Prediction of digestibility of organic matter and energy in the growing pig from an in vitro method

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Abstract

The method of Boisen and Fernandez [Boisen, S., Fernandez, J.A., 1997. Prediction of total tract digestibility of energy in feedstuffs and pig diets by in vitro analyses, Anim. Feed Sci. Technol. 68, 277–286] for measuring in vitro fecal digestibility of organic matter (OMdv) or in vitro digestible organic matter content (DOMv, g/kg) was used on 113 compound feeds (79 as mash and 34 as pellets) and 66 ingredients (as mash) whose digestibility of organic matter (OMd) and energy (Ed) and digestible energy content (DE, MJ/kg) had been measured in 60 kg growing pigs for all compound feeds and ingredients, and in adult sows for about 2/3 of the compound feeds (as mash); net energy (NE, MJ/kg) of these feeds were estimated from digestibility information. The repeatability and accuracy of the method were evaluated. Data obtained on compound feeds fed as mash were used to establish prediction equations of OMd, Ed, DE NE from OMdv or DOMv and chemical criteria. The levels of accuracy and repeatability of OMdv measurement were satisfactory and values for OMdv and OMd of mash compound feeds were very close and highly correlated ($r = 0.91$). Apart from OMdv, the best prediction equations of OMd or Ed included ash content and a cell wall criterion (ADF or crude fiber); for prediction of DE, fat content had also to be considered. The coefficient of variation of all equations was below 0.02. The equations allow a satisfactory prediction of OMd, Ed or DE of the 66 ingredients fed as mash. However, the equations established on data obtained on mash feeds underestimate the

Abbreviations: DM, dry matter; DE, digestible energy; NE, net energy; OM, organic matter; OMd, organic matter digestibility; Ed, energy digestibility; OMdv, in vitro organic matter digestibility; DOMv, in vitro digestible organic matter; OMdp, predicted OMd; Edp, predicted Ed; DEp, predicted DE content

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**1. Introduction**

The determination of energy value of pig feeds is principally based on their digestible energy content (DE), that value being used for estimation of metabolizable (ME) or net (NE) energy values (Noblet and van Milgen, 2004). This can be measured directly by collecting the excreta of the animals but this method is relatively complex, expensive and needs several weeks for obtaining the results. However, it has to be used as a reference method. A second solution for estimating DE value in the case of ingredients or compound feeds for which the ingredients composition is available is to utilize the average DE contents from feeding tables (INRA and AFZ, 2004). Even though this solution is sufficient in many cases, it cannot consider the variability in chemical composition of ingredients nor apply to compound feeds for which ingredients composition is unknown. In that case, the DE value can be estimated directly from parameters accessible on the feeds (i.e., chemical characteristics) according to regression equations (Noblet and Perez, 1993; Le Goff and Noblet, 2001). However, this approach is limited by the accuracy of the analytical methods and the delay necessary to realize the analyses and also the restrictions to apply the equations. These considerations led to look an assessment of methods for fast estimation of DE content.

Among these rapid methods, the near infrared techniques are adapted to the estimation of simple chemical characters such as moisture, nitrogen, amino acids and fat contents (Bertrand, 2002). The application for prediction of the nutritional value of pig feeds remains difficult, the main problem being the high number of reference samples (i.e. with available in vivo values) for calibration (Aufrère et al., 1996; Van Barneveld et al., 1999). The in vitro techniques that mimic the digestion can also be considered as rapid methods with either an inoculum prepared from pig digestive contents (Furuya et al., 1979; Löwgren et al., 1989) or enzymatic preparations (Van der Meer and Perez, 1992; Boisen and Fernandez, 1997). The method of these latter authors has been used in Denmark for routine feed energy evaluation.

