Feeding ground and pelleted hay rather than chopped hay to ponies
1. Consequences for in vivo digestibility and rate of passage of digesta

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Abstract

This study was designed to evaluate the effect of the physical form of a hay diet on total tract digestibility in ponies, with particular emphasis in fibre digestion and digesta passage rate. Ten gelded ponies (four of them fitted with cannulae in the cecum and the right-ventral colon) were kept on wood shavings and fed twice daily a maintenance diet of equal parts Lucerne and Cocksfoot hay. The hay was either chopped (CH) or ground (1.5 mm screen) and pelleted (GPH). The apparent total tract digestibility of dry matter (DM), organic matter (OM), and fibre fractions was measured in the six non-fistulated ponies using a crossover design. Two trials were conducted to measure mean retention time (MRT) of digesta in the whole digestive tract in four non-fistulated and four fistulated animals using rare earth labelled hay and Cr-EDTA as markers of the particles and solutes, respectively. In a third trial, MRTs in the hind gut and the colon, as well as in the entire tract, were determined in the fistulated ponies using various markers given by mouth and through the cannulae. OM and fibre digestibility were not significantly different ($P > 0.05$) between diets. However, particle ($P < 0.05$) and solute ($P < 0.001$) MRT were significantly longer on GPH compared to CH as a consequence of an increased retention in the colon. The longer MRTs with GPH did not significantly affect fibre digestibility. This implies a reduction in the rate of fibre degradation in the hindgut in the GPH fed animals. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Pony; Equine hindgut; Gastrointestinal passage rate; Hay processing; Fibre digestion

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1. Introduction

Expansion of riding activities has stimulated new ways of processing forages in order to solve feed transportation and storage problems, especially in urban areas. Modification of the physical form of hay, by grinding and pelleting, substantially reduces its bulkiness. Giving pelleted diets to horses has become very popular in France, as has bedding them on wood shavings instead of straw. However, there are few reports of studies of the effects of grinding and pelleting forages on the digestive efficiency and health in the horses when no other fibre source is available. Processing sometimes modifies the apparent digestibility of fibre, but results are contradictory (Haenlein et al., 1966; Hintz and Loy, 1966; Argenzio et al., 1974; Wolter et al., 1975; Schrug et al., 1978; Raina and Raghavan, 1985; Cymbaluk and Christensen, 1986; Cymbaluk, 1990; Tisserand and Faurie, 1995; Todd et al., 1995) mainly because experimental conditions vary, especially with respect to dry matter intake and particle size distribution in the ground hay.

It has been well established that the efficiency of dietary fibre utilisation by herbivores is correlated with three main factors:

1. the composition of the diet, especially the carbohydrate fraction (structural and non-structural fractions),
2. the fibre fermentation rate which can be estimated in situ with the nylon bag technique,
3. digesta rate of passage through the digestive tract, especially in the fermentation compartments, which is closely related to intake level and diet composition.

To properly determine the effect of physical form of hay on the subsequent efficiency of fibre utilisation, it is necessary to control experimental conditions, especially to prevent animals from eating any other fibre source.

In three experiments we have studied the ability of ponies to digest a diet of mixed Lucerne and Cocksfoot hay (50/50) given in two different physical forms, chopped or finely ground and pelleted. This paper reports the in vivo digestibility results and passage rate measurements through the entire digestive tract and its main compartments (the foregut, the cecum and the colon). The effects on other digestive parameters will be reported in a second paper (Drogoul et al., 2000).

2. Material and methods

2.1. Animals, management and diets

Ten crossbred gelded ponies (230 ± 50 kg average body weight) were used in this study. Four were fitted with cannula in the cecum and the right-ventral colon. The barrel of each cannula was 15 cm long and 2.25 cm internal diameter. At surgery, under general anaesthesia, a purse-string suture was applied to stabilise the cannula on the gut wall with the round flange inside. The cannula was maintained in place without any suture ring to press the tissue onto the internal flange. This technique (Tisserand et al., 1977 modified...
by Julliand and Faurie, unpublished technique) prevented adhesion of the gut wall to the abdominal wall and allowed more natural movement of the gut. Surgery was completed at least 10 months before the first experiment.

