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Cough sound analysis to identify respiratory infection in pigs

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ABSTRACT

Cough sound detection is a central element to diagnose common respiratory diseases like pneumonia in intensive pig farming. The aim of this work is the description of acoustic features of cough sounds originating from a lung infection and the comparison between these kind of cough sounds with those provoked by inhalation of citric acid.

Coughs have been recorded from infected animals in field conditions (pneumonia) and from healthy animals in laboratory (induced). After having completed the classification, the investigation on infectious and non-infectious cough sounds has involved the main differences among acoustic parameters, like the Root Mean Square (RMS), the peak frequency (Hz), the duration and the time occurring between successive coughs in a cough attack.

The results show a significant difference among the RMS, peak frequency and duration in cough sounds from healthy and infected animals. RMS was 0.215 for healthy animals and 0.124 for infected ones ($P = 0$). Non-infectious coughs have an average peak frequency of 1600 Hz, while infectious coughs stand around 600 Hz. Also the length of sounds is significantly lower ($P < 0.001$) for non-infectious coughs (average 0.43 s) than for infectious ones (average 0.67 s). The space of time between each sick cough in a cough sequence seems shorter than the interval occurring between healthy coughs (0.37 s versus 0.52 s).

The above mentioned findings could be surely helpful to develop a real-time cough classification algorithm, based on sound feature analysis, in order to acquire a monitoring system for automatic and continuous infection in pig houses.

1. Introduction

Respiratory pathologies have a high prevalence in intensive pig farming and cough is their principal symptom (Mousing, 1988). It is well-known that, under intensive breeding conditions, it is very unlikely for a pig to reach the slaughter weight without having shown any kind of respiratory infection (Leman et al., 1992).

Higher mortality (14.55%, Baumann and Bilkei, 2002) and drop in production for reduced feed conversion and growth rate (Pijpers et al., 1991; Greiner et al., 2000), are often related to expensive veterinarian intervention costs. Therefore the

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economic side of the problem is particularly relevant for farmers (Muirhead and Alexander, 1997). Moreover, it is proved that detecting animals illness and providing both individual care or group-by-group mass therapy does not seem to be a very operative instrument, but it is a very expensive one.

The best way to handle an illness would be to treat the animals pen per pen, since the animals in each one, being closely in contact the one with the others, can easily get infected with those diseases that are contagious by direct contact.

Actually within intensive pig farming it is praxis to treat the entire compartment and not the single animal. Furthermore, a specific treatment can stop the diffusion of the infection\disease in a timely manner.

Bio-acoustics can help farmers to early detect respiratory diseases by evaluating animal cough sounds through real time monitoring.

The above assumption is based on the hypothesis that, since cough sounds are easily distinguishable from other vocalizations, it is also reasonable to assume that they might have qualities which can identify their acoustic properties (Van Hirtum and Berckmans, 2002a).

This work aims to obtain acoustic features that could be used in a sort of alarm system able to inform the farmer about the health condition of his animals. In fact, since farmers are not able to constantly screen all their animals, normally the result is that the disease is detected to such a late stage that the whole herd needs a drug treatment. The study offers a comparison between infectious cough recorded in field condition and non-infectious cough obtained from previous studies (Moreaux et al., 1999; Van Hirtum and Berckmans, 2004).

The term “infectious cough” refers to a cough coming from a pig with clear signs of a clinical respiratory disease due to a bacterial infection, while a “healthy cough” refers to a cough registered from a pig without a repeated clinical evidence.

In particular, the infection was due to *Pasteurella multocida* type A, opportunistic bacteria, frequently involved in complicating super-infections during the course of respiratory disease in modern pig farming. It is considered able to worsen the physical status through hyperthermia and dyspnoea leading to a loss of weight in the sub-clinical form and to mortality in the acute disease (Pijoan, 1992; Christensen and Bisgaard, 2004).

Healthy coughs were induced by inhalation of citric acid. Pigs produced a dry protective cough which simulates the type of cough occurring normally in field condition when a protective cough is evoked to prevent the entrance of external material in the trachea (dust, ammonia, other irritants, Leith et al., 1986; Van Hirtum and Berckmans, 2004).