The objective of the present study was to propose equations for predicting the (in vivo) digestibility of organic matter (OMd) or energy (Ed) and the DE contents of pig feeds from the in vitro digestibility of organic matter (OMdv) measured according to the method of Boisen and Fernandez (1997). For this purpose, the OMdv of 115 compound feeds was measured; their (in vivo) OMd, Ed and DE values were previously measured on growing pigs. The prediction equations were validated on 68 ingredients also measured for their OMdv, OMd, Ed and DE values. This approach (i.e., equations from measurements on compound feeds and validation on ingredients) was preferred since it considers actually measured values for establishing the equations while most values on ingredients are usually indirectly obtained according to the so-called difference method and with a subsequent lower accuracy.
2. Material and methods

2.1. Feeds and in vivo measurement of feeds digestibility

A total of 115 compound feeds were measured for their OMd, Ed and DE in the 1990s at INRA; samples were stored at 2 °C in plastic containers before being measured for the present study over 2002. Most samples were kept as mash and only those with no apparent problem of storage were considered. About 2/3 of the compound feeds were those of the publication of Le Goff and Noblet (2001). The average and range for chemical characteristics are reported in Table 1. The methods for measuring the in vivo digestibility are described by Le Goff and Noblet (2001). In brief, total collection of excreta was carried out on about 60 kg castrated males for 8–10 days and collection started after a 7–10 days adaptation period. Feed was provided in two meals and feeding level represented 85–95% of the ad libitum level. Most of the feeds were fed as humidified mash; 34 were distributed as dry pellets. The average and range for in vivo OMd, Ed and DE values of the 115 compound feeds are reported in Table 1. As indicated in the publication of Le Goff and Noblet (2001), (2)/3 of the compound feeds were also measured as mash in adult sows fed slightly above their maintenance energy level. The methods used for characterizing the chemical composition of feeds have been described by Le Goff and Noblet (2001).

Table 1
Characteristics of compound feeds and ingredients used in the study

<table>
<thead>
<tr>
<th></th>
<th>Compound feeds (mash; n = 79)</th>
<th>Compound feeds (pellets; n = 34)</th>
<th>Ingredients (mash; n = 66)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Min–max</td>
<td>Mean</td>
</tr>
<tr>
<td>Chemical composition (g/kg DM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude protein</td>
<td>167</td>
<td>100–213</td>
<td>167</td>
</tr>
<tr>
<td>Ash</td>
<td>57</td>
<td>45–84</td>
<td>57</td>
</tr>
<tr>
<td>Fat</td>
<td>32</td>
<td>10–108</td>
<td>41</td>
</tr>
<tr>
<td>ADF</td>
<td>53</td>
<td>24–112</td>
<td>52</td>
</tr>
<tr>
<td>Crude fibre</td>
<td>44</td>
<td>19–108</td>
<td>43</td>
</tr>
</tbody>
</table>

In vivo digestibility

<table>
<thead>
<tr>
<th></th>
<th>OMd</th>
<th>Ed</th>
<th>DE (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.859</td>
<td>0.832</td>
<td>15.19</td>
</tr>
<tr>
<td>Min–max</td>
<td>0.737–0.911</td>
<td>0.703–0.887</td>
<td>12.66–16.92</td>
</tr>
</tbody>
</table>

In vitro digestibility

<table>
<thead>
<tr>
<th></th>
<th>OMdv</th>
<th>Edp1</th>
<th>Edp2</th>
<th>DEp (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.852</td>
<td>0.832</td>
<td>0.803</td>
<td>15.16</td>
</tr>
<tr>
<td>Min–max</td>
<td>0.760–0.915</td>
<td>0.751–0.898</td>
<td>0.701–0.872</td>
<td>13.57–17.09</td>
</tr>
</tbody>
</table>

a Compound feeds and ingredients with full fat rapeseed fed as normally ground mash were excluded (see text).
b OMd: in vivo organic matter digestibility; Ed: in vivo energy digestibility; DE: digestible energy content; OMdv: in vitro organic matter digestibility. Compound feeds that contain full fat rapeseed and not pelleted are not considered.
c Edp: estimated energy digestibility (Edp1: from Eq. (10) in Table 2; Edp2: from the equation of Boisen and Fernandez (1997), Ed = −0.140 + 1.106 OMdv); DEp: DE prediction from Eq. (14) in Table 2.
The OMd, Ed and DE values of the 68 ingredients used for the validation step were mostly calculated according to the difference method and obtained only on a mash form; they were included at various levels in the 115 compound feeds. Their characteristics (average and range) are listed in Table 1.

