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1 **Fluid mechanical consequences of pendular activity, segmentation, and pyloric**
2 **outflow in the proximal duodenum of the rat and the guinea pig**

3
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5
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11
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13 **Keywords:** small intestine, mixing, viscosity, gastrointestinal flow, lattice Boltzmann, diffusion

14
15 **Abstract**

16 We conducted numerical experiments that incorporated quantitative data from real contractile activity
17 to study the influence of non propagating contractions that are organised into discrete fixed domains,
18 i.e. pendular activity and segmentation, on flow and mixing.

19 Models of proximal duodenal flow were developed using a lattice-Boltzmann numerical method for
20 homogeneous viscous luminal content. The models simulated the fluid mechanical consequences for
21 each of 22 randomly selected sequences of high definition video of real longitudinal and radial
22 contractile activity in the isolated proximal duodenum of the rat and guinea pig.

23 During pendular activity in the rat duodenum, the flow was pulsatile with the formation of regions of
24 high shear rate. Mixing from sustained pendular activity was governed by shearing deformation of the
25 fluid that increased the interface between adjacent domains and accelerated their inter-diffusion. When
26 the diffusion coefficient of the marker was below $\sim 10^{-8}$ m²/s the influence of pendular activity on axial
27 dispersion was greater than that in the purely diffusive case. These relative effects increased as the
28 diffusion coefficient decreased. When pendular activity was associated with a slow gastric outflow
29 characteristic of post-prandial period, the dispersion was also improved, especially near the walls. In
30 contrast, isolated segmentative contractions in the guinea pig duodenum caused the viscous fluid to be
31 deformed but mixing was not promoted as fluid particles recovered their original positions on
32 subsequent relaxation and was not notably influenced by pylorus outflow.

33 We concluded that pendular activity generates mixing of viscous fluids '*in situ*' and accelerates the
34 diffusive mass transfer of small molecules as glucose or bile micelles; whereas segmentation may be
35 more important in mixing particulate suspensions with high solid volume ratios.

36

37 **1. Introduction**

38 The proximal small intestine is an important site for the physical and chemical processing of digesta. A
39 number of workers have suggested [1, 2] that the gastro-intestinal tract can be represented as a series of
40 chemical reactors. Their conclusions showed that for tubular reactors, such as the small intestine to
41 function efficiently, conditions within the lumen must resemble those in a longitudinal array of perfectly
42 mixed stirred tank reactors with ongoing slow axial transfer of reactants between them [3, 4]. Such
43 findings underscore the need for zones within the lumen of the small intestine [3, 4] in which there is
44 efficient mixing with little propulsion and for quantitative evaluation of the behaviour of digesta during
45 such non-propagating contractile activity [5].

46
47 Most studies of intestinal mixing have investigated the influence of propagating peristaltic activity [6-9],
48 whilst mixing generated by non propagating contractile activity, i.e. segmentation [10-12] and pendular
49 contractions [13], has not been rigorously evaluated, chiefly as the relative magnitudes of the
50 component contractile processes have not been quantified until recently [10, 14]. Early workers
51 concluded that longitudinal contractions alone could induce flow between the core and the periphery of
52 the luminal content [13] and generate laminar mixing [15]. However, these conclusions were not
53 supported by detailed physiological data. *In vitro* and analytical models of segmentation [16] have served
54 to demonstrate the influence of the symmetry and mobility of the contraction on absorption but again
55 lack the necessary physiological detail to obtain quantitatively reliable results.

56
57 The recent development of high resolution spatio-temporal mapping techniques to quantify the circular
58 and longitudinal components of contractile activity in isolated segments of the gastro-intestinal tract
59 [17] in conjunction with the development of numerical methods that are capable of modelling gastro-
60 intestinal flows with complex geometries [7, 18-20] offer a more precise means of evaluating the effects
61 of various contractile processes on flow and mixing in the small intestine. Further, the recent description
62 of the component zones of longitudinal contractions in discrete stationary domains that together
63 engender pendular movements [14] enables the effects on mixing along a length of duodenum to be
64 modelled (Fig. 1). Further, the direct incorporation of these recorded datasets into suitable fluid
65 mechanical models may allow a more detailed evaluation of the mechanics of the mixing that they
66 engender.

67

68 The aim of this study was to investigate the fluid mechanical consequences of pendular activity,
69 segmentation, and pyloric outflow in the isolated proximal duodenum of the rat and guinea pig and to
70 explore the effect of (Newtonian) viscosity of the luminal content on mixing. After defining the
71 conditions that govern bulk flow in the duodenal lumen, we developed three sets of boundary conditions
72 (BC) by which the radial and longitudinal velocity of the walls set the luminal content in motion. The first
73 (BC1), was based on parameters derived by analysis of longitudinal strain rate maps of pendular activity
74 in the rat duodenum and was used to describe the general characteristics of pendular flow. The second
75 (BC2) and third (BC3) boundary conditions incorporated real time data from 22 randomly selected high
76 definition video sequences of pendular activity in the isolated proximal duodenum of the rat (BC2) and of
77 segmentation in the guinea pig (BC3) and were used to examine flow and mixing generated by real
78 motility.

79

80 **2. Methods**

81 *a. Assumptions regarding bulk flow in the duodenal lumen*

82 The proximal duodenum was modelled as a tube of diameter D (m) and length L (m) between the
83 pylorus and the pancreatic duct. The flow generated by non propagating contractions was modelled
84 using the incompressible Navier-Stokes equations. The rheological properties of the chyme depend on
85 the digestive phase and are so temporally inconsistent. We restricted our analysis to homogeneous
86 Newtonian chyme with a constant viscosity μ (Pa.s). The role of non Newtonian behaviour will be
87 discussed later. Three levels of viscosity were examined 1 (i.e. water), 10 and 100 mPa.s. We assumed
88 that the characteristics of the contractile activity were independent of the viscosity of the lumen
89 contents. This hypothesis was based on the observations that the spatio-temporal characteristics of
90 circular and longitudinal contraction during propagating peristalsis in the terminal ileum of the possum
91 did not vary with the apparent viscosity of the perfusate [21].

92

93 *Dimensionless numbers governing the flow*

94 To facilitate the analysis of flow, we reformulated the Navier-Stokes equations in a dimensionless form
95 to enable the parameters to be regrouped as dimensionless variables. Hence, variables with dimensions
96 such as velocity were scaled by their appropriate characteristic values to give the dimensionless form.
97 The characteristic values included the characteristic velocity of the flow V_c (m/s) that corresponded to
98 the maximal longitudinal or radial velocity of the wall, the diameter of the duodenum D and the fluid

99 density ρ ($=10^3$ kg/m³ in the whole paper). The dimensionless values are identified by the symbol ' . Thus,
100 we have

101

$$102 \quad \vec{u}' = \frac{\vec{u}}{V_c}, x' = \frac{x}{D}, y' = \frac{y}{D}, t' = \frac{t}{D/V_c}, p' = \frac{p}{\rho V_c^2}, \dot{\gamma}' = \frac{\dot{\gamma}}{V_c/D}$$

103

104 where \vec{u} is the velocity field (m/s), x the longitudinal abscissa (m), y the radial abscissa (m), t the time
105 (s), p the pressure (Pa) and $\dot{\gamma}$ the shear rate (s⁻¹).

106 The flow is governed by the Reynolds Re number which represents the ratio of the inertial forces to the
107 viscous forces and is defined by

108

$$Re = \frac{\rho V_c D}{\mu} \quad (1)$$

109

110 Classically, the flow in a tubular conduit is turbulent when Re is high. Such turbulence leads to the
111 formation of unstable eddies of differing scales that promote efficient and rapid mixing of fluids.
112 However, intestinal flows are generally characterised by Reynolds numbers below 200 [7, 8], so that flow
113 is laminar and mixing by advection is correspondingly more limited. An extreme case of laminar flow,
114 termed Stokes flow, occurs when the Reynolds number approaches zero, i.e. when the viscosity of the
115 lumen content is very high. Under such conditions, flow is reversible [22], i.e. a fluid element that is
116 displaced by a deformation of the wall will return to its original position as the deformation relents.

117

118 As pendular contractions vary cyclically with time at a frequency f (Hz), flow is pulsatile and can be
119 described by the Strouhal number Sr which represents the ratio of the time scale of the longitudinal
120 activity $1/f$ to the time scale of the flow D/V_c and is defined by

121

$$Sr = \frac{fD}{V_c} \quad (2)$$

122

123 Pulsatile flow can also be characterised by the Womersley number Wo , a procedure that is more popular
124 in physiology and biofluidics than the use of the Strouhal number Sr [23, 24]. In effect Wo is a
125 combination of Re and Sr

126

$$Wo = D \sqrt{\frac{f\rho}{\mu}} = \sqrt{ReSr} \quad (3)$$

127
 128 The Womersley number can be viewed as the ratio of the diameter of the intestine D to the depth of the
 129 layer of fluid $\sqrt{\mu/f\rho}$ that oscillates against the wall. When both Sr and Wo are low, flow occurs in a
 130 “quasi-steady” manner [24], i.e. the instantaneous flow rate is given by the instantaneous pressure
 131 gradient any movements at the boundary with the contracting wall are readily transmitted through the
 132 adjacent fluid and the thickness of the oscillating fluid layer is maximised. Flow characteristics depart
 133 progressively from this behaviour. As conditions change to increase the values of the two dimensionless
 134 parameters [24] boundary conditions are less readily transmitted through the adjacent fluid and the
 135 oscillating boundary layer of fluid becomes thinner.

136
 137 *Oral and aboral conditions*

138 In a first step, we defined oral and aboral conditions so as to avoid inducing extraneous flow
 139 phenomena. Null radial velocity components and pressures were imposed at the oral and aboral ends of
 140 the duodenum and the flow field was defined as null at the commencement of the simulation.

141 In a second step, we modelled the simultaneous effects of the pyloric outflow of chyme and pendular
 142 activity on mixing during post-prandial period. The velocity profile at the level of the pylorus was
 143 assumed to be parabolic (i.e. Poiseuillar flow) with a maximal velocity of 0.2 mm/s. This order of
 144 magnitude was determined by considering that the residence time of the chyme in proximal duodenum
 145 of the rat during the post-prandial period is around 3 min [25] and the length of the duodenum was
 146 around 40 mm [14]. Two situations were explored in the second step, firstly assuming that gastric
 147 emptying resulted simply from a sustained increase in fundal and corporal tone [18, 26] inducing a
 148 constant inflow of chyme and secondly assuming sinusoidal modulation of inflow by antral contraction
 149 waves [18, 26] with a frequency of 5 cycles by minute for the rat [27] and a mean maximal velocity of
 150 0.2 mm/s.