Out of this study, features from infectious cough sounds will be extracted for a qualitative monitoring of respiratory disease in real time. This bio-acoustical real time monitoring system is required for early detection of pulmonary infections, based on an algorithm that recognizes the types of coughs from their acoustic identification during an on-line continuous monitoring of sounds in piggeries.

2. Materials and methods

The two groups of compared coughs came from records concerning different animals in different health and environmental conditions.

The 300 pigs affected by pneumonic pasteurellosis came of an hybrid commercial strain Landrace × Large White + Danish Duroc boar and their weigh, at the beginning of the fattening period, was around 40 kg of lbw.

The diagnostic suspect was set on clinical (cough with copious expectorate) and anatomopathological basis when fibrinous and haemorrhagic lobular pneumonia was observed. The definitive diagnosis was performed by isolating the *P. multocida* type A in pure culture.

Within the experimental group of animals it has been found an endemic infection and this matched with those elements of clinical nature (presence of typical and reiterable symptoms, necroscopic and serologic analysis) that always supported the *P. multocida* diagnosis. This infection is supposed to be due to the environmental conditions of the breeding within the fattening sector.

The non-infectious cough was induced by inhalation of citric acid. For the database of non-infectious coughs we are going to use the ones recorded in the study of Moreaux et al. (1999). They inducted cough in ascertained healthy animals, free of respiratory diseases, by inhalation of citric acid (namely 0.8 moles/l of citric acid dissolved in a saline solution of 0.9% NaCl) in six Belgian Landrace × Duroc piglets with a live weigh between 20 and 40 kg. The nebulisation of citric acid stimulates the cough receptors and immediately leads to cough. The experiments were effected on single healthy animals (for more information on material and method and the data acquisition process, see references Moreaux et al., 1999; Van Hirtum and Berckmans, 2004). To obtain sure non-infectious cough test induction has to be done on surely healthy animals. To this purpose laboratory condition seems to be the best solution, since in piggeries under intensive farming condition, normally animals have certain respiratory infections.

This cough induction method causes a temporary irritation of the upper respiratory tract (throat and larynx), but once the animals get over such irritation they stop coughing: in fact, this irritation, once healed, does not cause any lesions to their respiratory system. On the contrary, the infectious cough sounds were caused by a deep bacterial infection of the lungs, since the infectious process, in this case, starts at the alveolar bronchiole junction producing exudates.

The recording device used was an omnidirectional Electret microphone (Monacor ECM 3005) with frequency response from 50 to 16,000 Hz connected to a mobile laptop carried by the operator all around the stable in order to get closer to the animals when they were coughing (max. 1 m distant). The recorded signal was digitalized with a standard soundcard Realteck AC97 at 16 bits and a sampling rate of 44.100 Hz.

The digitalization and labelling program we used for the recorded sounds was Adobe Audition 1.5; for the signal processing (frequency/amplitude/duration analysis) we used Matlab 7.1® and SAS 2004 for the statistical analysis (GLM procedure).

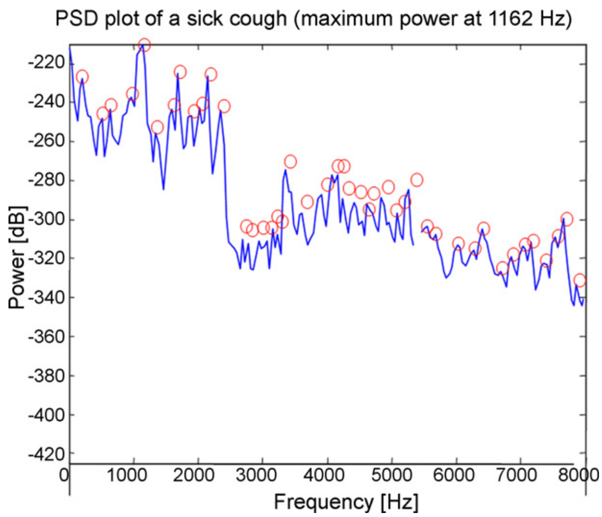

Fig. 1 – Power spectral density of a sick pig cough. The figure is a periodogram of the result of Fourier analysis and it represents the distribution of the intensity per frequency. The red circles are the local maxima, or else, the maximum peaks detected by the algorithm. In this case we see there is an elevated energy up to frequency of 1162 Hz. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Labelling is a manual procedure, based on acoustic analysis combined with visual spectral analysis, which is used to extract cough sounds from the entire recordings. From the recorded sound sessions, collected in 3 days in early spring, labelling was done offline to extrapolate only those sounds that the visual observation of the spectrogram and the auditive confirmation of the operator classified as cough attacks.