2.2. In vitro digestibility method

The method for in vitro digestibility of organic matter proposed by Boisen and Fernandez (1997) is a multi-enzymatic method, which has three successive incubations with pepsin, pancreatin and Viscozyme (multi-enzymes complex that contains arabinase, cellulase, B-glucanase, hemicellulase and xylanase; Novo-Nordisk, Bagsvaerd, Denmark). It was realized according to the protocol described by Boisen and Fernandez (1997). The analyses were serially performed (24 measurements per series) with three replicates per feed sample in the same series; all results were kept for calculation of average values per sample. In each series, a control (wheat) and a blank sample were measured in triplicates. At the time of OMdv measurements, the ash and dry matter contents of the feed sample were determined. Each measurement was done on about 500 mg of feed ground with a 1 mm mesh screen. The analyses were conducted on the 115 compound feeds and the 68 ingredients.

The sample is placed in a 100 ml flask with a magnetic bar and 25 ml 0.1 M phosphate buffer, at pH 6.0 and shaken at the ambient temperature for 1–2 min. The pH of the solution is lowered with 10 ml of 0.2 M hydrochloric acid solution and adjusted at pH 2.0 (±0.05) with 1 M hydrochloric acid and 1 ml of pepsin (porcine, 2000 FIP U/g; reference Merck 7190) solution containing 25 mg of pepsin per ml of ultra pure water is added. In order to minimize the fermentations in the different incubation steps, 0.5 ml solution of chloramphenicol (0.5 g in 100 ml ethanol) is added in the mixture. The capped flasks are placed in a water bath with agitation (shake) (150 rpm) kept at 39 °C during 2 h ± 1 min (preliminary incubation).

After this preliminary incubation, the flasks are taken out of the water bath and 10 ml of 0.2 M phosphate buffer at pH 6.8 and 5 ml solution of 0.6 M NaOH are added to the mixture and the pH is adjusted at 6.8 ± 0.05 with 1 M hydrochloric acid or 1 M NaOH. One milliliter of a pancreatin solution (porcine, grade IV, reference Sigma P-1751) containing 100 mg of pepsin per ml ultra pure water is added to the mixture. The flasks are capped and placed in a 39 °C water bath for 4 h (second incubation).

At the end of the second incubation, the mixture is added with 10 ml of 0.2 M EDTA and the pH is lowered at 4.8 ± 0.05 with a 30% acetic acid solution; 0.5 ml of Viscozyme 1201 (reference Sigma V 2010) is then added in each flask. After 18 h of incubation (third incubation) in the water bath at 39 °C, the enzymatic reaction is blocked with 1 ml solution of phenyl-methyl-sulfonyl-fluoride (reference Sigma P-7626) containing 10 mg/ml of methanol and it is shaken for 2 min at the ambient temperature.

Before the filtration, 400 ± 50 mg of Celite is added in the crucible that is placed in the furnace at 550 °C during 4 h and weighed very exactly after cooling in a desiccator. The residue of the successive incubations is collected in porosity 2 fritted crucibles (reference Foss TEC 10001172) by filtration after several rinses with ultra pure water. The residue is further rinsed two times with about 10 ml ethanol, one time with about 10 ml acetone and one more time with ultra pure water. The crucibles are placed in the
desiccator (dry oven) at 103 °C during 4 h, cooled in the desiccator and weighed; they are subsequently placed in a furnace at 550 °C during 4 h, cooled in the desiccator and weighed.