151
 152

153 ***b. Boundary conditions during contraction***

154 Three sets of boundary conditions were developed that determined the position and the longitudinal or
155 radial velocity of the walls of the duodenum during contractile activity.

156
157 *BC1: Simplified pendular activity*
158 Pendular activity was modelled by dividing the proximal duodenum into 4 domains of contractile activity
159 (Fig. 1 & 2) each of length $2l$ with half domains each of length l at the two ends. The longitudinal strain ε
160 was defined by $\Delta L/L$ where L is the length of a segment of muscle and ΔL is its change of length due to
161 muscle contraction. The cyclic variation of the longitudinal strain rate $\dot{\varepsilon}$ ($= \partial\varepsilon/\partial t$, s^{-1}), i.e. the rate of
162 local lengthening (if $\dot{\varepsilon} < 0$) or shortening (if $\dot{\varepsilon} > 0$), along the mesenteric and antimesenteric axis that
163 occurred in each specific domain was represented by a sinusoidal function

$$164 \quad \dot{\varepsilon}(x, t) = A(x)\sin(2\pi ft + \phi) \quad (4)$$

165
166 where t is the time, x the longitudinal abscissa, ϕ the phase and $A(x)$ the strain rate amplitude. For each
167 domain, $A(x)$ was parameterised by a parabola of centre x_0

$$168 \quad A(x) = A_{max} \left[1 - \left(\frac{x - x_0}{l} \right)^2 \right] \quad (5)$$

169
170 The velocities $V(x, t)$ of the walls were determined by integration of Eq. 4.
171 A ratio L/D of 5 and a phase lag of 180° were used as a base case, in the numerical simulations
172 (Table S1). This resulted in the maximal longitudinal velocity V_{max} for each domain being given by

$$173 \quad V_{max} = \frac{2}{3} A_{max} l \quad (6)$$

174
175 The values for the parameters in these equations (Table 1) were obtained from one dimensional fast
176 Fourier analysis of maps of longitudinal strain rate reported in the proximal duodenum of the rat (Fig. 1)
177 [14].

178
179 The results are given for a pseudo-steady state, i.e. the flow parameters depend only on the time relative
180 to one cycle of activity, and the variables, as the pressure p , are averaged over one-half cycle

181

$$\bar{p}_{T/2}(\vec{x}) = \frac{2}{T} \int_0^{T/2} p(\vec{x}, t) dt \quad (7)$$

182

183 *BC2: Real pendular activity*

184 Pairs of longitudinal strain rate maps were acquired from five separate *ex vivo* preparations of the
 185 proximal duodenum of the rat (Fig. 1) [14]. Each pair described the spatiotemporal evolution of
 186 longitudinal contractions along the mesenteric and antimesenteric surfaces respectively. This allowed for
 187 any effects of the asymmetry of the contractile activity on the flow features to be incorporated into the
 188 analysis. Ten representative video sections, each of 20 seconds duration (5 rats x 2 sequences) were
 189 sampled from sequences that showed arrays of non propagating longitudinal contractions organised into
 190 domains (Fig 1). After interpolation of the strain rate maps to correspond to the mesh of the numerical
 191 model, the longitudinal velocity of the mesenteric and antimesenteric surfaces were determined by
 192 integration in the space dimension.

193 Circular activity and consequent alterations in wall thickness was neglected in this situation as no
 194 noticeable passive bulging of the wall was observed during longitudinal shortening and non-propagating
 195 circular contractions were of low amplitude in the duodenum of the rat (<15% of the diameter at
 196 rest) [14].

197 After simulation, the absolute value of the data of interest, as the pressure p , was averaged over
 198 20 seconds for each spatial-coordinate

199

$$\overline{|p|}_{20}(\vec{x}) = \frac{1}{20} \int_0^{20} |p(\vec{x}, t)| dt \quad (8)$$

200

201 *BC3: Real segmentative activity*

202 Segmentative contractions occur singly in the isolated guinea pig proximal duodenum and are not
 203 temporally and spatially synchronized [10, 14] in the manner described by Cannon [11]. We therefore
 204 modelled the flow during each of 12 randomly chosen isolated contractions (4 guinea pigs x 3 examples).
 205 Each contraction was individually parameterized. The evolution of the diameter was fitted with the
 206 function

207

$$D(x, t) = D_0 - a_0(x)te^{-t/a_1} \quad (9)$$

208

209 where D_0 is the diameter at rest, a_1 is a time constant characteristic of the relaxation, and $a_0(x)$
 210 corresponds to the dependence of the diameter on a spatial dimension that was close in form to that of
 211 a parabola ($R^2 \approx 0.95$)

$$212 \quad a_0(x) = U_{max} \left[1 - \left(\frac{x - x_0}{l} \right)^2 \right] \quad (10)$$

213
 214 where U_{max} is the maximal radial velocity in the centre of the contraction, x_0 the centre of the
 215 contraction and $2l$ the length of the contraction. The length of the contractile domain was about 6 mm
 216 [14]. D_0 , a_1 , and U_{max} were determined by fitting Eq. 9 to the data using a least square fitting
 217 procedure (Table 1). The radial velocity of the boundary was determined by taking the derivative of
 218 Eq. 9.

$$219 \quad \frac{\partial D}{\partial t} = a_0(x) t e^{-t/a_1} \left(\frac{t}{a_1} - 1 \right) \quad (11)$$

220
 221 ***c. Evaluation of intestinal mixing***

222 The displacement of 150 small and massless particles spaced regularly within the lumen was calculated
 223 so as to assess the extent to which contained material could be advected by the flow field.

224
 225 We examined the extent to which deformations in the flow of the contents increased the lengths of
 226 interfaces between different elements of fluid and hence improved the diffusion process between them.
 227 The parameter of interest in this case was the shear rate component of the strain rate field of the flow
 228 noted $\dot{\gamma}$ (in s^{-1})

$$229 \quad \dot{\gamma} = \frac{1}{2} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \quad (12)$$

230
 231 where u and v are the axial and radial velocity; respectively.

232 We determine the dispersion of a diffusive tracer from its starting position comprising three pairs of lines
 233 that were oriented radially across the lumen, each pair being located so as to be in the middle of a
 234 domain of contraction during pendular activity. The resulting concentration field was compared with that
 235 from a case where molecular dispersion was restricted to diffusion. Given that the residence time of the
 236 chyme in the rat proximal duodenum during post-prandial period is around 3 min [25], we modelled

237 periods of video activity of 4 min duration that consisted mainly of pendular activity. The evolution of the
 238 concentration C of this tracer was modelled by the advection-diffusion equations

$$239 \quad \frac{\partial C}{\partial t} + \bar{u}\nabla C = \alpha\nabla^2 C \quad (13)$$

240
 241 where α is the diffusion coefficient. The flux of the diffusive tracer was null at all the boundaries of the
 242 duodenum. The temporal evolution of the variance of the concentration field was calculated to quantify
 243 and compare the impact of the intestinal motility on mixing.

244
 245 ***d. Numerical resolution by the lattice-Boltzmann method (LBM)***

246 The use of the LBM for solving Navier-Stokes equations has only relatively recently been described.
 247 Contrary to other computational fluid dynamics methods, instead of solving the discretized Navier-
 248 Stokes equations, LBM simulates the streaming and collision processes that result from the longitudinal
 249 and radial movements of the walls, across a limited number of particles interacting on a network of
 250 nodes within the duodenal lumen. The velocity and pressure fields can then be calculated. The LBM is
 251 capable of modelling complex flow phenomena as flow with deformable boundaries on a Cartesian mesh
 252 [28, 29] without the remeshing methods that are generally used with finite element methods. Motility
 253 data obtained by spatio-temporal mapping can be easily incorporated in the model. The LBM has been
 254 successfully used to model gastric flow [18] and the coupling of micro- and macro- flow around small
 255 intestinal villi [19, 20].

256
 257 We used a lattice Boltzmann BGK scheme (LBGK) developed by Guo et al. [30] as, unlike other LBGK
 258 schemes, the use of this method allows the incompressible Navier-Stokes equations to be exactly
 259 recovered [30].

260
 261 The geometry of the duodenum was modelled only in two dimensions (2D) in order to reduce the
 262 computational time. Previous comparisons of flow patterns in two dimensional models of the intestine
 263 with those in axisymmetric geometries have shown that 2D models capture similar fluid motions and
 264 produce only modest quantitative differences in pressure and velocity [31, 32]. More importantly, this
 265 simplification was necessary to incorporate real experimental data as this was derived from videos i.e
 266 was measured in 2D.

267

268 The oral and oboral pressure and velocity conditions were modelled using the non-equilibrium
269 extrapolation method of Guo *et al.* [33].

270
271 For each location and each time step, the longitudinal and radial displacement of the walls calculated
272 with each of the three types of boundary conditions (§2.b) were incorporated in a numerical scheme
273 that considered moving and curved boundary conditions. The less computationally intensive and second-
274 order methods were based on an interpolation method developed by Filippova and Hanel [34] and
275 improved by Mei *et al.* [35] which is more accurate in regard to flux, forces at the wall and vorticity than
276 are other methods of interpolation [36].

277
278 The advection-diffusion equations (Eq. 13) were solved by the revised moment propagation method for
279 scalar transport proposed by Yu *et al.* [37].

280
281 The set of equations was solved directly in MATLAB R2010b (The Mathworks, Natick, MA). Preliminary
282 numerical simulations indicated that to obtain a sufficiently high degree of computational accuracy the
283 radius of the duodenum must be meshed with a minimum of 30 cells.

284
285 Two benchmarks were used to validate the implementation of the LBM.
286 The 2D unsteady Womersley flow [23, 24] was solved on a domain of 30 by 30 nodes under periodic
287 boundary conditions. The relative error with the analytical solution [24] was calculated with

288

$$E_2 = \frac{\{\sum(u - u_{exact})^2\}^{1/2}}{\{\sum(u_{exact})^2\}^{1/2}} \quad (14)$$

289
290 where u is the axial the velocity calculated with the model and u_{exact} is the exact solution. E_2 was 3.4
291 10^{-3} and $1.7 \cdot 10^{-3}$ for Wo of 5 and 1 respectively. So, the model was able to simulate unsteady flow
292 accurately.

