Prendre en compte la localisation dont sont issus les spécimens coliques,
- Avoir une répartition homogène entre hommes et femmes, sujets minces et sujets obèses, âges variables.

Nous devrons donc compléter cette étude par la réalisation de tests biaxiaux, cylindriques et de compression.

7. Conclusion

L'objectif de cette étude était d'étudier la réponse mécanique du colon humain soumis à une sollicitation uniaxiale afin de reproduire les conditions locales d'un traumatisme conduisant à la rupture colique.

Le colon se comporte comme un matériau viscoélastique ductile et bicouche. Il se produit une première rupture de la couche séreuse/musculaire externe puis une seconde rupture de la couche interne composée de la musculaire interne/sous-muqueuse/muqueuse.

La réponse mécanique enregistrée est différente en fonction de l'orientation de la sollicitation : les niveaux de contrainte et de déformation au point de rupture étaient statistiquement plus élevés en termes de contrainte transversale que longitudinale.

La vitesse de sollicitation modifie la réponse mécanique enregistrée. Le colon est moins rigide en situation quasi-statique et présente des niveaux de rupture plus faibles sous sollicitation dynamique.

Le module d'Young est modifié en fonction de la localisation sur le cadre colique avec un comportement moins rigide du colon droit et du colon sigmoïde. Le sexe et la méthode de conservation représentent également des facteurs responsables d'une modification de la réponse mécanique du colon sous sollicitation dynamique.

En situation statique, la présence du *taenia coli* rend le tissu plus rigide ; cela se traduit par des niveaux de contrainte et de déformation à la rupture plus faibles qu'en l'absence de *taenia coli*.

L'âge et la durée de conservation des sujets anatomiques ne modifient pas la réponse mécanique du colon.

La réalisation de futurs protocoles expérimentaux devra privilégier des sujets frais ou à défaut non-embaumés, en tenant compte du sexe et de l'origine des spécimens sur le cadre colique.

La réalisation d'études bi-axiales et cylindriques permettront d'améliorer la connaissance du comportement mécanique du colon lors des traumatismes fermés de l'abdomen.

Cette étude permettra l'intégration du colon dans des simulateurs chirurgicaux ou dans des outils de traumatologie virtuelle. Néanmoins, la prise en compte du mésocolon et de ses insertions, ainsi que le volume du chyme alimentaire contenu dans le tube digestif, devront être intégrés dans ces modèles.

De nouveaux dispositifs de sécurité automobiles pourraient être testés grâce à notre étude.

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Liste des abréviations utilisées

cm : centimètre (unité de mesure)
ET : écart-type
Go : gigaoctet (unité de mesure)
HUMOS : *HUman Model for Safety*
IFSTTAR : Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux
LBA : Laboratoire de Biomécanique Appliquée
m : mètre (unité de mesure)
mm : millimètre (unité de mesure)
N : Newton (unité de mesure)
OMS : Organisation Mondiale de la Santé
Pa : Pascal (unité de mesure)
TDM : Tomodensitométrie
UFR : Unité de Formation et de Recherche
3D : tridimensionnel

Résumé

Introduction

Le tube digestif est fréquemment atteint dans les traumatismes fermés de l'abdomen. La connaissance des propriétés mécaniques des différents organes est indispensable à la mise en place d'outils numériques de traumatologie virtuelle. L'objectif de cette étude est de déterminer la réponse mécanique du colon en traction uniaxiale jusqu'à la rupture et quels sont les facteurs la modifiant.

Matériel et méthodes

Nous avons réalisé des essais dynamiques uniaxiaux de spécimens coliques humains. Trois vitesses de sollicitation étaient testées : dynamique (1m/s), intermédiaire (10cm/s) et quasi-statique (1cm/s).

Une étude cinématographique et mécanique était réalisée pour chaque spécimen.

Résultats

Vingt-huit colons humains réfrigérés ont été testés avec un total de 344 spécimens inclus dans l'étude. Le colon présente un comportement mécanique bicouche avec une première rupture de la couche externe comprenant séreuse/musculaire externe puis une seconde rupture de la couche interne composée de la musculaire interne/sous-muqueuse/muqueuse.

Le comportement mécanique est variable en fonction de la localisation sur le cadre colique avec un comportement plus élastique du colon droit et du colon sigmoïde. Le sexe représente également un facteur responsable d'une modification de la réponse mécanique du colon. La durée de conservation des corps et le *tænia coli* ne représentaient pas un facteur influençant le comportement mécanique dynamique du colon.

La réponse mécanique enregistrée est différente en fonction de l'orientation de la sollicitation : les niveaux de contrainte et de déformation étaient statistiquement plus élevés sous sollicitation transversale que longitudinale.

La vitesse de sollicitation modifie la réponse mécanique enregistrée. Le colon est plus élastique en situation quasi-statique et présente des niveaux de rupture plus faibles sous sollicitation dynamique.

Sous sollicitation dynamique, le type de conservation ne modifie pas la raideur du tissu mais modifie la déformation et la force nécessaires pour obtenir des lésions coliques.

Conclusion

Le colon se comporte comme un matériau viscoélastique ductile et bicouche. Son comportement mécanique est dépendant de la localisation sur le cadre colique, du sexe, des méthodes de conservation et des vitesses de sollicitation. Cette étude permettra l'intégration de données biomécaniques dans des modèles de traumatologie virtuelle ou de simulation chirurgicale.

Mots clés : traumatisme, colon, biomécanique

Abstract

Introduction

The digestive tract is frequently affected in blunt abdominal trauma. The knowledge of the mechanical properties of the various organs is essential to the implementation of virtual tools of traumatology. The objective of this study is to determine the mechanical response of the colon in uniaxial traction until rupture and what are the modifying factors.

Material and methods

We performed uniaxial dynamic tests of human colonic specimens. Three loading speeds were tested: dynamic (1m / s), intermediate (10cm / s) and static (1cm / s). A cinematographic and mechanical study was carried out.

Results

Twenty-eight refrigerated human colons were tested with a total of 344 specimens included in the study. The colon exhibits a bi-layered mechanical behavior with a first rupture of the outer layer comprising serosa / external muscle and then a second rupture of the inner layer composed of the internal muscle / submucosa / mucosa.

The mechanical behavior is variable according to the localization on the colonic frame with a more elastic behavior of the right colon and the sigmoid colon. Gender is also a factor responsible for a change in the mechanical response of the colon. The shelf life of the body and *tænia coli* were not a factor influencing the mechanical behavior of the colon under dynamic solicitation.

The recorded mechanical response is different depending on the orientation of the stress: the stress and strain levels were statistically higher under circumferential stress than longitudinal.

The loading speed changes the recorded mechanical response. The colon is more elastic in a quasi-static situation and has lower levels of rupture under dynamic stress. Under dynamic loading, the type of preservation does not modify the stiffness of the tissue but modifies the stress and strain necessary to obtain colonic lesions.

Conclusion

The colon behaves like a ductile and bilayer viscoelastic material. Its mechanical behavior is dependent on the location on the colonic frame, gender, methods of conservation and rates of solicitation. This study will allow the integration of biomechanical data into models of virtual trauma or surgical simulation.

Keywords: trauma, colon, biomechanics