2.3. Calculation of digestibility coefficients

The in vitro digestibility coefficient of organic matter (OMdv) was calculated for each flask and similarly to the calculation of the in vivo digestibility coefficient: \( \text{OMdv} = \frac{\text{feed OM} - \text{residue OM}}{\text{feed OM}} \) where feed OM and residue OM correspond to the organic matter weight in the feed and in the residue and obtained as the difference between the quantity of dry matter and ash measured after incineration of feed or residue. The in vitro digestible organic matter content (DOMv) was also calculated as the product of feed organic matter and OMdv.

2.4. Calculations and statistical analyses

The series effect (or repeatability) has been evaluated from the repeated measurements on the wheat samples (38 repeats; 114 measurements). The accuracy of the method has been quantified according to the residual standard deviation (R.S.D.) of the analysis of variance applied to the data obtained in triplicates for the 183 feeds. The prediction equations of OMd, Ed, DE and NE from OMdv (or DOMv) and chemical criteria were calculated by multiple stepwise regression methods; only linear models were tested and no interaction between variables was assumed; highly correlated variables (such as crude fibre and ADF for instance) were not tested simultaneously. Variables kept in the final equations were significant at the 0.05 level. The value of OMdv used in the calculations is the average of the three measurements carried out on each sample. The effect of pelleting of the compound feeds on the coefficients or the intercept of the equations was measured by covariance analyses. Finally, regression equations between the observed values and predicted values for ingredients OMd (OMdp) or Ed (Edp) or DE (DEp) were established in the evaluation stage of the equations. The SAS (1990) program was utilized for all the analyses.

3. Results and discussion

The visual analysis of results showed very quickly that the OMdv of the two not pelleted compound feeds containing normally ground full fat rapeseed and also the corresponding full fat rapeseeds was markedly higher than the measured OMd. For the other feeds, even those including full fat rapeseed but as very finely ground and/or pelleted, OMdv and OMd were very close (Fig. 1 and Table 2). This observation for full fat rapeseed should be related to the results of Skiba et al. (2002) who indicated a clear effect of either particle size or pelleting (whatever the particle size) on fat and energy digestibility of full fat rapeseed. For that ingredient, a technological treatment is then necessary to maximize the fat and energy digestibilities of full fat rapeseed and then to obtain values that agree with the in vitro measurements. This also means that the in vitro method is unable to discriminate this
Fig. 1. Relationship between the in vivo (OMd) and in vitro digestibility of organic matter (OMdv) for compound feeds fed as mash (solid symbols and solid line); diets with full fat rapeseed (opened symbols) were excluded.

ingredient according to the technology that has been used or the differences in availability of fat for the pig. Consequently, the values of these two compound feeds and the two corresponding full fat rapeseeds were excluded from the data analysis. The data set includes therefore 179 feeds with 66 ingredients and 113 compound feeds of which 79 had been pelleted (Table 1).

Table 2
Prediction equations of digestibility of organic matter (OMd) or energy (Ed) and digestible energy and net energy contents (DE and NE, MJ/kg of dry matter) of pig feeds from in vitro digestibility of organic matter (OMdv), or quantity of in vitro digestible organic matter (OMdv, g/kg dry matter) and chemical characteristics (g/kg dry matter)