In this way we obtained a database of infectious coughs to be compared with the database previously collected of healthy animal coughs.

Signal processing allowed to identify the peculiar features, in time and frequency domain, of the two groups.

Comparisons were based on the Root Mean Square (RMS) normalized pressure, the peak frequency (frequency with maximal energy content) and the duration of the signals (in s). The root mean square reflects the fraction of the time in which the signal amplitude is near its maximum (Bellieni et al., 2004). The RMS is directly related to the energy carried by a sound wave (intensity) and it was calculated as follows:

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum\left(\frac{x_i}{\max(x_i)}\right)^2}$$

with x_i the time signal and n the number of samples of signal x_i.

To calculate the frequency content, Fast Fourier analysis (FFT) used the Welch method with a Hamming window of 40 ms and an overlap of 20 ms was used to generate the power spectral density (in Matlab). The peak frequency was extracted by locating frequency with the highest intensity. An example of a power spectral density of a cough signal is shown in Fig. 1. Then the signal was band pass filtered between 100 and 10,800 Hz to get rid of the low frequency noise. In this way we could eliminate most of the background noise present in the stable (ventilation noise, animals steps, grunts). The upper cut off frequency was chosen to be 10,800 Hz as the cough characteristics we are interested in do not exceed this frequency.

Other features calculated are the length of a cough, the length between two hits in a cough attack and the total length of the cough sequence in both sick and healthy groups. The criterion used to recognize sounds was the identification of the sudden increase of amplitude in both spectrogram and wave-

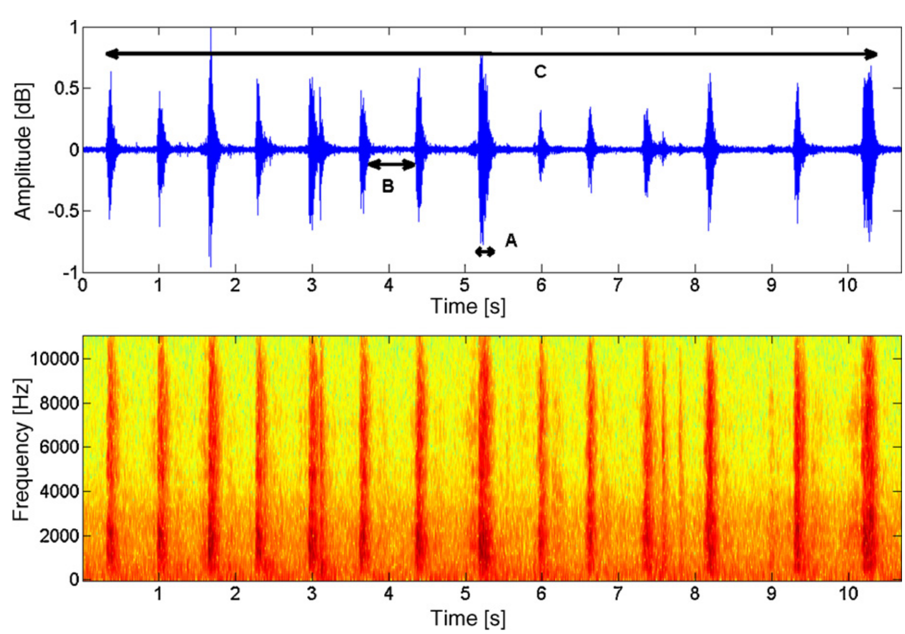

Fig. 2 – Spectrogram of a pig cough attack (consisting of 14 coughs hits) represented in time domain (above) and in frequency domain (below). The arrows indicate the studied parameters by manual labelling procedure: (A) length of a cough, (B) time in between two coughs, (C) total length of a cough attack. The *y*-axis in the figure above shows the sound envelope ranging from 0 to ±0.8 dB, and the *y*-axis in the one below shows frequencies from 0 to 2000 Hz.