293 To analyse the accuracy of the boundary treatment, the flow generated by a travelling wave with a
294 sinusoidal shape in two different frames of reference was simulated under periodic boundary conditions
295 on a grid of 40x100. The wave length was 100 and the amplitude was 14 cells. In the first case, the wave
296 moved axially with a velocity of 0.05, whereas in the second case the wave was steady and the upper
297 boundary moved axially with a velocity of -0.05. When reported in the same frame of reference, both
298 flows are equivalent. The error E_2 (Eq. 14) for the axial, radial velocity and the pressure were $4.7 \cdot 10^{-3}$,

299 $6.3 \cdot 10^{-2}$ and $5.4 \cdot 10^{-2}$; respectively. These results were consistent with those obtained by Wang et al. [19]
300 with a different lattice-Boltzmann model., Hence this procedure demonstrated that moving boundaries
301 could be incorporated without causing numerical inconsistency.

302

303 ***e. Statistical analysis of the flow parameters***

304 When necessary, flow parameters were transformed using the Johnson transformation algorithm in
305 MINITAB (Sydney, Australia) to obtain a normal distribution. They were subsequently analysed in the
306 SYSTAT software suite, version 11 (Chicago, USA) by two way ANOVA with “Rat” and “Viscosity” as
307 factors. When significant overall differences were obtained ($p < 0.05$), the effects of the various factors
308 were compared by Bonferroni *post hoc* comparison. The values are given as the mean \pm standard
309 deviation.

310

311 **3. Results**

312 ***a. Influence of dimensionless parameters on pendular flow (BC1)***

313 In the proximal duodenum of the rat, the Reynolds number Re varied between 0 and 10 during pendular
314 contraction (Table 1). Similarly the Strouhal and Womersley numbers varied between 1 and 10, and
315 between 0 and 10, respectively. The simulations conducted with the boundary conditions of simplified
316 pendular activity (BC1), showed that flow was pulsatile and the flow parameters oscillated between a
317 negative and positive value. Maps of velocity and shear rate fields (Fig. 3) showed that the strongest fluid
318 motions and greatest shear rates were localised at the walls and located at the junctions of successive
319 contractile domains.

320

321 Two flow regimes could be distinguished. The first was obtained when Re and Sr were large (i.e. with
322 high Wo). In this case, the flow and regions of greatest shear rate were confined to a thin oscillating
323 boundary layer (Fig. 3 & 4) that remained close to the walls. The second was obtained when Re and Sr
324 were small (i.e. small Wo), the longitudinal velocity of the wall propagated further into the lumen, i.e.
325 further along the radial dimension toward the central longitudinal axis, and symmetrical vortices
326 developed between adjacent domains (Fig. 2 & 4). The direction of rotation of fluid particles inside a
327 vortex varied from clockwise to anti-clockwise during a period of longitudinal muscle contraction. As Re
328 and Sr tended to zero, the flow tended to an asymptotic solution that corresponded to the “quasi-
329 steady” flow where the boundary conditions were fully transmitted across the radial dimension.

330

331 ***b. Effects of real pendular activity on mixing (BC2)***

332 In line with the previous results, radial velocity values averaged over 20 seconds (i.e. about 14 cycles of
333 activity) (Fig. 5) showed a tendency for higher values to be grouped in regions of the lumen field that
334 corresponded to longitudinal contractile domains. The amplitudes of radial velocities with fluids of lower
335 viscosity (1 mPa.s) were lower than those with fluids of higher viscosity (10 mPa.s). The maximal radial
336 velocity was around 80 $\mu\text{m/s}$ with a viscosity of 1 mPa.s (N=10) (Table 2), the velocity of the lumen
337 contents being no further augmented by any additional increase of their viscosity above 10 mPa.s (Table
338 2).

339
340 The displacement of massless particles (Fig. 6) were influenced by fluid inertia of the contents such that
341 the position around which they oscillated moved about 300 μm in the axial direction and 30 μm in the
342 radial direction over a period of 20 s when the viscosity was low (1 mPa.s). Hence globally, the flow was
343 not fully reversible, however the net axial flow generated by pendular activity in one direction or the
344 other was negligible compared with the amplitude of the oscillation.

345
346 Comparisons of the spatial patterns of variation in shear rate across the field of the lumen (Fig. 7) when
347 the viscosity of the lumen content was 10 mPa.s showed asymmetrical regions of high shear rate that
348 were interspersed between adjacent contractile domains due to the asymmetry of the contractions. The
349 pattern of local variation in shear rate varied within between preparations (Fig. 7). The various
350 parameters that described the shear rate field (Table 2) differed significantly only when the viscosity of
351 the lumen content was increased from 1 to 10 mPa.s, but not when it was further increased, i.e. from 10
352 to 100 mPa.s. Between 1 and 100 mPa.s, the maximal shear rate was significantly reduced from a factor
353 1.8 (from 0.85 to 0.47 s^{-1}).

354
355 The shear generated by pendular activity increased the interface between adjacent domains and hence
356 improved mixing by diffusion. Observation of the degree of deformation and change in breadth of local
357 regions in the initially radially orientated lines of the diffusive tracer over time confirmed this behaviour
358 (Fig. 8a). The deformation of the lines of tracer oscillated at the frequency of the longitudinal
359 contractions augmenting overall diffusion by expanding the length of the lines (and hence the area of
360 interface) and displacing the developing diffusion gradient to give a smudging effect. When the diffusion
361 coefficient of the marker was below $\sim 10^{-8} \text{ m}^2/\text{s}$ the influence of pendular activity on axial dispersion was
362 greater than that in the purely diffusive case (Fig. 8b & Fig. A in Supplementary results). These relative

363 effects increased as the diffusion coefficient decreased. Conversely, when the diffusion coefficient of the
364 marker was greater than $\sim 5 \cdot 10^{-8} \text{ m}^2/\text{s}$, the shearing deformations generated by pendular activity were
365 too small to improve diffusive mass transfer.

366
367 When pendular activity was associated with pyloric outflow, the dispersion was improved, mainly near
368 the walls of the duodenum, compared to the case where mass transfers were only driven by pyloric
369 outflow and diffusion (Fig. 9a). The variance of concentration decreased more quickly in the first than in
370 the second case (Fig. 9b), but the pattern of pyloric outflow (i.e. steady or oscillating) did not appear to
371 influence the outcome.

372

373 ***c. Effects of real segmentative activity on mixing (BC3)***

374 Observations of the displacement of small particles (Fig. 10) showed that they were advected by the flow
375 generated during segmentative contractions, but that they returned to a position that was very close to
376 their starting position after relaxation was complete. This behaviour was observed in the 12 video
377 sequences that were examined and was independent of viscosity. When segmentation was associated
378 with pyloric outflow, the difference was insubstantial. Modelling the dispersion of a diffusive scalar over
379 4 minutes of segmentative activity was not possible as sustained activity over 4-5 cycles of contractions
380 had not been observed in our previous study [14].

381

382 **4. Discussion**

383 ***a. Methodological advances modelling of flow within the gut***

384 Whilst a number of previous workers [7, 8, 18] have directly incorporated image data that described the
385 evolution of propagating radial constriction in fluid mechanical models, the present study is the first to
386 explore the physical processes of digestion during pendular and segmentative activity in the absence and
387 presence of pyloric outflow using models that integrate the physics of fluids with real physiological and
388 morphological data that incorporate inter- and intra- individual variability. This method is also a simpler
389 alternative than the construction of stochastic models of intestinal motility [16]. This study provides
390 insights into the relative contribution of the various types of static contractile activity in securing mixing
391 and digestion and permits some statistical assessment of the variation in flow with viscosity and
392 between subjects. Again models that incorporate such sophisticated data may help in the design of food
393 and pharmaceutical products to optimize absorption.

394

395 Whilst the use of these methods have allowed us to generate data with a level of detail that is currently
396 not possible to obtain directly, either *in vivo* or *ex vivo*, some form of direct validation of the model is
397 desirable though technically difficult. In this respect, we are currently developing a method based on
398 residence time distribution of dye tracers [6].

399

400 ***b. Pendular activity and 'mixing in situ'***

401 The results show that non propagating longitudinal contractions in arrays of contractile domains within
402 the proximal duodenum of the rat generate corresponding arrays of non-steady vortices with a relative
403 increase in lumen pressure in areas between adjacent vortices (Fig. 3). This result matches qualitatively
404 with manometric data from the isolated small intestine of the rabbit [38] and confirm hypotheses based
405 on a simple mechanical models that longitudinal small intestinal contractions can generate vortices [13].
406 However, our quantified results showed that conclusions of previous workers [13, 15] on the effects of
407 longitudinal contractions on vortices and laminar mixing were oversimplified. Indeed, the generation of
408 vortices does not appear to govern the mixing process as the amplitude of the radial velocity is low (Fig.
409 5) and so the content of the lumen cannot flow between the core and the periphery of the duodenum
410 during one cycle of contraction (Fig. 6). Rather, our results indicate that pendular activity induces a cyclic
411 deformation of boundaries between adjacent elements of fluid lumen content that locally increase the
412 area of interface between them and accelerates inter-diffusion (Fig. 8). Hence, contrary to the actions of
413 peristaltic contractions that engender mixing during axial propulsion [7, 8], pendular activity can mix
414 content 'in situ.' Indeed, the disposition and mode of action of pendular activity appears to reflect
415 chemical process engineering design insofar as it minimises propulsion whilst maximising dispersion [3,
416 4].

417 Moreover, the fact that the effects of pendular activity on dispersion increased as the diffusion
418 coefficient of the marker material decreased (Fig. 8) highlights the importance of longitudinal motility in
419 the proximal duodenum in the digestion of larger and more slowly diffusive molecules such as glucose
420 ($\alpha \approx 8.10^{-10} \text{ m}^2/\text{s}$, [39]) or aggregates of molecules such as biliary micelles ($\alpha \approx 1.10^{-10} \text{ m}^2/\text{s}$, [40]).The
421 principal factor limiting the efficient mixing of lumen contents with a low Reynolds number is the
422 symmetric reciprocating motion of the walls. The association of pendular activity with pyloric outflow
423 has been hypothesized to improve mixing by precluding the consequent reciprocal motion of the
424 adjacent fluid. Our results support this conclusion indicating that mixing in the duodenum is facilitated
425 by the concerted action of the gastric and duodenal musculature. However it is noteworthy that whilst
426 the dispersion of nutrient molecules would be improved by pyloric outflow (Fig. 9), the concerted action

427 the antrum and pylorus in generating pulsatile flow [18, 26] did not augment such dispersal. In this
428 regard it is noteworthy that our two dimensional analysis could not incorporate any effect of the pyloric
429 torus. This structure, an asymmetrically positioned pad projecting into the pyloric lumen, along with its
430 associated muscular loops [41], may serve to vary the position of the outflow within the duodenal bulb
431 and further increase dispersion [42].