<table>
<thead>
<tr>
<th>Equation</th>
<th>( r^2 )</th>
<th>R.S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)OMd = 0.999 + 0.891 OMdv</td>
<td>0.82</td>
<td>0.017</td>
</tr>
<tr>
<td>(2)OMd = 0.316 + 0.671 OMdv − 0.00067 CF</td>
<td>0.87</td>
<td>0.014</td>
</tr>
<tr>
<td>(3)OMd = 0.367 + 0.651 OMdv − 0.00060 CF − 0.00060 ash</td>
<td>0.89</td>
<td>0.014</td>
</tr>
<tr>
<td>(4)OMd = 0.362 + 0.624 OMdv − 0.00070 ADF</td>
<td>0.88</td>
<td>0.014</td>
</tr>
<tr>
<td>(5)OMd = 0.409 + 0.608 OMdv − 0.00063 ADF − 0.00061 ash</td>
<td>0.90</td>
<td>0.013</td>
</tr>
<tr>
<td>(6)Ed = 0.976 OMdv</td>
<td>0.77</td>
<td>0.020</td>
</tr>
<tr>
<td>(7)Ed = 0.301 + 0.663 OMdv − 0.00077 CF</td>
<td>0.84</td>
<td>0.017</td>
</tr>
<tr>
<td>(8)Ed = 0.355 + 0.640 OMdv − 0.00068 CF − 0.00068 ash</td>
<td>0.85</td>
<td>0.016</td>
</tr>
<tr>
<td>(9)Ed = 0.362 + 0.602 OMdv − 0.00082 ADF</td>
<td>0.85</td>
<td>0.016</td>
</tr>
<tr>
<td>(10)Ed = 0.410 + 0.585 OMdv − 0.00074 ADF − 0.00064 ash</td>
<td>0.87</td>
<td>0.015</td>
</tr>
<tr>
<td>(11)DE = 0.0189 OMdv</td>
<td>0.60</td>
<td>0.57</td>
</tr>
<tr>
<td>(12)DE = 1.12 + 0.0168 OMdv + 0.0184 EE</td>
<td>0.83</td>
<td>0.37</td>
</tr>
<tr>
<td>(13)DE = 5.02 + 0.0127 OMdv + 0.0172 EE − 0.0124 CF</td>
<td>0.87</td>
<td>0.33</td>
</tr>
<tr>
<td>(14)DE = 6.05 + 0.0116 OMdv + 0.0166 EE − 0.0135 ADF</td>
<td>0.88</td>
<td>0.32</td>
</tr>
<tr>
<td>(15)NE = 2.42 + 0.0078 OMdv + 0.0041 ST + 0.0203 EE − 0.0099 CF</td>
<td>0.94</td>
<td>0.22</td>
</tr>
<tr>
<td>(16)NE = 3.22 + 0.0072 OMdv + 0.0039 ST + 0.0197 EE − 0.0109 ADF</td>
<td>0.94</td>
<td>0.20</td>
</tr>
</tbody>
</table>

*a Equations established from the data obtained on 79 compound feeds presented as mash (see Table 1); all the coefficients are significant (P<0.01); Ash: crude ash, CF: crude fiber, ADF: acid detergent fiber, ST: starch, EE: ether extract; NE calculated from Eqs. (4) and (5) (average value) of Noblet et al. (1994).
3.1. Methodological aspects

The repeated analysis of the wheat samples showed that the effect of series of analysis on OMdv was significant \((P<0.01)\). However, the average values of OMdv varied from only 0.894 to 0.906 or a maximum interval of 0.012 U between extreme series values and for successive analyses conducted over several months. The R.S.D. of the variance analysis which considers the series effect is then logically quite low (0.004 point of OMdv). The analysis of variance on OMdv data for the compound feeds and ingredients \((n=179)\) also indicates a low R.S.D. value (0.007 point OMdv); it is comparable for the compound feeds and the ingredients. To our knowledge, there is no comparable information in the literature on repeatability and accuracy of the \textit{in vitro} method proposed by Boisen and Fernandez (1997).

3.2. Prediction equations of digestibility of organic matter or energy from \textit{in vitro} digestibility of organic matter

Compound feeds were fed and measured \textit{in vivo} as pellets or mash feed. Covariance methods on these data indicate that the intercept \((P<0.01)\) of the equations presented in Table 2 and, to a lesser extent \((0.05<P<0.10)\), the regression coefficients were affected by technology (mash \textit{versus} pellet). As an example, for a given OMdv value, the values of OMd and Ed were respectively 0.008 and 0.019 point higher when the feed was pelleted (Eqs. (5) and (10)). Similarly, DE content was 0.35 MJ higher (per kg of dry matter) for the pelleted presentation (Eq. (14)). The average values reported in Table 1 also illustrate this situation. In other words, different equations should be used for mash and for pelleted feeds and the equations established on mash feeds underestimate the values of OMd, Ed and DE for pelleted feeds. Consequently, the equations that are presented in Table 2 were calculated only from measurements conducted with the mash compound feeds \((n=79)\). No equation was proposed for pelleted feeds in order not to be confusing; in addition, the accuracy of the equations obtained only on pelleted feeds was lower.