Table 1 – Cough database collected in laboratory (non-infectious) and in field conditions (*P. multocida*)

Type of cough	Number of attacks	Number of coughs	Minimum number of coughs in attack[a]	Maximum number of cough in attack[a]	Mean number of coughs[a]
Non-infectious	11	149	4	22	13.54
P. multocida	91	851	5	25	9.35

[a] Quantitative observations were not used for analysis.

Table 2 – Descriptive statistic non-infectious sounds

Variable	N	Mean	S.E.	S.D.	Minimum	Maximum
Number	149	73.5	3.5	42.3	1	146
Duration (s)	149	0.43	0.0072	0.13	0.14	0.6
RMS	149	0.215	0.0025	0.06	0.09	0.37
Frequency (Hz)	149	1603	60.62	732.5	387.6	4694

Means procedure SAS.

form together with the subsequent decrease. Fig. 2 shows a spectrogram of a cough attack consisting of several individual coughs. The parameters we investigated are marked with A, B and C, representing, respectively, the length of a cough, the time between two cough and the total length of the cough attack.

The average values of the above-mentioned three parameters for both cough sounds were compared by One way Analysis of Variance (GLM procedure, SAS 2004).

3. Results

During the recording sessions, in an intensive pig farm, 91 infectious coughs attacks were collected, while 11 non-infectious attacks were available from the work of Moreaux et al. (1999). From these attacks 851 infectious cough sounds and 149 non-infectious cough sounds have been extracted (Table 1).

The reason why the number of infectious coughs is higher than the number of non-infectious coughs is that much more recordings were done on infectious cough. The non-infectious cough sounds were available from a previous study, as already mentioned. To be clear, the lower amount of cough sounds for non-infectious coughs does not mean that the animals coughed less. The lower quantity of coughs is due to a lower number of recordings. The big number of infectious cough sounds is justified to assure a certain quality of the cough sounds, since in field conditions it is more likely that sounds are not as pure as if recorded in laboratory, as they might contain overlapped animal and environmental noise.

A descriptive statistic was done over the non-infectious coughs sounds in order to understand if our samples was representative (Table 2). In this analysis the duration of single sounds, the RMS and the fundamental frequency have been considered.

All the three parameters showed a distribution about to a normal one with minimum and maximum values as the tails of the distribution.

The ranges are shown in Table 2; we suppose there might be a wider range of values for each parameter but specific literature on pigs non-infection cough sounds is not available.

Table 3 shows the mean duration of coughs and cough attacks for the two groups of cough sounds (A and C in Fig. 2). The length of single coughs shows a significant difference between the two groups ($P < 0.0001$) with an average duration of 0.67 s for infectious coughs and 0.43 s for healthy coughs (Fig. 3). The mean length of sequence of coughs was 8.61 s for non-infectious sounds and 6.77 s for infectious ones. This difference was not statistically relevant, showing $P < 0.34$.

Besides the duration of the cough event, it was calculated also the time between two subsequent coughs during an attack. The mean duration for pigs infected with *P. multocida* is significantly lower, 0.36 s, than the one recorded for healthy pigs, 0.52 s ($P < 0.002$). The RMS value shows also a significant difference between the groups, being 0.124 for *P. multocida* and 0.215 for non-infectious coughs ($P = 0$). The analyzed values of RMS are reported in Table 4 for the two types of coughs and are illustrated in Fig. 4, that shows also the bar plot of values. These RMS values indicate that the stationary character of the overall cough intensity cannot be compared in healthy and infectious coughs. In other words, the lapse of time during which the signal is near to its maximum is also influenced by the type of airway irritation (upper or deep in the respiratory system).