Indoor housing consisted of concrete-floored individual boxes. Ponies were kept on wood shavings, except during faecal collection periods. They were allowed unlimited access to fresh water and to trace mineralised salt blocks. The ponies were fed twice daily (8:00 h, 16:00 h) equal meals of mixed Lucerne hay and Cocksfoot hay (50/50). The hay was given either chopped (CH) or ground and pelleted (GPH). The hay was ground through a 1.5 mm screen and compressed into 3 mm diameter pellets. The particle size distributions of the diets were measured by wet-sieving using sieves with mesh openings 4, 2.5, 1.25, 0.8, 0.5, 0.25, 0.16 and 0.1 mm. Each animal was weighed on two consecutive days before each diet adaptation period and the CH diet was fed at maintenance energy level according to French recommendations (0.038-UFC/MBW, Martin-Rosset et al., 1994). The GPH diet was offered at the same dry matter intake as the CH diet.

2.2. Experiment 1: in vivo digestibility and passage rate on non-fistulated ponies

For the digestibility trial, six non-fistulated ponies were used in a crossover design (2 diets × 2 periods × 3 animals/diet). All animals were randomly assigned to diet. Each experimental period consisted of 21 days for diet adaptation in individual boxes, 9 days for digestibility measurement in crates, and 9 days for passage rate measurement in tie-stalls on rubber mats. Only four of the ponies were used for the passage rate measurements, but all of them were tethered in stalls until the experimental period ended.

The apparent total digestibility of dry matter (DM), organic matter (OM), crude protein (CP), neutral-detergent fibre (NDF) and acid-detergent fibre (ADF) was measured. A total collection of faeces was made using metabolic crates designed to separate faeces and urine. Faeces were collected on plastic-lined trays. The ponies were placed in the crates for 3 days prior to starting the faecal collection. The amount of feed offered and refused, and the total amount of faeces excreted was measured for every 24 h (at 8:00 h prior to feeding) during 6 successive days. Aliquots of faeces (10% of fresh matter), the diet offered and refusals, if any, were taken daily and dried at 65°C in a forced-air oven to constant weight. The daily samples of feed, refusals and faeces were composited for the total collection period. These composite samples were ground through a 1 mm screen before analysis. Ash content was determined after incineration for 6 h at 550 ± 10°C. NDF and ADF were determined using the procedure of Van Soest and Wine (1967). CP was determined using a semi-automated micro-Kjeldahl method. All analyses were performed in triplicate. Apparent digestibility data were calculated from total dry matter intakes and faecal dry matter outputs over the 6 days collection periods.

Following the digestibility trial, 4 ponies (2 on each diet) were used to study the rate of passage of digesta markers through the gastrointestinal tract. Animals were tethered individually, next to each other, in tie-stalls on rubber mats, in order to make frequent faecal collections. They had two days to adapt before passage measurements started. The
indigestible markers used to determine the mean retention time (MRT) in the whole digestive tract were: Yb-labelled hay, as the particle marker, and Cr-EDTA solution (Binnerts et al., 1968), as the solute marker. A single dose of labelled hay (60 g) was given to each pony mixed with one third of its morning meal. After 1 h the refusals, if any, were removed. Just after labelled meal ingestion, each pony was immediately given 120 ml of Cr-EDTA solution via a stomach tube. The rest of the meal was then given and the rubber mats cleaned of faeces. The immediate resumption of the meal was required to indicate that the procedures had not significantly disturbed the animals. For each pony, excreted faeces were collected at 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 27, 30, 33, 36, 40, 46, 52, 58, 64, 72, 84, 96, 108, 120, 144, and 168 h after the start of the labelled meal. For each time interval, faeces were weighed, mixed and an aliquot sample (300 g of fresh matter) taken for DM and marker determination. Cr and Yb were solubilised for each sample in duplicate according to Christian and Coop (1954) as modified by Siddons et al. (1985). The Cr and Yb contents of samples were determined using an electrothermal atomic absorption spectrophotometer (SpectrAA 300 Zeeman VARIAN — 91941 Les Ulis, France) with wavelength set at 398.8 nm for Yb and 357.9 nm for Cr. All spectrophotometer analyses were performed in duplicate.

MRT in the whole digestive tract was calculated (Faichney, 1975) as

\[
\text{MRT} = \frac{\sum M_i t_i}{\sum M_i}
\]

where \( t_i \) is the time elapsed between the introduction of the markers (time zero) and the middle of the \( i \)th collection interval and calculated as \( \frac{1}{2} (t_i + t_{i-1}) \) (\( t_i \) being the time to the end of the \( i \)th interval), \( M_i \) is the amount of marker excreted in the \( i \)th interval and all marker has been excreted by the \( n \)th interval.