432

433 ***c. Effects of the rheological properties of the chyme on mixing***

434 The flow generated by pendular activity is weakly dependant on viscosity when chyme behaves as a
435 simple Newtonian fluid (Table 2). Such a situation is likely to occur during the post prandial period when
436 significant quantities of drink are ingested. A second model that incorporated shear thinning behaviour
437 of the chyme [43] was developed and will be presented in a further paper. It shows that similar
438 phenomena are likely to occur during the later part of the post-prandial period and during the inter-meal
439 interval with moderate qualitative differences.

440

441 ***d. Segmentative activity***

442 During a single segmentative contraction in the guinea pig duodenum, the flow was reversible even
443 when the viscosity of chyme was low (Fig. 9). It is possible that sustained segmentative activity in the
444 manner described by Cannon (1902) may mix the luminal content by a similar mechanism to that during
445 pendular activity (Fig. 8). However such activity has not been reported in isolated preparations [10, 14].
446 Moreover, segmentative activity appears to be more evident in the isolated duodenum of the
447 herbivorous guinea pig [44] than the omnivorous rat [45]. Typically the chyme of herbivores has a high
448 volume of insoluble particles and behaves as a weak gel exhibiting a degree of elasticity and plasticity
449 [43]. Such rheological behaviour will promote irreversibility in the flow as duodenal contractions induces
450 structural changes in the chyme from extrusion of the liquid phase and from incomplete re-expansion
451 and recovery of this fluid during the relaxation [46]. Further the extrusion of the liquid phase during
452 compression may augment any slip at the wall [5, 47]. Conversely such behaviour would render mixing
453 by pendular activity inefficient, as the presence of expressed fluid at the wall would promote slip and
454 prevent longitudinal contractions from transmitting shear to the lumen content. Hence, segmentation
455 may be more developed when dietary habit results in chyme with high solid volume ratios and pendular
456 activity may be more developed when solid volume content of chyme is low. These differences in the
457 predominant type of stationary contractile activity appear to be reflected in the relative proportions of
458 longitudinal and circular muscles in the duodenal *tunica muscularis* in the rat and the guinea pig [14].

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571 6. Tables and figures captions

572
 573 **Table 1: Parameters of pendular activity and of segmentative activity in the proximal duodenum of the**
 574 **rat and the guinea pig respectively.**

575
 576 **Table 2: Variation in descriptors of the mean radial flow (in $\times 10 \mu\text{m/s}$) and shear rate (in s^{-1}) field with**
 577 **viscosity obtained with model incorporating data from real pendular activity (BC2) in the proximal**
 578 **duodenum of the rat (N=10).**

579
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582 (A) shows a rat proximal duodenum with the pylorus on the left and the pancreatic duct on the right. The
 583 strain rate map (B) presents 4 spatial domains (*). In each of them, the strain rate oscillates between a
 584 minimal and a maximal value. (C) shows the strain rate amplitude at the dominant frequency as a
 585 function of the duodenum length. Local maxima in strain rate amplitude (*) vary in position within each
 586 domain. The phase diagram at the dominant frequency (D) presents steps between each domain of
 587 about 180° .

588
 589 **Figure 2: Simplification of pendular activity in the duodenum of the rat and notations used in the first**
 590 **boundary conditions BC1.**

591 The proximal duodenum comprises 4 domains of equal length $2l$ and 2 half domains of length l at each
 592 end of the duodenum. At the mesenteric and antimesenteric surfaces, the strain rate $\dot{\epsilon}$, with which the
 593 walls shorten, oscillates at a frequency f and with a phase lag of 180° between adjacent domains. The
 594 velocities V (used as boundary conditions in the model) were directly determined by integration of the
 595 strain rate $\dot{\epsilon}$ along the length of the duodenum. The pressures p at the pylorus and the pancreatic duct
 596 are designated as equal.

597
 598 **Figure 3: Showing variation in flow (top), shear rate (middle) and pressure (bottom) fields with the**
 599 **Reynolds Re and Strouhal St numbers obtained using the simplified model of pendular activity in the**
 600 **duodenum of the rat (BC1, Fig. 2).**

601 The velocity, the shear rate and the pressure were each averaged over half of the period of the cycle of
 602 muscular contraction. The vector field shows the mean direction of flow of chyme during this time.

603 Two main types of flow regime were identified depending on the magnitude of Re and Sr (see text).
604 Arrows indicate transects location used for Fig. 4.

605
606 **Figure 4: Influence of the Reynolds Re (A) and the Strouhal Sr (B) numbers on the dimensionless mean**
607 **radial velocity at a transect through the gut obtained from the simplified model of pendular activity in**
608 **the duodenum of the rat (BC1, Fig. 2) at $Sr=5$ and $Re=1$ respectively.**

609 The transect was located between adjacent vortices traversing the point where the radial component of
610 velocity is the most developed (indicated by the arrows on Fig. 3). When either Re or Sr increase, the
611 radial velocity profile becomes progressively less developed and more constrained to regions near the
612 walls. Conversely at low Re and Sr , the radial velocity profile tends to an asymptotic solution (bold plain
613 line).

614
615 **Figure 5: Results from modelling (BC2) of a 20 second period of spatiotemporally mapped pendular**
616 **activity in the duodenum of the rat showing the effect of the viscosity of the luminal content on local**
617 **radial velocity.**

618 The strain rates map (A) shows four active domains in the first 30 mm of the duodenum (*). The vertical
619 direction corresponds to the time and the horizontal direction corresponds to the distance along the
620 duodenum. The grey scale corresponds to the strain rate.

621 Absolute values of radial velocities at each location are averaged over 20 seconds and plotted as isovalue
622 maps whose axes correspond to the axial and radial dimensions of the proximal duodenum (B, C and D).
623 The domain of each longitudinal contraction corresponds to a zone of higher velocity. The zone is located
624 nearer to the anti-mesenteric (lower) than the mesenteric wall as a result of radial asymmetry in the
625 amplitude of longitudinal contractions. The flow is less developed at low viscosity (B) than at high
626 viscosity (C and D).

627
628 **Figure 6: Results from modelling (BC2) of 20 second sequences of spatiotemporally mapped pendular**
629 **activity in the duodenum of the rat showing their effect on advection**

630 Cumulative mean radial (dashed line) and axial (plain line) displacements of small particles (5 rats x 2
631 sequences x 150 particles) over time resulting from flow advection with chyme viscosity at 1 mPa.s. The
632 limits of the shaded areas correspond to \pm standard deviation / 2.

633

634 **Figure 7: Results from modelling (BC2) of two 20 second sequences of spatiotemporally mapped**
 635 **pendular activity in the ex vivo duodenum of five rats showing variation in the spatial patterns of**
 636 **shear rate with the viscosity.**

637 (a) shows isovalues of shear rate for a viscosity of 10 mPa.s. The absolute value of the shear rate was
 638 averaged at each location over each 20 s time sequence to produce a map of isovalues whose axis
 639 represent the axial and radial dimensions of the proximal duodenum. The regions of highest shear rate
 640 are spaced between adjacent contractile domains and are localised near the walls (Fig. 2). The shear rate
 641 is radially asymmetric as a result of radial asymmetry of the longitudinal contractions.

642 (b) shows variation in distribution of shear rate across the radial dimension of the lumen with viscosity.
 643 For each rat and each sequence, the absolute value of the shear rate was first averaged in the axial
 644 direction of the duodenum and subsequently these means were averaged for all the rats and all the
 645 sequences (plain lines). The limits of the envelope curves correspond to \pm standard deviation /2.

646
 647 **Figure 8: Results from modelling (BC2) of 4 minute sequences of spatiotemporally mapped pendular**
 648 **activity in the ex vivo duodenum of a rat showing the influence of different diffusion coefficients α on**
 649 **mixing.**

650 Three radially orientated lines of a diffusive tracer ($\alpha = 5.10^{-9} \text{ m}^2/\text{s}$) were placed between adjacent
 651 longitudinal contractile domains (see Methods).

652 (a) The evolution of the tracer during 4 minutes of pendular activity plus diffusion (right) is compared
 653 with the case where the process is purely diffusive (left). The shear generated during pendular activity
 654 deforms the chyme, increases the size of the interface between adjacent domains and accelerates
 655 diffusive mass transfer across the longitudinal dimension.

656 (b) Shows the temporal evolution of the ratio of the variances of concentration obtained with pendular
 657 activity plus diffusion to those obtained with diffusion alone using tracers with different diffusion
 658 coefficients α (see also Fig. A in Supplementary results).

659
 660 **Figure 9: Results from modelling (BC2) of 4 minutes sequences of spatiotemporally mapped pendular**
 661 **activity in the ex vivo duodenum of a rat associated with pyloric outflow and diffusion (see Methods)**
 662 **showing the influence on longitudinal dispersion.**

663 A radially orientated line of a diffusive tracer ($\alpha = 5.10^{-9} \text{ m}^2/\text{s}$) was placed at the site of the pylorus.

664 (a) The evolution of the tracer during 4 minutes of pendular activity along with steady pyloric outflow
 665 and diffusion (right) is compared with the case where the dispersion is governed by steady pyloric
 666 outflow and diffusion with no pendular activity (left).

667 (b) Compares the temporal evolution of the variance of the concentration when a steady or oscillating
668 gastric outflow is associated with pendular activity and diffusion with the case where there is no
669 pendular activity.

670
671 **Figure 10: Showing the influence of segmentation on the displacement of small particles in a model**
672 **incorporating spatiotemporally mapped sequences of segmental motility in the duodenum of the**
673 **guinea pig (BC3).**

674 Left panel: Temporal profile of change in the diameter at the centre of a region of segmental contraction
675 (■: experimental data from Lentle *et al.* (2012), plain line: Eq. 9)

676 Right panel: Plots of isovalues of velocity and displacement of small particles advected by the flow
677 (o: initial position, ●: instantaneous position) at three different time points with viscosity of lumen
678 contents of 1 mPa.s.