The frequency analysis investigated the power spectral density of cough as the energy distribution of sound signal over the frequencies. Fig. 1 shows peaks of high-energy

Table 3 – Mean of the signal duration in both infectious and non-infectious cough

Type of cough	Mean duration attack (s)	Mean duration single cough (s)	S.D. single coughs
Non-infectious	8.61	0.43	0.13
P. multocida	6.77	0.67	0.2

Table 4 – RMS values for non-infectious and infectious cough sounds

Type of cough	RMS average	RMS S.D.	RMS median value	RMS minimum value	RMS maximum value
Non-infectious	0.215	0.06	0.21	0.09	0.37
P. multocida	0.124	0.045	0.12	0.04	0.24

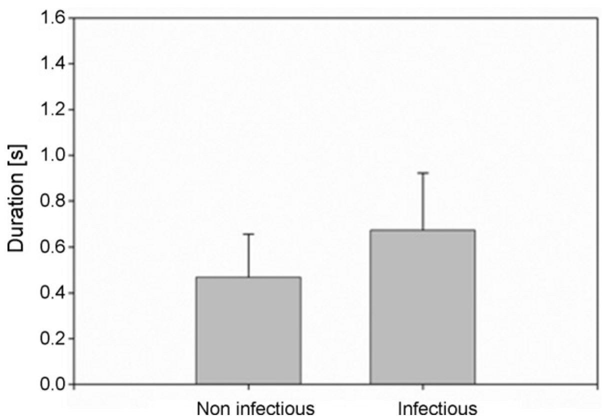

Fig. 3 – Barplot of the duration in non-infectious and infectious single cough. The length of single coughs refers to parameter (A) in Fig. 2. The difference between the two groups is significant ($P < 0.0001$). See Table 3 for the overview of the duration analysis values.

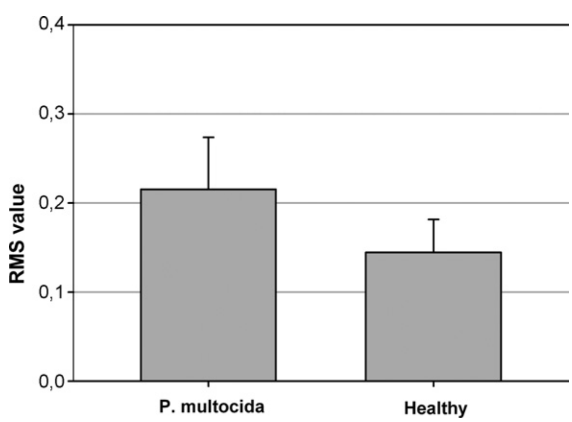

Fig. 4 – Barplot of the RMS values organized in mean columns. The RMS value shows also significant difference between the means of the two groups for $P = 0$. See Table 4 for the overview of RMS average values in the two groups.

concentration up to about 2800 Hz; from this point on there is a decay as for the energy concentration towards higher frequencies. In the case reported in Fig. 1 peak frequency occurs around 1162 Hz. The extension of this peak frequency

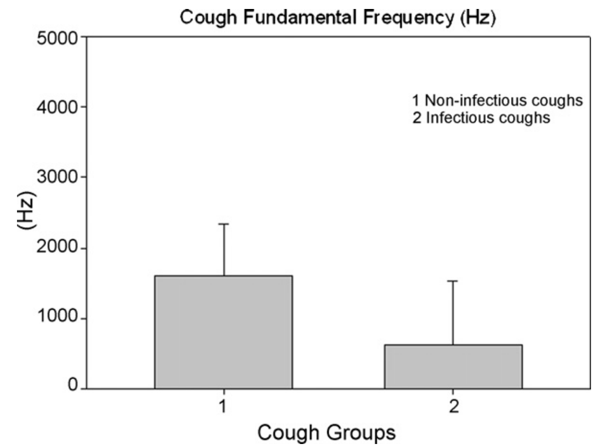

Fig. 5 – Barplot of the extend of peak frequency between non-infectious (1) and infectious cough sound (2) frequency. The analysis of variance shows significant difference between the classes ($P < 0.0001$). See Table 5 for the overview of frequency average values in the two groups.

for the two groups of cough sounds is represented in the barplot of Fig. 5. There is a significant difference between the peak frequency of infected and healthy coughs ($P < 0.0001$): *P. multocida* cough values stand around 600 Hz, while the average value for healthy coughs is 1600 Hz (Table 5). Coughs resulting from this respiratory disease have a typical very "moist" (producing expectoration) sound reflected in the lower frequencies of the signal.