The labelled hays used in this trial were the same as those given to the ponies as feeds. They were labelled by first washing them in a domestic washing machine (60°C for 45 min) using a commercial washing detergent (without EDTA, Gama™ Colgate Palmolive, 92401 Courbevoie Cedex, France), then by soaking in an YbCl3 solution (40 mg of Yb/g of hay DM, pH 2.5) for 24 h. After soaking, the unbound or weakly bound marker was eliminated by soaking the labelled hays in a large volume of tap water (1 h) followed by washing under running tap water (5 min). This soaking–rinsing procedure was repeated three times. The marked hays were then dried (24 h at 65°C). As the pellets were dispersed during the labelling procedures, ground labelled hay had to be pelleted again before incorporating in the meal. In order to prevent the loss of particles, chopped and ground hay were placed in nylon bags (Blutex™ T120 with pores of 46 μm) during all the washing and rinsing procedures.

2.3. Experiment 2: passage rate in the whole digestive tract of fistulated ponies

The four fistulated ponies were used in a crossover design (2 diets × 2 periods × 2 animals/diet). All animals were randomly assigned to diet. Each experimental period consisted of 3 weeks for diet adaptation in individual boxes, 6 weeks for digestive parameter measurements (reported in Drogoul et al., 2000) and 9 days for rate of passage measurements using the procedure described in Experiment 1.
2.4. Experiment 3: passage rate in different sections of the gastrointestinal tract

In order to aid the interpretation of results from the first two experiments, a third one was conducted to study the rate of passage of digesta markers through the colon, the hind gut (cecum + colon) and the whole digestive tract. This trial was conducted with the four fistulated ponies in a crossover design (2 periods × 2 diets × 2 ponies/diet). All animals were randomly assigned to diet. Each experimental period consisted of 3 weeks for diet adaptation in individual boxes, 5 weeks for cecal fluid volume measurements (reported in Drogoul et al., 2000) and 9 days for rate of passage measurements. Five indigestible markers were used:

- Europium (Eu) bound to fed hay as a particle marker to estimate MRT in the whole digestive tract as in Experiment 1.
- Cr-EDTA and Cobalt (Co)-EDTA, introduced manually through the cannula as solute in the cecum (Cr) or in the colon (Co), to estimate solute MRT in the hindgut (cecum + colon) and the colon, respectively.
- Yb and Thulium (Tm) bound to faecal particles, introduced manually through the cannula, as particles markers for MRT measurements, respectively, the hind gut and the colon.

Faecal particles to be labelled were collected during the in vivo digestibility trials for each diet. Labelling of hay and faecal particles and procedures for total sequential collection of faeces were as described in Experiment 1.

The delays between the oral dose of Eu-labelled hay and the manual introduction of markers in the cecum or the right-ventral colon were determined in a previous experiment, as the time to reach a peak Yb concentration in each compartment when a single dose of Yb bound to chopped or ground and pelleted hay particles was given to the same ponies fed the CH or GPH diet, respectively. For the CH diet, particle and solute markers were introduced simultaneously, into the cecum and the colon at 2.5 and 3.5 h, respectively, after the labelled meal intake. For GPH diet, the delays were 3 and 4 h, respectively.

Marker MRTs were calculated from their excretion curves in the faeces according to Experiment 1. MRTs in the foregut and the cecum were calculated by difference:

- particle MRT from mouth to cecum = Eu-MRT − Yb-MRT,
- particle MRT through the cecum = Yb-MRT − Tm-MRT,
- solute MRT through the cecum = Cr-MRT − Co-MRT.

2.5. Data treatments and statistical analysis

All statistical analysis were performed using the Statistical Analysis System (SAS) (SAS/STAT, 1998).

Digestibility data were analysed using the general linear model (procGLM) of SAS where classification factors were animal (6 levels) and diet (2 levels), and considering the animal factor as a random effect. Means were compared using the Student t test.
Retention time data were analysed using the same model with the classification factors: animal (4 levels), diet (2 levels) and digesta phase (2 levels).

3. Results

No statistically \((P > 0.1)\) significant interactions between diets or digestive compartments were observed for any of the parameters studied.