679 At the peak of the contraction ($t=0.8$ s), the particles undergo significant advection by the flow field, but
680 return to their initial position when relaxation is complete ($t=3.8$ s).

681 ($U_{max}=3.9$ mm/s; $a_1=0.85$ s; $D_0=4.8$ mm; $2l=8.6$ mm; $\mu=1$ mPa.s)

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 686
 687 **Table 1: Parameters of pendular activity and of segmentative activity in the proximal duodenum of the**
 688 **rat and the guinea pig respectively.**
 689

	Symbol	Typical value	Reference
Pendular activity – Proximal duodenum of the rat			
Maximal amplitude of strain rate	A_{max}	0.09-0.21 s ⁻¹	[14]
Diameter of the duodenum	D	4-6 mm	[14]
Frequency	f	0.56-0.64 Hz	[14]
Length of a domain	$2l$	7.5-11.2 mm	[14]
Duodenum length	L	40-45 mm	[14]
Number of domains	N	4-6	[14]
Maximal longitudinal velocity	V_{max}	0.4-1.6 mm/s	Eq. 6
Phase lag between adjacent territories	ϕ	135-225°	[14]
Viscosity of the chyme	μ	> 1 mPa.s	
Reynolds number	Re	0-10	Eq. 1
Strouhal number	Sr	1-10	Eq. 2
Womersley number	Wo	0-10	Eq. 3
Segmentation – Proximal duodenum of the guinea pig			
Relaxation time	a_1	0.6-0.9 s	Calculated from [14]
Diameter of the duodenum	D	4.5-8.1 mm	Calculated from [14]
Length of a domain	$2l$	3.0-8.8 mm	[14]
Number of domains	N	4-5	[14]
Maximal radial velocity	U_{max}	2.4-5.4 mm/s	Calculated from [14]
Viscosity of the chyme	μ	> 1 mPa.s	
Reynolds number	Re	0-43	Eq. 1

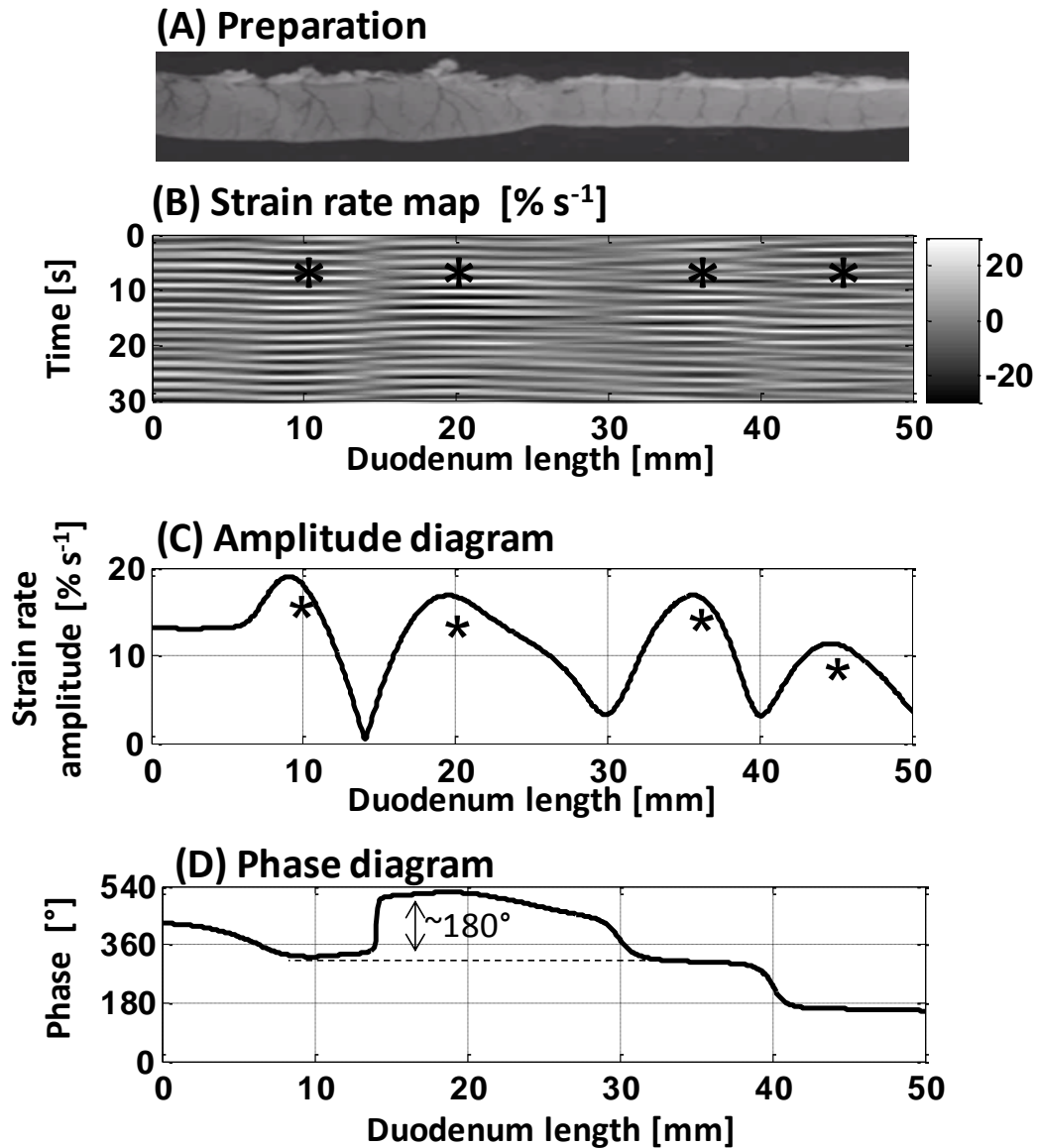
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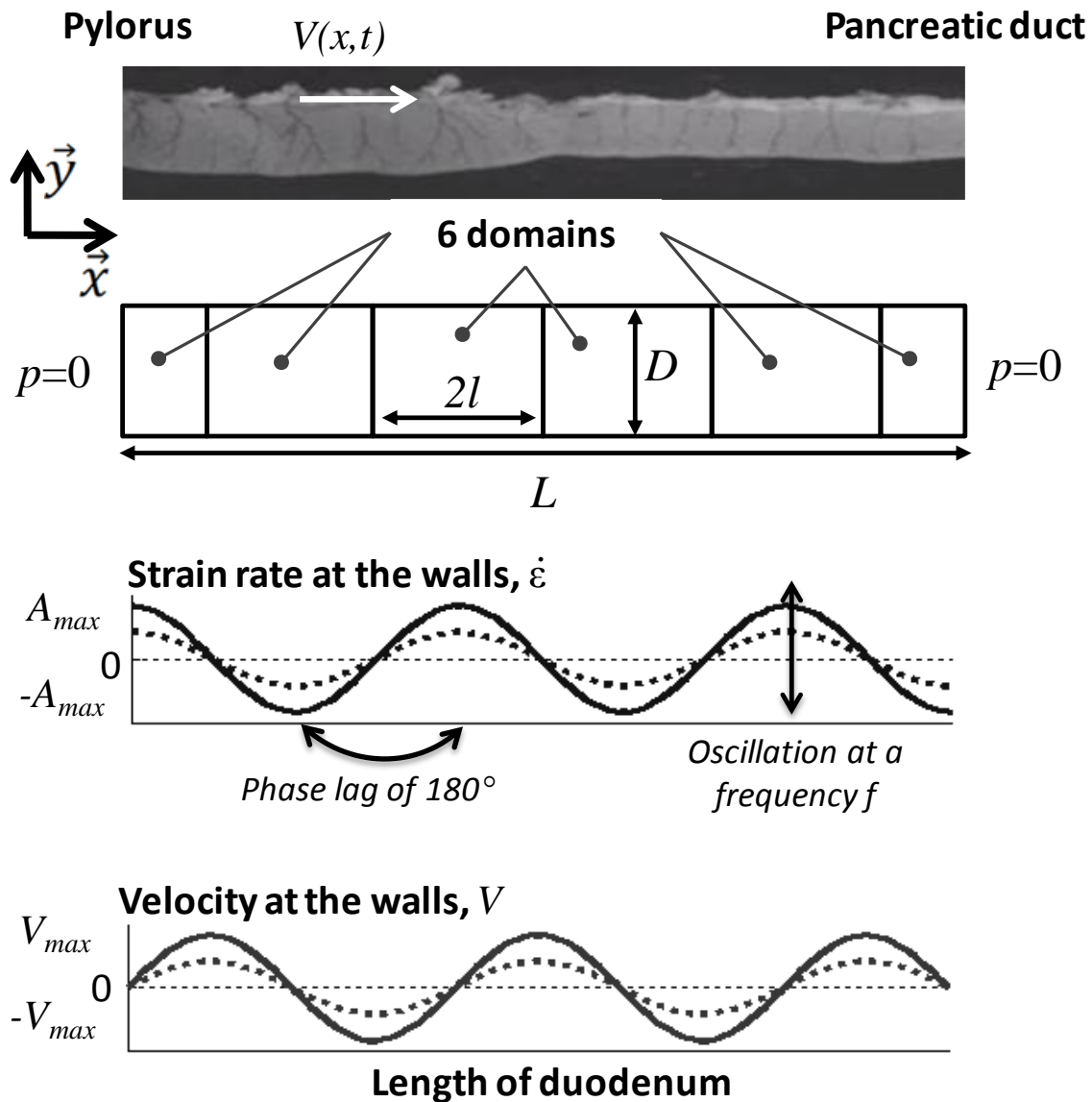
Viscosity:	1 mPa.s	10 mPa.s	100 mPa.s
Maximal axial velocity	6.0 \pm 2.0 (a)	7.7 \pm 2.8 (b)	7.6 \pm 2.4 (b)
Mean shear rate at the mesenteric surface	0.36 \pm 0.10 (a)	0.24 \pm 0.06 (b)	0.21 \pm 0.06(b)
Mean shear rate in the middle of the lumen	0.024 \pm 0.006 (a)	0.039 \pm 0.006 (b)	0.039 \pm 0.008 (b)
Mean shear rate at the anti-mesenteric surface	0.41 \pm 0.14 (a)	0.26 \pm 0.08 (b)	0.23 \pm 0.08 (b)
Shear rate averaged on all the lumen	0.15 \pm 0.04 (a)	0.13 \pm 0.02 (a)	0.11 \pm 0.02 (a)
Maximal shear rate	0.85 \pm 0.36 (a)	0.51 \pm 0.16 (b)	0.47 \pm 0.14 (b)