4. Discussion

A first step towards the automatic recognition of cough sounds through continuous sound registration is the capability to easily distinguish between symptomatic or non-symptomatic cough.

This article has focused on the differences of the acoustic footprint of induced cough in healthy subjects and spontaneous coughs in infected pigs. In this work we have assumed that sounds from infected lungs are different from the ones coming from healthy lungs, because of a variation in the sound source, which takes place only if there is a disease. Therefore we decided to study one of the most

Table 5 – Frequency values for non-infectious and infectious cough sounds

Type of cough	Frequency average	Frequency S.D.	Frequency median value	Frequency minimum value	Frequency maximum value
Non-infectious	1603	732.5	1507	387.6	4694
P. multocida	618	668.5	417	159	3488

typical and frequent respiratory diseases in pig fattening farming.

The type of cough described as "moist" is typical of this respiratory productive infection with copious expectoration.

On the other side, the inhalation of citric acid irritates temporary the upper respiratory tract. The mentioned clearance function of cough is associated with a "dry" cough sound in clinical practice denoted with "non-productive". This kind of upper irritation simulates the irritation from dust or ammonia, which is a very common condition in piggeries. The influence of the chosen exposure of ammonia concentration on the pig respiratory system is proved (Urbain et al., 1996a,b).

This assumption, based on sound production, is supported physiologically by considering the common function of cough as a result of aerial pollutants (Moreaux et al., 1999; Morice, 1996).

These environmental pollutants are a source for non-infectious cough sounds, which are known by farmers: during routine inspection they may hear lot of coughs but these, when due to ammonia, do not need antibiotics, but only a better management of the air quality in the buildings.

The generality of the biomarkers is supposed to be due to the common mechanism involved in protective cough both in inducted and spontaneous coughs; for this reason the input for a spontaneous and for an inducted cough is the same. In fact, animals cannot be asked to cough but they can be inducted to do it by stimulating the same receptors (C-fibres, Rapidly Adapting Receptor) causing cough in pulmonary diseases (Karlsson et al., 1988).

When considering the cough data in detail, the difference between the two classes of cough is that in one case the status of the respiratory system is damaged, and in the other case it is not.

Actually what changes in the two database is the status of the respiratory system, which results to be damaged only in one case.

Even though healthy animals do cough, the nature of these sounds needs to be known in order to provide pharmaceutical treatment only when necessary.

The different genetic strain of pigs used in the trial did not influence our results since both the types were hybrid commercial for fattening. The weight and the structure of the respiratory system was similar for both groups.

Cough sounds have been studied in the past on both humans and animals to prove the correlation between different infections and the type of sound signals (Korpáš et al., 1987), to prove the systems for sounds acquisition and analysis (Höglung and Michaelson, 1950; Reece et al., 1966; Subburaj et al., 1966), the labelling of sounds that allows a system to recognize and discriminate cough signals or other animal and environmental noises (Robertson and Benzie, 1989; Van Hirtum and Berckmans, 2003a, 2004; Aerts et al., 2005) and to improve an algorithm for automatic cough detection from continuous recording (Van Hirtum and Berckmans, 2002b, 2003b; Guarino et al., 2004; Jans et al., 2004). In the past decade improvements in recording technology have allowed ambulatory recordings, but these studies have always been limited in size and scope by the laborious task of manually counting the cough sounds (Thorpe et al., 1992; Hsu et al., 1994; Van Hirtum and Berckmans, 2003b, 2004). Despite the remarkable interest in lung sounds (Korpáš et al., 1987, 1993a; Pijoan, 1992), the use of tussiphonography and the importance of the cough as a symptom of respiratory disease, there is more research to be done on the acoustic parameters of coughs and on the relation between alterations of breathing system and types of coughs. The physiopathologic time variation of the breathing system and the large variation in acoustic properties of cough sounds is probably the explanation for the disappointing results obtained up to date from automated cough counting algorithms. Fast Fourier Analysis (FFT) of normal breathing sounds, crackles and wheezing sounds has been performed on humans (Gavriely et al., 1981, 1984; Dalmasso et al., 1984; Piirila and Sovijärvi, 1989). The FFT spectra of the voluntary cough sound of patients with asthma, chronic bronchitis and bronchial carcinoma showed higher frequencies than cough sounds from healthy volunteers (Debrezeni et al., 1990). Secretions in the airways influence the character of cough sounds (Korpáš et al., 1993b). Subjects with diseases mucus or chronic bronchial obstruction show multiple flow spikes and long cough sequences (Piirila and Sovijärvi, 1995). Van Hirtum has already shown several ways to work with pig cough, from the assessment of the cough towards vocalization (2002a), through the automated recognition of spontaneous cough versus voluntary cough, to the classification of cough sound by using an algorithm for recognition in lab condition (Van Hirtum and Berckmans, 2003b, 2004).