In these equations, the first predictor in the stepwise regression methods was always OMdv (or DOMv for DE and NE) but the prediction was improved when one dietary fiber criteria was included (ADF or crude fiber). Such a combination of OMdv and crude fiber was suggested by Van der Meer and Perez (1992). Ash content also improved the prediction. In the case of DE content equations, fat level in the feed was a logical additional predictor. The R.S.D. of the equations obtained in the present study \((0.015\) for Ed or OMd) is lower than in the equations proposed by Van der Meer and Perez (1992) or Boisen and Fernandez (1997). It can also be mentioned that the R.S.D. of the proposed equations is lower than the R.S.D. of equations only based on chemical criteria \((0.015–0.025\) for Ed in the studies of Noblet and Perez, 1993; Le Goff and Noblet, 2001 \textit{versus} 0.015–0.016 in the best prediction equations of Table 2). In other words, OMdv is an interesting criterion to include for characterizing the energy value of feeds.

Current results show that the \textit{in vitro} organic matter digestibility method is capable to predict with a satisfactory accuracy the \textit{in vivo} digestibility of organic matter, the average values of OMd and OMdv being quite comparable in our study for the compound feeds fed as mash (0.859 and 0.852; Table 1). Therefore, the \textit{in vitro} method simulates quite well the
in vivo digestion in the growing pig, at least for the compound feeds used in the present study with digestibilities of OM ranging between 0.76 and 0.92. The introduction of ADF content (or crude fibre) and ash content in the equations is probably related to the fact that these two components affect the endogenous secretions in the digestion process in pigs (Noblet and Perez, 1993; Noblet et al., 2003). In addition, we have to notice that the in vitro method used in our study does not permit the maximal digestion of the organic matter since the OMdv values are about equal to the OMd value measured in growing pigs (Fig. 1 and Table 2) and then significantly lower than the in vivo values measured in the adult pig that are usually 0.02–0.05 U higher than in growing pigs (Fig. 2; Le Goff and Noblet, 2001). The adaptation of the method for a better simulation of digestion in the large intestine should then be studied for expanding or adapting the method to the situation of the adult pig. In the mean time, the proposals of Noblet et al. (2003, 2004) for estimating energy values in adult pigs from energy values in growing pigs can be used.

3.3. Evaluation of the prediction equations; application to ingredients

As mentioned earlier, the equations proposed in Table 2 were obtained with only the mashed compound feeds. Their application to the pelleted feeds lead to an average underestimation of about 2% of the DE content or the Ed. This 2% value corresponds to the average improvement in digestibility of energy and organic matter that is usually observed (Noblet et al., 2003). Covariance analysis indicated that pelleting affected only the intercept of the equations. Even though it would deserve further refinement and studies, the equations in Table 2 could be applied to pelleted feeds but obtained values should be increased by about 1.8% or 0.35 MJ/kg of dry matter for Ed or DE, respectively. However, this average correction does not take into account some specific effects of pelleting or other technological treatment that might be more or less important than this average correction (Noblet et al., 2003; Noblet, 2006).