703 Results are given as mean \pm standard deviation
704 $p < 0.05$ are indicated by different letters (a & b)



705
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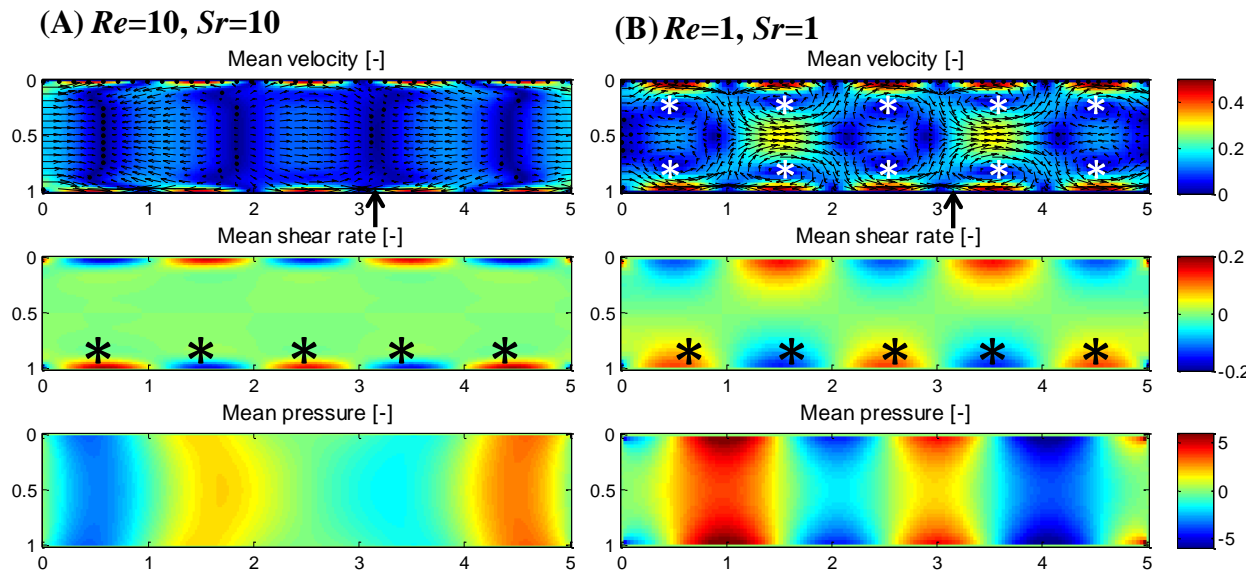


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718 The proximal duodenum comprises 4 domains of equal length $2l$ and 2 half domains of length l at each
 719 end of the duodenum. At the mesenteric and antimesenteric surfaces, the strain rate $\dot{\epsilon}$, with which the
 720 walls shorten, oscillates at a frequency f and with a phase lag of 180° between adjacent domains. The
 721 velocities V (used as boundary conditions in the model) were directly determined by integration of the
 722 strain rate $\dot{\epsilon}$ along the length of the duodenum. The pressures p at the pylorus and the pancreatic duct
 723 are designated as equal.

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729 **Figure 3: Showing variation in flow (top), shear rate (middle) and pressure (bottom) fields with the**
730 **Reynolds Re and Strouhal Sr numbers obtained using the simplified model of pendular activity in the**
731 **duodenum of the rat (BC1, Fig. 2).**

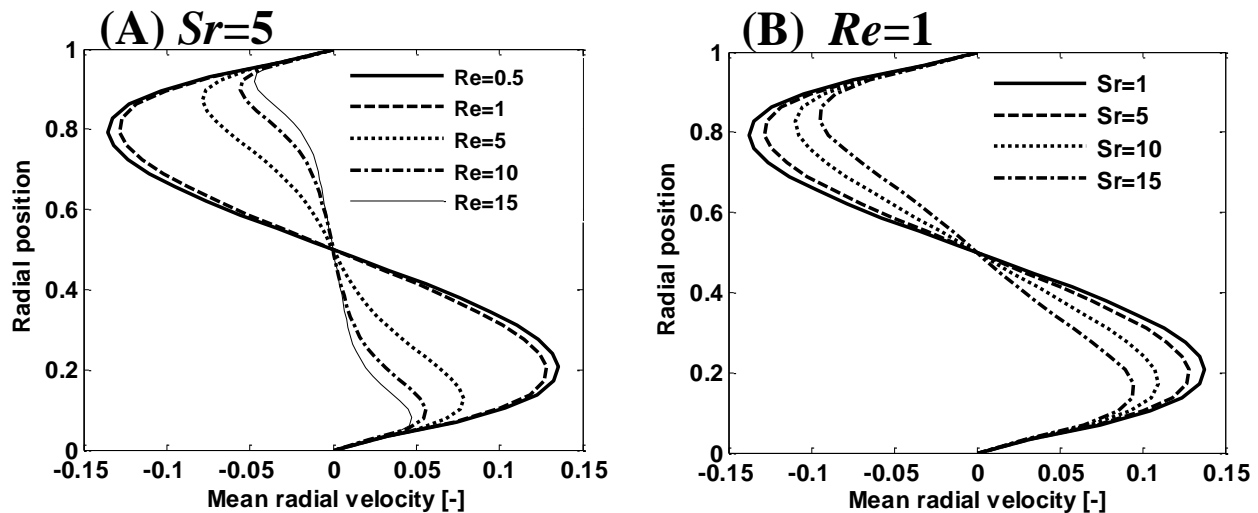
732 The velocity, the shear rate and the pressure were each averaged over half of the period of the cycle of
733 muscular contraction. The vector field shows the mean direction of flow of chyme during this time.

734 Two main types of flow regime were identified depending on the magnitude of Re and Sr (see text).

735 Arrows indicate transects location used for Fig. 4.

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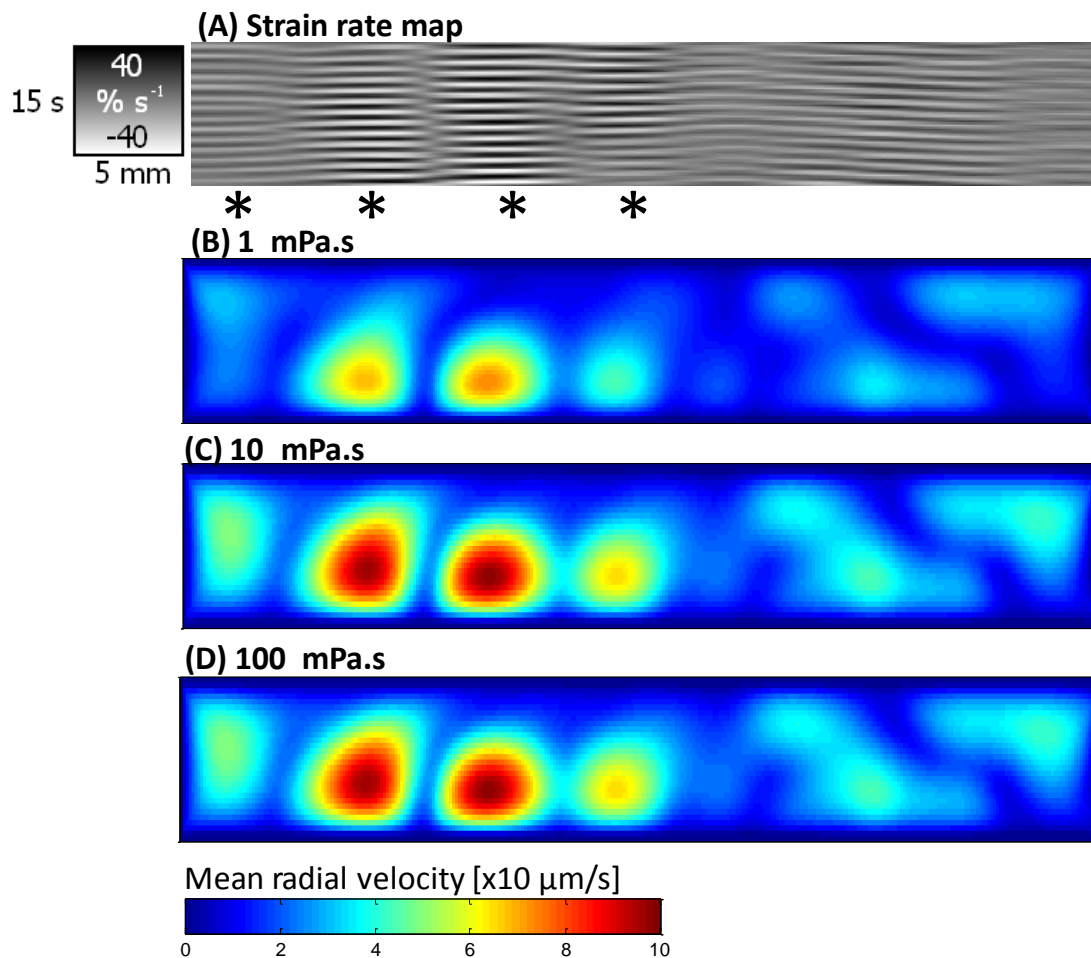
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747 **Figure 4: Influence of the Reynolds Re (A) and the Strouhal Sr (B) numbers on the dimensionless mean**
 748 **radial velocity at a transect through the gut obtained from the simplified model of pendular activity in**
 749 **the duodenum of the rat (BC1, Fig. 2) at $Sr=5$ and $Re=1$ respectively.**

750 The transect was located between adjacent vortices traversing the point where the radial component of
 751 velocity is the most developed (indicated by the arrows on Fig. 3). When either Re or Sr increase, the
 752 radial velocity profile becomes progressively less developed and more constrained to regions near the
 753 walls. Conversely at low Re and Sr , the radial velocity profile tends to an asymptotic solution (bold plain
 754 line).