3.1. Diet characteristics, intake and live weight changes

The chemical composition of CH and GPH is shown in Table 1. Grinding and pelleting slightly, but not significantly \((P > 0.1)\) altered the chemical composition of the hay; the exception was ADF content \((P < 0.01)\). The chemical composition of the GPH was constant during all the experiments, because the same hay was used for preparing the total amount of GPH needed. CH chemical composition varied slightly according to hay supply, but the variability remained low for most components, except NDF (Table 1). The particle size distribution of CH and GPH is shown in Table 1. 84% of GPH particles were able to pass the 0.8 mm sieve, while 78% of CH particles were retained on sieves > 0.8 mm. CH was chopped to 3 cm and very few particles exceeded this size length. Chopping of the hay, combined with deep feeding troughs, minimised spillage of CH. No GPH refusals were observed. Dry matter intake remained the same for the two diets, throughout the experiment (Table 2) as intended, and individual body weights remained unchanged (standard deviation of each pony’s live body weight, never exceeded 5% of mean live body weight).

Table 1
Chemical composition and particle size distribution of chopped hay (CH) or ground and pelleted hay (GPH)\(^a\)

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>CH (g/kg DM (SD))</th>
<th>GPH (g/kg DM (SD))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>93 (8) a</td>
<td>102 (3) a</td>
</tr>
<tr>
<td>Organic matter</td>
<td>907 (8) a</td>
<td>898 (3) a</td>
</tr>
<tr>
<td>Crude protein</td>
<td>155 (15) a</td>
<td>159 (4) a</td>
</tr>
<tr>
<td>Neutral detergent fibre</td>
<td>629 (46) a</td>
<td>589 (10) a</td>
</tr>
<tr>
<td>Acid detergent fibre</td>
<td>409 (15) a</td>
<td>356 (6) b</td>
</tr>
</tbody>
</table>

Sieve mesh sizes (mm)  Percent proportion of DM retained on sieve

<table>
<thead>
<tr>
<th></th>
<th>CH</th>
<th>GPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4</td>
<td>22.4 a</td>
<td>0.0 b</td>
</tr>
<tr>
<td>4–2.5</td>
<td>6.8 a</td>
<td>2.3 b</td>
</tr>
<tr>
<td>2.5–1.25</td>
<td>32.0 a</td>
<td>5.7 b</td>
</tr>
<tr>
<td>1.25–0.8</td>
<td>16.3 a</td>
<td>8.1 b</td>
</tr>
<tr>
<td>0.8–0.50</td>
<td>9.2 a</td>
<td>16.4 b</td>
</tr>
<tr>
<td>0.50–0.25</td>
<td>10.4 a</td>
<td>28.9 b</td>
</tr>
<tr>
<td>0.25–0.16</td>
<td>1.6 a</td>
<td>11.8 b</td>
</tr>
<tr>
<td>0.16–0.10</td>
<td>0.8 a</td>
<td>9.6 b</td>
</tr>
<tr>
<td>&lt;0.10</td>
<td>0.5 a</td>
<td>17.2 b</td>
</tr>
</tbody>
</table>

\(^a\) Values in the same row with different letters differed significantly at \(P < 0.01\) (Student \(t\) test).
3.2. Apparent digestibility of diets (Experiment 1)

The apparent digestibility of the main components of the experimental diets is shown in Table 2. None of the differences observed between diets were statistically significant.

3.3. Rate of passage of solute and particles markers in the whole digestive tract and its main segments

Average recovery rates of markers were always above 94% of the dose over the 7 days collection periods and no marker was excreted beyond the sampling period.

3.4. Experiments 1 and 2

The MRTs of both Cr-EDTA and Yb in the whole tract of non-fistulated and fistulated ponies (Experiments 1 and 2) are shown in Table 3. The cumulative excretion curves of both markers are shown in Figs. 1 and 2.

When ponies were fed GPH compared to CH, individual variability was greater for all animals, especially for the MRT of the particle marker (Yb). In both types of animals, MRT was longer for Yb than for Cr-EDTA in ponies fed CH.