The best evaluation of the proposed equations would be given by measurements conducted on samples not involved in the establishment of the prediction equations and the comparison of the predicted values of OMd, Ed or DE to the corresponding in vivo measured values. Apart from the data on pelleted feeds, which we have already discussed, such a data base was not available. Therefore, we have evaluated these equations on the set of data obtained on ingredients measured in vivo in the laboratory of the authors for their Ed and OMd values in the 1990s and for in vitro OM digestibilities more recently. Due to large differences in chemical composition of ingredients, the range for Ed, OMd and OMdv was larger than for compound feeds (Table 1). However, it must be noted that these ingredients were mostly included in the compound feeds used to establish the prediction equations. Therefore, the evaluation of the equations is not perfect. In spite of these limitations, Fig. 3 shows that if values for normally ground full fat rapeseed are excluded, predicted and measured Ed values were highly correlated (r = 0.97); in addition, the slope is very close to one (1.01) and the intercept is not different (P > 0.05) from 0. A higher dispersion is observed for the low Ed values and corresponds to products such as straw and hulls (rapeseed, sunflower, cacao, etc.). But it should also be noticed that the in vivo values for these products are also rather inaccurate. Then, if these products are excluded, it can be concluded that the prediction method provides Ed and DE values of ingredients with a satisfactory precision.
In contrast, the prediction equations of Ed or DE established with only chemical criteria and from measurements on compound feeds are difficult to apply to ingredients and provide rather inaccurate estimates (Noblet, 1996, 2006). The utilization of equations specific of a group of ingredients having a common botanical origin is then suggested. In other words, OMdv allows taking partly into account this botanical origin effect and it improves highly the accuracy of the prediction.

Boisen and Fernandez (1997) proposed a prediction equation of Ed from only OMdv (Table 1). It can be assumed that the OMdv values obtained by these authors and ours should be equivalent for a given feed. It is then possible to compare the Ed estimated from their equation with our measurements for the compound feeds of our study (Fig. 4) or for the ingredients (Fig. 3). These two figures and also the average values reported in Table 1 (Edp2) show that Ed is underestimated when the equation proposed by Boisen and
Fernandez (1997) is applied; the difference is about 3% for the 79 compound feeds and 4% for the 66 ingredients (Table 1). Additionally, the underestimation is more important when the feed Ed value is low. Apart from a systematic bias of the OMdv measurement between the two laboratories or a systematic difference in the in vivo values due to feed preparation or animal effects, the reasons for this difference are not clear. The Ed and OMd values of the current study have been obtained in 60–65 kg live weight pigs and, as far as the information is available, in pigs heavier than those used by Boisen and Fernandez (1997) for establishing their equation. Furthermore, the method used by these authors for establishing their prediction equation is relatively opposed to ours since they calculated their equation from data obtained on ingredients. Their situation was advantageous since the range of in vivo values was much wider but values were probably less accurate since many of them were probably calculated (difference method or regression method). In our situation, only directly measured values on compound feeds were used. Finally, we can notice that the prediction equation of Boisen and Fernandez (1997) can be highly improved by including additional chemical criteria (crude fiber or ADF and ash) for which the measurement accuracy is satisfactory.

3.4. Application to the prediction of net energy content

The energy value of pig feeds is generally appreciated according to their NE content (Noblet et al., 1994; Noblet and van Milgen, 2004; Noblet et al., 2004; Noblet, 2006). The first solution for estimating NE from OMDv consists in estimating DE content from the equations reported in Table 2 and utilize this DE value in the equations proposed by Noblet et al. (1994, 2004) for the calculation of NE content. Other solutions consist in using Eqs. (15) and (16) reported in Table 2 that give directly an estimate of NE content from DOMv and chemical characteristics (fat and starch).
4. Conclusion

The current study performed on a considerable number of feeds shows that DE and even NE contents of feeds can be estimated for growing pigs and fed as mash with a satisfactory accuracy from measurement of in vitro digestibility of organic matter, both for compound feeds and ingredients. Although no direct comparison was done in the present study between prediction from in vitro criteria and chemical criteria or from only chemical criteria, the accuracy of the in vitro method is at least equivalent to the accuracy of equations based on chemical criteria. In addition, the in vitro digestibility method, despite its relative complexity, is accurate and repeatable. The restrictions for its application were evaluated in the case of pelleted feeds. More generally, the effects of (bio)technological treatments on nutrients and energy availability are little evaluated in this in vitro method. Furthermore, the direct applicability of this method for estimating energy value in adult pigs requires further studies.

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References