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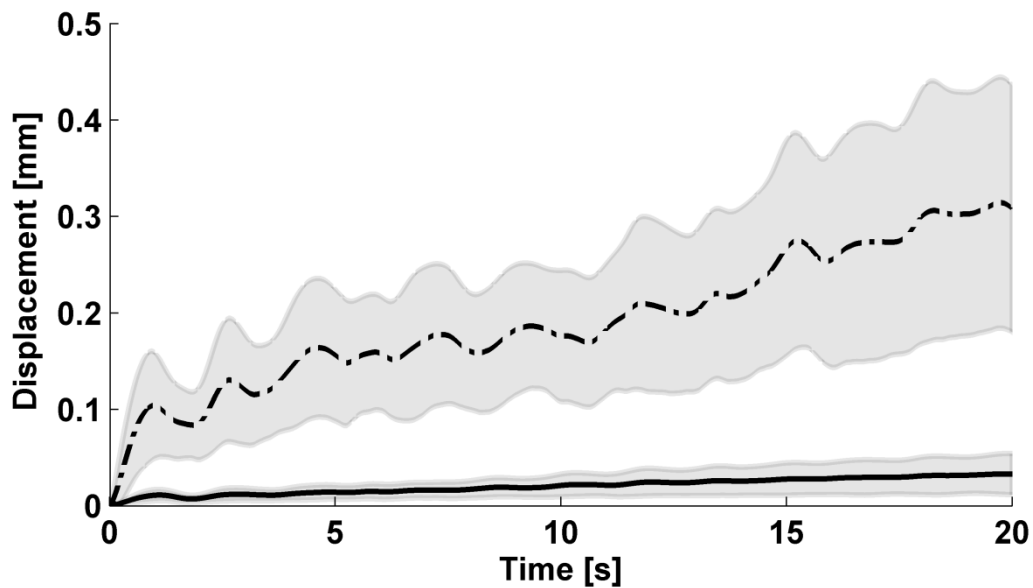
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759 **Figure 5: Results from modelling (BC2) of a 20 second period of spatiotemporally mapped pendular**
 760 **activity in the duodenum of the rat showing the effect of the viscosity of the luminal content on local**
 761 **radial velocity.**

762 The strain rates map (A) shows four active domains in the first 30 mm of the duodenum (*). The vertical
 763 direction corresponds to the time and the horizontal direction corresponds to the distance along the
 764 duodenum. The grey scale corresponds to the strain rate.

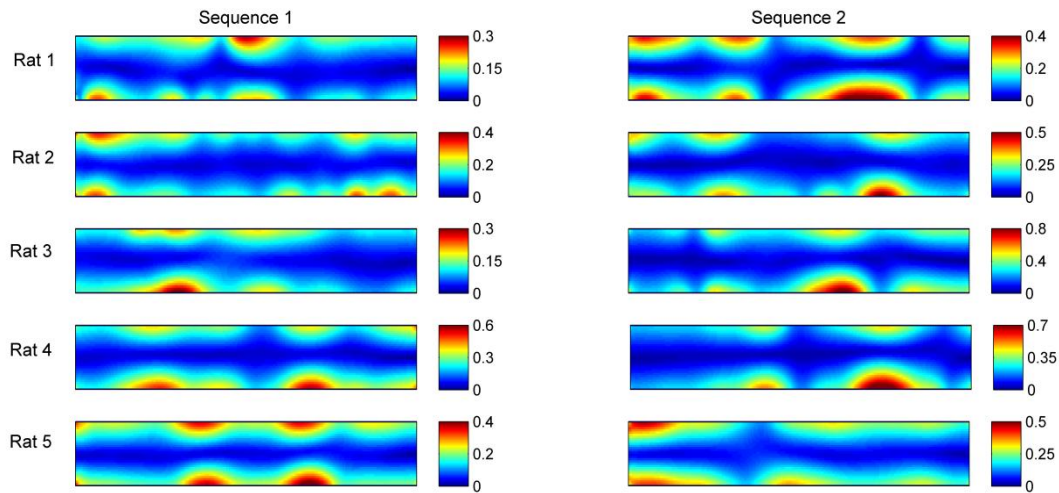
765 Absolute values of radial velocities at each location are averaged over 20 seconds and plotted as isovalue
 766 maps whose axes correspond to the axial and radial dimensions of the proximal duodenum (B, C and D).
 767 The domain of each longitudinal contraction corresponds to a zone of higher velocity. The zone is located
 768 nearer to the anti-mesenteric (lower) than the mesenteric wall as a result of radial asymmetry in the
 769 amplitude of longitudinal contractions. The flow is less developed at low viscosity (B) than at high
 770 viscosity (C and D).

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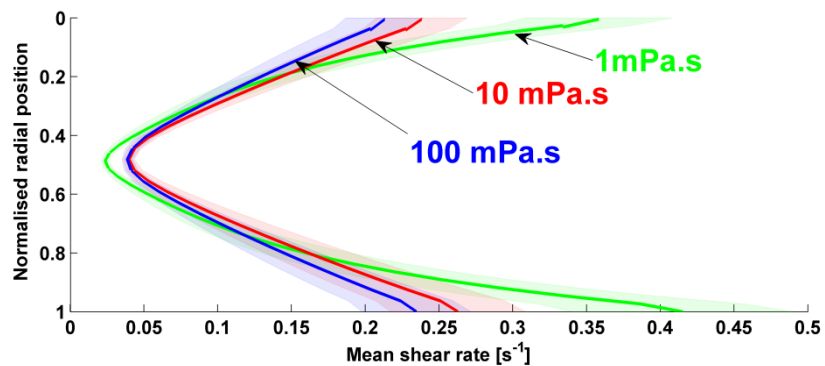
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780 **Figure 6: Results from modelling (BC2) of 20 second sequences of spatiotemporally mapped pendular**
781 **activity in the duodenum of the rat showing their effect on advection**
782 Cumulative mean radial (dashed line) and axial (plain line) displacements of small particles (5 rats x 2
783 sequences x 150 particles) over time resulting from flow advection with chyme viscosity at 1 mPa.s. The
784 limits of the shaded areas correspond to \pm standard deviation / 2.
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786 (a)



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788 (b)



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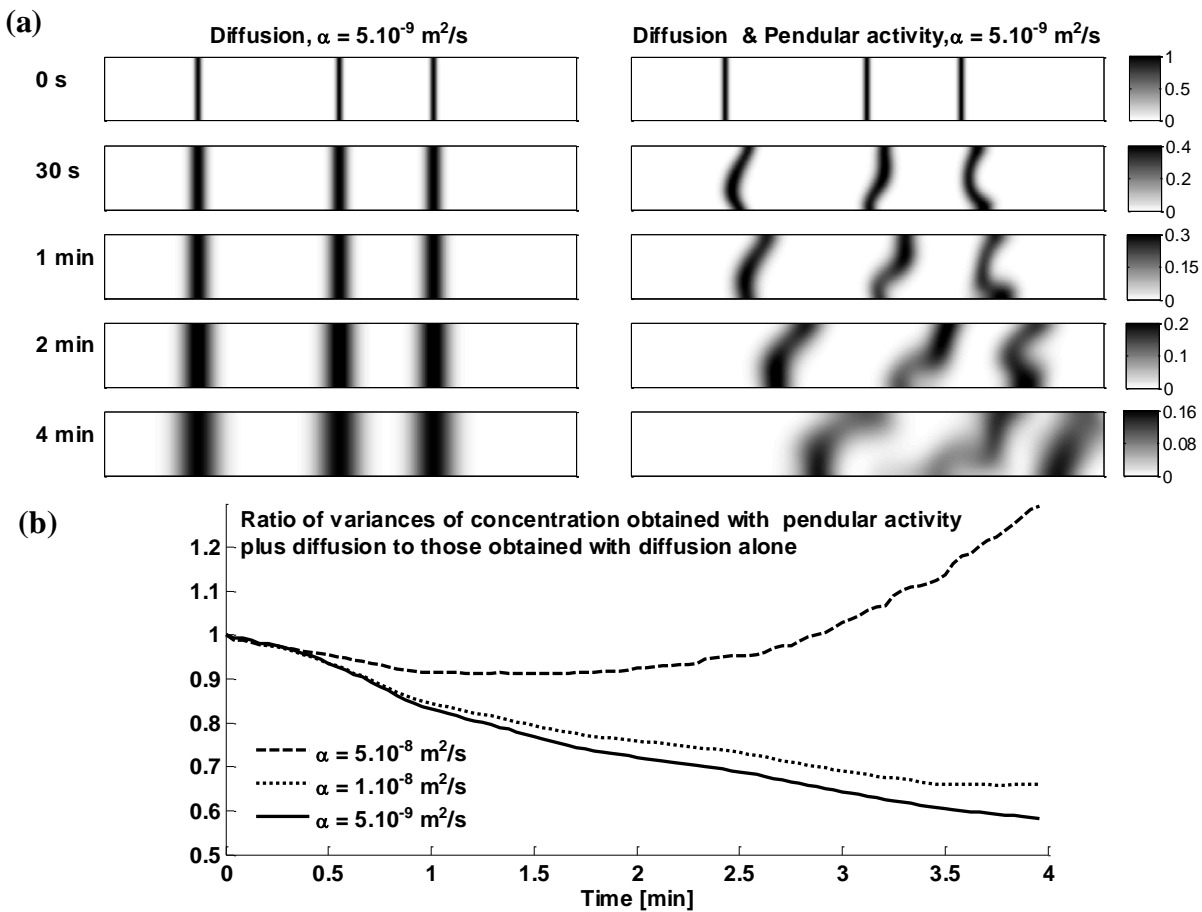
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791 **Figure 7: Results from modelling (BC2) of two 20 second sequences of spatiotemporally mapped**
 792 **pendular activity in the ex vivo duodenum of five rats showing variation in the spatial patterns of**
 793 **shear rate with the viscosity.**

794 (a) shows isovalues of shear rate for a viscosity of 10 mPa.s. The absolute value of the shear rate was
 795 averaged at each location over each 20 s time sequence to produce a map of isovalues whose axis
 796 represent the axial and radial dimensions of the proximal duodenum. The regions of highest shear rate
 797 are spaced between adjacent contractile domains and are localised near the walls (Fig. 2). The shear rate
 798 is radially asymmetric as a result of radial asymmetry of the longitudinal contractions.

799 (b) shows variation in distribution of shear rate across the radial dimension of the lumen with viscosity.
 800 For each rat and each sequence, the absolute value of the shear rate was first averaged in the axial
 801 direction of the duodenum and subsequently these means were averaged for all the rats and all the
 802 sequences (plain lines). The limits of the envelope curves correspond to \pm standard deviation /2.