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Table 2
Apparent digestibility (standard deviation) of dry matter and its main components in ponies given chopped (CH) or ground and pelleted (GPH) hay at the same level of intakea

<table>
<thead>
<tr>
<th>Component</th>
<th>CH</th>
<th>GPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter</td>
<td>51.4 (1.8) a</td>
<td>53.8 (2.2) a</td>
</tr>
<tr>
<td>Organic matter</td>
<td>52.1 (2.0) a</td>
<td>55.2 (2.6) a</td>
</tr>
<tr>
<td>Neutral detergent fibre</td>
<td>44.2 (3.9) a</td>
<td>47.0 (3.7) a</td>
</tr>
<tr>
<td>Acid detergent fibre</td>
<td>39.6 (4.6) a</td>
<td>39.6 (3.2) a</td>
</tr>
<tr>
<td>Crude protein</td>
<td>72.6 (1.7) a</td>
<td>71.5 (1.0) a</td>
</tr>
<tr>
<td>DM intake (kg/100 kg of live body weight)</td>
<td>1.7 (0.1) a</td>
<td>1.7 (0.2) a</td>
</tr>
</tbody>
</table>

a Values in the same row with different letters differed significantly at $P < 0.01$ (Student $t$ test).

Table 3
Total tract MRT (h) in non-fistulated (Experiment 1) and fistulated (Experiment 2) ponies given either chopped (CH) or ground and pelleted (GPH) hay using Cr-EDTA as a solute marker and Yb as a particle marker

<table>
<thead>
<tr>
<th></th>
<th>Cr-EDTA</th>
<th>Yb</th>
<th>Statistical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH</td>
<td>GPH</td>
<td>CH</td>
</tr>
<tr>
<td>Cr-EDTA Yb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-fistulated</td>
<td>27.7</td>
<td>43.1</td>
<td>46.7</td>
</tr>
<tr>
<td>Fistulated</td>
<td>23.4</td>
<td>47.7</td>
<td>37.2</td>
</tr>
</tbody>
</table>

a NS: not significant ($P > 0.1$); +: ($P < 0.1$); * ($P < 0.05$); ** ($P < 0.01$); *** ($P < 0.001$).
Solute were retained 56 and 104% longer in the non-fistulated and fistulated ponies on diet GPH ($P < 0.001$), respectively; particles were retained only 12 and 27% longer ($P < 0.05$). The MRT ratio Yb/Cr-EDTA, which measures the preferential retention of Yb, was 1.7 and 1.6 for, respectively, the non-fistulated and fistulated ponies on diet CH, but only 1.2 and 1.0 for diet GPH. Thus grinding the hay virtually eliminated the

Fig. 1. Non-fistulated animals.

Fig. 2. Fistulated animals.
preferential retention of particle marker in both groups of ponies, even if this effect is less
pronounced in fistulated ponies. However, these difference could not be attributed solely
to fistulation, because it had not be obtained in the same ponies before and after
fistulation.

3.5. Experiment 3

MRTs in the whole tract or in its main segments for particle (Yb, Eu and Tm) and
solute markers (Cr- and Co-EDTA) measured directly or calculated by difference, are
summarised in Table 4.

For both diets, MRT of particles in the colon represented at least 80% of their MRT in
the entire gut. A similar response to the physical form of hay was observed in this trial
compared with Experiment 2: grinding and pelleting the hay increased MRT of particles
in the entire tract. This was due to a 13 h (36%) increased retention in the colon
\[ (P < 0.001) \] which was much greater than the 3.3 h decrease in the cecum \[ (P < 0.001) \],
plus the 1.6 h decrease proximal to the cecum \[ (P < 0.01) \].

The MRT ratio Yb/Cr-EDTA (preferential retention of Yb) was 1.4 h on CH, but only
1.1 h on GPH in the colon, whereas it fell from 2.5 to 0.8 h in the cecum, confirming
the virtual elimination of preferential retention of Yb by grinding, observed in Experiment 2.

4. Discussion

4.1. Apparent digestibility of diets (Experiment 1)

Our results showed that the physical form of hay had no statistical \[ (P > 0.1) \] influence
on total tract digestibility of the main components of the hay, especially of the cell-wall
fraction. These results are in agreement with several published data from experiments

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Table 4

Total and partial tract MRTs (h) in fistulated ponies \( (n = 4) \) given chopped (CH) or ground and pelleted (GPH) hay using different particle markers (Eu, Yb and Tm) and solute markers (Cr- and Co-EDTA) introduced into different compartments of the digestive tract (Experiment 3)