Until now a quantitative cough-description has usually been obtained by spectral analysis (Korpáš et al., 1996; Rietveld and Tijssenbeek-Nouwens, 1998). Discriminant analysis between asthmatic and voluntary cough spectral features results in classification error rates of 20–30% (Murata et al., 1998). The named papers clearly show spectral differences between 'spontaneous' and 'voluntary' cough classes.

Literature on acoustic features of coughs, specifically on those caused by aging of animals or by microbiological agents, is still unknown.

In this paper our sound analysis considers features like frequency energy content, duration and RMS of a cough.

In terms of peak frequency, infectious coughs show a significantly lower peak frequency than non-infectious ones. This is in contradiction with the findings of Korpáš et al. (1996) who states that, as far as a human individual is concerned, frequencies of 300–500 Hz are the most significative for healthy coughs, whereas in bronchitis cough sounds the energy ranges between 500 and 1200. Sound differences in cough between humans and pigs can be explained by differences in the amount of air pushed in through the air pipe or by the dimension and conformation of the respiratory system itself. On the other hand Van Hirtum and Berckmans (2003a) showed that frequency for inducted cough sounds in laboratory conditions is higher than coughs from infected animals. We also confirm this latter assumption in our study in field condition.

Considering the duration of labelled single cough, it is demonstrated that there is a significant difference between the two groups, having an average duration of 0.67 s for infectious coughs and 0.43 s for healthy ones. This trend has been also observed by other authors, concluding that the duration of a sick cough is longer compared to a healthy one, due to obstruction by infection and inflammation of the airways

(Korpáš et al., 1996; Van Hirtum and Berckmans, 2002b), both in humans and pigs. As for the duration of a single cough or of a cough attack nothing has been found in literature. In this study it was observed that the time elapse between two coughs is shorter in sick animals than in healthy ones. A possible explanation stands in the need to expectorate mucus for sick subjects, thus leading to faster cough hits.

The RMS value reflects the number of energy peaks in a signal. It is used by Doherty et al. (1997) who showed two energy peaks found at the beginning and at end of the cough sound signals. Other investigators (Korpáš et al., 1987; Kelemen et al., 1987) showed that some individuals did not have this double-peaked cough but instead had either a single energy peak or multiple peaks. Thorpe et al. (1992) showed that, although single-peaked cough sounds were more common in disease status, they occasionally occur in normal subjects. These findings suggest that the number of high-energy peaks within a cough holds specific diagnostic value, indeed the results on RMS analysis showed significant difference for the two types of coughs.

5. Conclusions

The findings in this work show the possibility to discriminate sounds from acoustical analysis. We satisfy the hypothesis that a different status provide different sounds, with typical and repeatable acoustical parameters. The respiratory system is the source of cough sounds and its alterations gives different sound emissions.

After manual labelling, a comparison between the two classes of cough was done using sound analysis by investigating physical features of the sound wave forms of coughs. This allowed comparison between infectious and non-infectious cough sounds.

As this work opens up characterisation of the features of pig cough, caused by a specific agent, in terms of acoustical parameters, it might be useful to study more typical respiratory disease in piggeries to improve the database of labelled pig cough sounds.

This bio-acoustic study will allow the design of an early detection method, based on “on-line” cough counter algorithm, to recognize sick animals in breeding farms. Hence sound analysis in field conditions will provide additional, useful, non-invasive objective and quantitative information about animal health and welfare and it is a candidate for developing automatic on-line monitoring tools of biomarker indicating the presence of pulmonary disease in a farm.

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