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805 **Figure 8: Results from modelling (BC2) of 4 minute sequences of spatiotemporally mapped pendular**
 806 **activity in the ex vivo duodenum of a rat showing the influence of different diffusion coefficients α on**
 807 **mixing.**

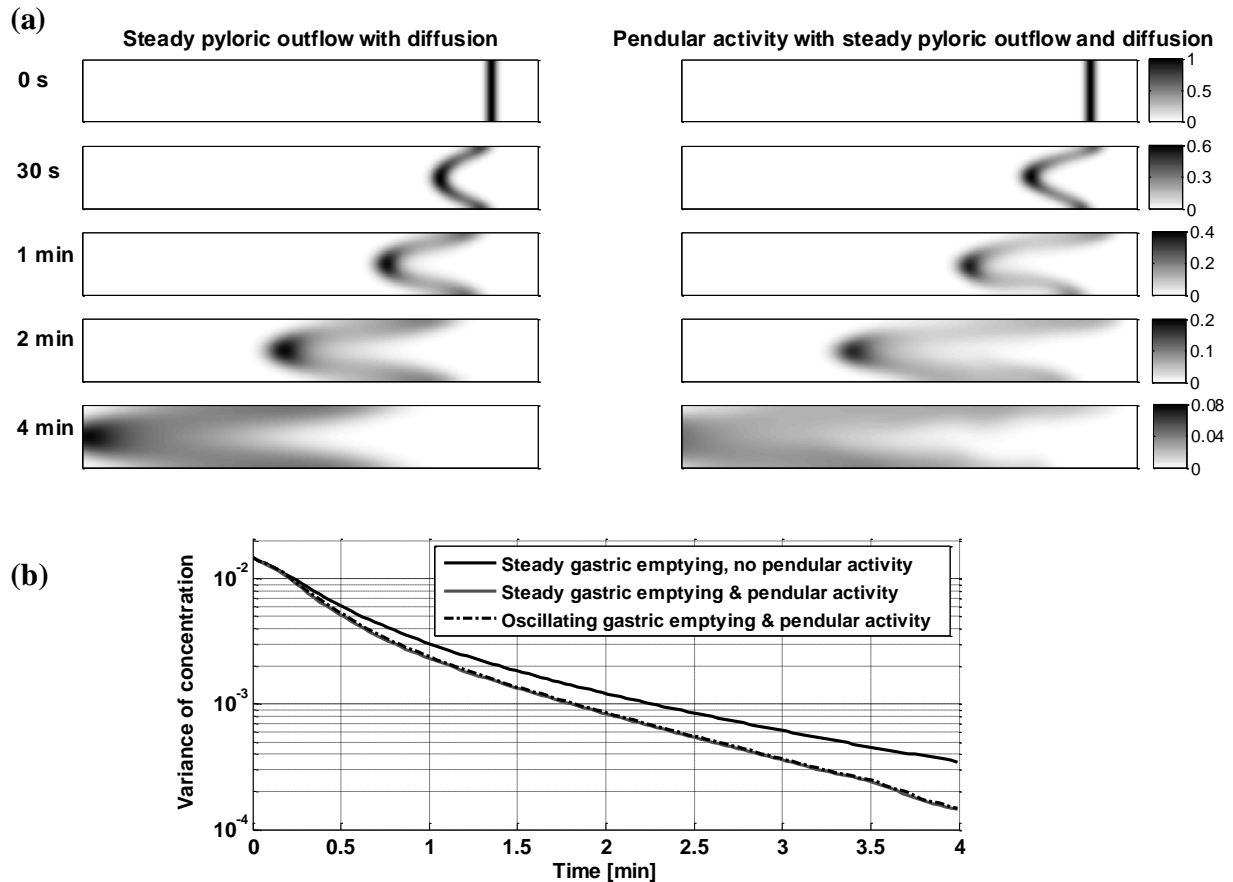
808 Three radially orientated lines of a diffusive tracer ($\alpha = 5.10^{-9} \text{ m}^2/\text{s}$) were placed between adjacent
 809 longitudinal contractile domains (see Methods).

810 (a) The evolution of the tracer during 4 minutes of pendular activity plus diffusion (right) is compared
 811 with the case where the process is purely diffusive (left). The shear generated during pendular activity
 812 deforms the chyme, increases the size of the interface between adjacent domains and accelerates
 813 diffusive mass transfer across the longitudinal dimension.

814 (b) Shows the temporal evolution of the ratio of the variances of concentration obtained with pendular
 815 activity plus diffusion to those obtained with diffusion alone using tracers with different diffusion
 816 coefficients α (see also Fig. A in Supplementary results).

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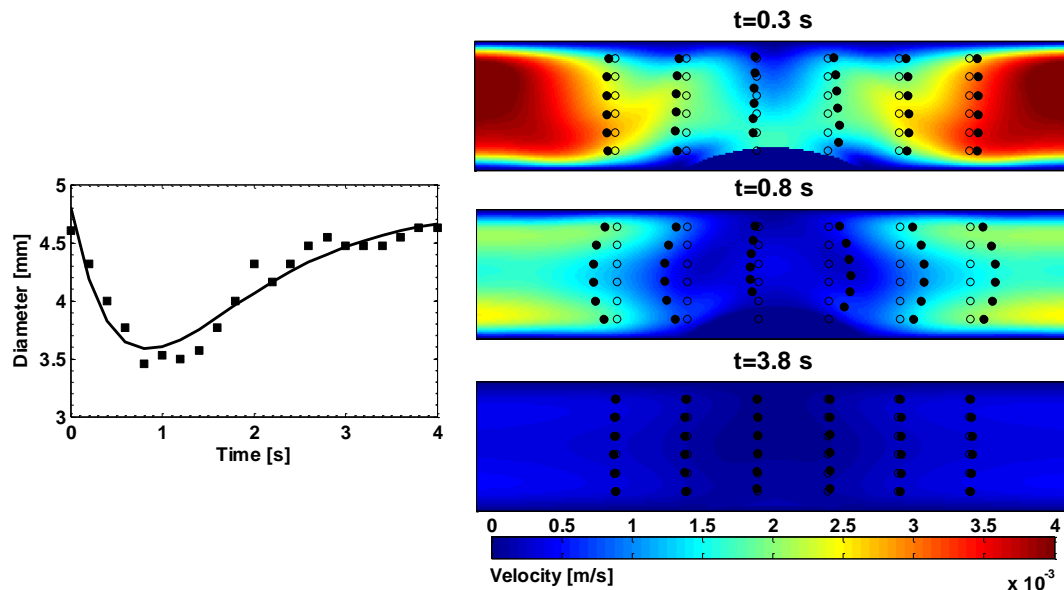
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823 **Figure 9: Results from modelling (BC2) of 4 minutes sequences of spatiotemporally mapped pendular**
824 **activity in the ex vivo duodenum of a rat associated with pyloric outflow and diffusion (see Methods)**
825 **showing the influence on longitudinal dispersion.**

826 A radially orientated line of a diffusive tracer ($\alpha = 5.10^{-9} \text{ m}^2/\text{s}$) was placed at the site of the pylorus.

827 (a) The evolution of the tracer during 4 minutes of pendular activity along with steady pyloric outflow
828 and diffusion (right) is compared with the case where the dispersion is governed by steady pyloric
829 outflow and diffusion with no pendular activity (left).

830 (b) Compares the temporal evolution of the variance of the concentration when a steady or oscillating
831 gastric outflow is associated with pendular activity and diffusion with the case where there is no
832 pendular activity.

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840 **Figure 10: Showing the influence of segmentation on the displacement of small particles in a model**
841 **incorporating spatiotemporally mapped sequences of segmental motility in the duodenum of the**
842 **guinea pig (BC3).**

843 Left panel: Temporal profile of change in the diameter at the centre of a region of segmental contraction
844 (■: experimental data from Lentle *et al.* (2012), plain line: Eq. 9)

845 Right panel: Plots of isovalues of velocity and displacement of small particles advected by the flow
846 (o: initial position, •: instantaneous position) at three different time points with viscosity of lumen
847 contents of 1 mPa.s.

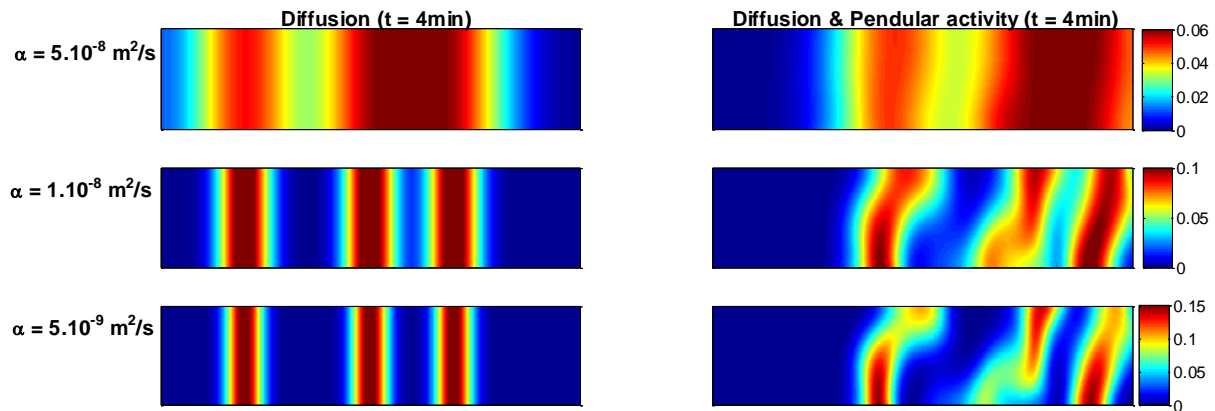
848 At the peak of the contraction (t=0.8 s), the particles undergo significant advection by the flow field, but
849 return to their initial position when relaxation is complete (t=3.8 s).

850 ($U_{max}=3.9$ mm/s; $a_1=0.85$ s; $D_0=4.8$ mm; $2l=8.6$ mm; $\mu=1$ mPa.s)

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852 **7. Supplementary results**

853



854 **Fig. A: Results from model (BC2) incorporating a 4 minute sequence of spatiotemporally mapped**
 855 **pendular activity in the duodenum of a rat showing their influence on the mixing of three tracers with**
 856 **different diffusion coefficients α .**

858 Three radially orientated lines of a diffusive tracer were placed between adjacent longitudinal contractile
 859 domains (see Methods & Fig. 8). The field of concentration after 4 minutes of pendular activity (right) is
 860 compared with the case where the process is purely diffusive (left) using three tracers with different
 861 diffusion coefficients. Pendular activity increases diffusive mass transfers when $\alpha < 1.10^{-8} \text{ m}^2/\text{s}$.

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