<table>
<thead>
<tr>
<th>Diet Statistical analysis</th>
<th>CH</th>
<th>GPH</th>
<th>SEM</th>
<th>Diet effect</th>
<th>Marker effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solute</td>
<td>Particle</td>
<td>Solute</td>
<td>Particle</td>
<td>Solute</td>
</tr>
<tr>
<td><strong>(a) Direct measurements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole digestive tract (Yb)</td>
<td>ND</td>
<td>42.2</td>
<td>ND</td>
<td>50.4</td>
<td>1.41</td>
</tr>
<tr>
<td>Hindgut (Cr, Eu)</td>
<td>26.9</td>
<td>38.6</td>
<td>45.5</td>
<td>48.4</td>
<td>1.52</td>
</tr>
<tr>
<td>Colon (Co, Tm)</td>
<td>24.9</td>
<td>33.7</td>
<td>43.6</td>
<td>46.8</td>
<td>1.59</td>
</tr>
<tr>
<td><strong>(b) By difference calculation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ante cecal fraction</td>
<td>ND</td>
<td>3.6</td>
<td>ND</td>
<td>2.0</td>
<td>0.40</td>
</tr>
<tr>
<td>Cecum</td>
<td>2.0</td>
<td>4.9</td>
<td>1.9</td>
<td>1.6</td>
<td>0.50</td>
</tr>
</tbody>
</table>

\[ a \text{ NS: not significant } (P > 0.1) \]; \[ + : (P < 0.1) \]; \[ * (P < 0.05) \]; \[ ** (P < 0.01) \]; \[ *** (P < 0.001) \].
where intake of ground hay was adjusted to that observed with the control (CH) diet (Wolter et al., 1975; Tisserand and Faurie, 1995; Todd et al., 1995). Indeed, in ad libitum feeding conditions, experiments testing the effect of grinding forages in horses, concluded that digestion of fibre in ground and pelleted feeds was reduced as voluntary DM intake was increased (Schrug et al., 1978; Todd et al., 1995). Digestibility coefficients of CH reported here agreed with previous results from our laboratory with the same mixture of Lucerne/Cocksfoot hay (Drogoul et al., 1988; Julliand et al., 1992; Tisserand and Faurie, 1995) and with some other studies using similar diets (Cymbaluk and Christensen, 1986; Cymbaluk, 1990).

4.2. Passage rate in the whole digestive tract and its main segments (Experiments 1–3)

4.2.1. MRT in the whole digestive tract

The particle MRT values estimated here using rare earth markers in ponies fed CH were close to those reported for Cr-mordanted hay in Shetland ponies fed chopped forages equivalent to the hay fed in this trial (Cuddeford et al., 1995; Yodder et al., 1997) at similar feed intake.

Our finding that feeding ground and pelleted hay rather than chopped hay (at similar feed intake) increased marker MRT in the pony, is not consistent with some results previously reported in horses (Hintz and Loy, 1966; Wolter et al., 1974) and ruminants (Haenlein et al., 1966; Journet and Demarquilly, 1967; Shaver et al., 1986; de Vega et al., 1992; Mambrini and Peyraud, 1997). Nevertheless, it agrees with others in ruminants (Faichney, 1983) or in rabbits (Gidenne et al., 1990; Gidenne, 1992; Gidenne and Perez, 1996). It is a constant feature of our results that agrees with a previous study from our laboratory with donkeys fed chopped or ground pelleted straw (Ouedraougo, 1998).

However, the comparison of results from different experiments in equids (or in ruminants) is difficult because experimental conditions are often very different (intake levels, particle size distribution of ground material which is rarely indicated, methods of measurement). Most of the differences observed between studies are of methodological origin (nature of markers, labelling technique, data modelling). Compared with hay particles that markers are supposed to mimic, the Styrofoam particles used by Hintz and Loy (1966) differed in specific gravity. Coloured beads used by Wolter et al. (1974) differed in size. Chromic oxide used by Van der Noot et al. (1967) cannot be considered to specifically associate with any phase of digesta. In contrast, mordanted or rare earth labelled fibres, used in all the recent studies, whose characteristics do not greatly differ from that of unlabelled ones, are considered to associate almost exclusively with particles and have probably the same behaviour in the digestive tract; Co-EDTA and Cr-EDTA remain largely in solution in the liquid phase of digesta.

4.2.2. MRT in main segments of the digestive tract

Our observations on the MRT of particles and solutes in different parts of the gastrointestinal tract (Table 4) are in agreement with those of Argenzio et al. (1974), Sellers et al. (1982) and Sperber et al. (1992). These results suggest a possible explanation for variations in passage rates of the two markers when animals were fed CH or GPH. There was a strong selective retention of particle markers relative to solute
markers with CH. The difference (19 and 14 h in non-fistulated and fistulated ponies, respectively) is about twice the difference predicted from the results of Argenzio et al. (1974), which, in turn, were much higher than the differences reported by Uden et al. (1982) and Orton et al. (1985). Two selective retention phenomena take place in the hindgut (see Fig. 3). On one hand, the cecum (Sellers et al., 1982), the ventral colon (Dellow, 1982, cited by Hume and Sakagushi, 1991) and the ventral–dorsal colonic junction (Argenzio et al., 1974) are the major barriers to the flow of coarse particles (longer than 1 cm) outflow. Indeed, our results showed that MRT of hay particles was longer in the cecum with CH compared to GPH. On the other hand, some mechanism, at the boundary of the dorsal and the distal colon, preferentially retains fluid and smaller particles (below 2 mm) compared to coarse particulate matter (Sperber et al., 1992). This latter mechanism, known as the “Colonic Separation Mechanism” (CSM) has been found previously in many herbivores, especially in small species such as rabbits, lemmings and guinea pigs (Björnhag, 1989).

The difference between particle and solute retention times retention times disappeared in fistulated ponies fed the GPH diet (Tables 3 and 4). Thus solute and particle in the digestive tract of ponies given GPH may flow through the entire gut as homogeneous digesta. Indeed results from Experiment 3 showed that in the two compartments where selection may operate (the cecum and the colon) the MRTs of both markers were similar with fine grinding. Thus the treatment virtually eliminated the discrimination between particles and solutes. The smaller the particles, the higher the ratio of bound/free water would be, and the more homogeneous the digesta consistency would be.

In the study reported here, 92% of GPH particles passed a 1.25 mm sieve, so that the particles size spectrum was probably low enough for the CSM to occur. This may explain the fact that, when GPH was fed, the rate of passage of both particles and solutes was

![Fig. 3. Location of main selective retention phenomena in the hindgut of equids.](image-url)
reduced and became similar. Another hypothesis to explain the increase in MRT of digesta when ponies were fed GPH, is that fine grinding, as in ruminants, may have impaired gut motility (Baumont et al., 1990). In contrast, the retention mechanism of coarse particles in the ventral colon (Fig. 3) may have been quite efficient when the animals were fed CH, and may explain the differential passage rate of the two markers observed with this diet in all animals.

4.2.3. Fistulation effect on digestive passage rate in the hindgut

Our results for markers passage rates in the entire gut (Experiments 1 and 2, Table 3) showed a difference between fistulated and non-fistulated animals. However, MRT of particles in the entire gut obtained with fistulated animals (Experiment 3, Table 4) were similar to those obtained with non-fistulated animals (Experiment 1, Table 3). One must be careful when comparing results in Table 3. Indeed, the three experiments were undertaken at different times. In addition, the number of animals was small ($n = 4$) and individual variability was substantial.

Due to the location of the cannula in the right-ventral part of the colon, fistulation might have reduced the ability of the ventral colon to selectively retain coarse particles when the CH diet is fed, as a consequence of lack of motility of this proximal portion of the colon as suggested by Pulse et al. (1973). In contrast, the “CSM” (Sperber et al., 1992) concerning the small particles and the liquid could have been less disturbed; this may help to explain why differences between fistulated and non-fistulated animals were not observed when ponies were fed GPH.

5. Conclusion

In this work, feeding ground and pelleted hay instead of chopped hay, a same amount of DM intake (1.7 kg/100 kg BW), did not significantly alter apparent digestibility of fibre in the pony, whereas it did significantly increase retention time, especially in the colon, compared to chopped hay. These results suggest that the expected increase in digestibility as a result of an increase in both particle MRT and particle area in contact with enzymes, may be offset by a decrease in the rate of the cell-wall degradation rate in the hindgut. Further investigations are needed to give information on the effect of forage physical form on cellulolytic activity in the equids digestive ecosystem. These results are presented in a companion paper (Drogoul et al., 2000).

However, in this trial, the hay was finely ground and its consumption by the ponies was restricted. These responses of the digestive tract of horses to physical form of forage need to be confirmed with commercial available ground and pelleted feeds and with different feeding levels

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