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Comparison of different ultra-high-frequency transponder ear tags for simultaneous detection of cattle and pigs

Nora Hammer*, Felix Adrion, Max Staiger, Eva Holland, Eva Gallmann, Thomas Jungbluth

University of Hohenheim, Institute of Agricultural Engineering, Livestock Systems Engineering, Garbenstraße 9, 70593 Stuttgart, Germany

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A B S T R A C T

Electronic animal identification is an important technology in modern animal husbandry providing great benefits. Low-frequency applications are state-of-the-art within the radio frequency identification of animals. Quasi-simultaneous detection of several animals and reading of the transponders over longer distances is impossible with low-frequency systems. Ultra-high-frequency (UHF) applications are suitable for this purpose. However, UHF systems have disadvantages through their susceptibility to metallic surfaces and liquids. Thus, the reflection and absorption of electromagnetic radiation in the animals' environment is often problematic. Consequently, an adjustment of the transponder ear tags regarding mechanical stability and functionality close to water (ear tissue) is necessary. In this project, targeted adjustments and a further development of UHF transponder ear tags concerning the resonance frequency were made. Three trials with cattle and two trials with pigs were performed in this study. Cattle were driven through a reader gate for ten rounds and six different types of transponder ear tags designed in-house were tested. The influence of the environment (indoor vs. outdoor), reader orientation at the gate (sideways vs. above) and output power of the readers (1.0 vs. 0.5 W) were tested in two experiments. The average number of readings per round and the reading rates of the transponder ear tag types were taken as target variables. In the trials with pigs, three transponder ear tag types were compared. The animals were driven through the gate for five rounds per repetition, but neither the reader output power nor the reader orientation were varied. The pig experiments were performed indoors.

The results of the cattle experiments showed that the average number of readings per round and the reading rates were significantly higher indoors compared to outdoors. The reader output power of 1.0 W achieved significantly better results compared to 0.5 W. The same applied to the reader orientation 'above' compared to 'sideways'. It could also be shown that an improvement of the transponder and, thus, an adjustment to the animal's ear could be achieved during transponder ear tag type development. A maximum reading rate of 100% was reached with the cattle transponder types finally developed (B3-4, B4-4 and B5).

In addition, an average reading rate of 100% was achieved for one pig transponder ear tag type (C2). However, these experiments have to be treated with caution due to a very low sample size.

1. Introduction

Electronic animal identification is an important technology in modern animal husbandry. It can provide great benefits regarding process control on farms, animal or disease monitoring, animal and meat traceability, and improvement in the entire farm management (Artmann, 1999; Babot et al., 2013; Geers, 1994).

Radio waves are one option for individual electronic animal identification (radio frequency identification, RFID). In addition to the standard low-frequency band (LF, 120–135 kHz) used, high-frequency (HF, 13.56 MHz) and ultra-high-frequency (UHF, 868 MHz, 915 MHz) bands have become more popular and have been tested increasingly in research (Hessel and Van den Weghe, 2013; Hogewerf et al., 2013; Maselyne et al., 2014; Reiners et al., 2009; Stekeler et al., 2011a; Umstatter et al., 2014). Low-frequency RFID systems cannot identify several animals simultaneously and a separation of the animals is unavoidable (Barge et al., 2013; Ribó et al., 2001; Stekeler et al., 2011b). Even when an anti-collision technique is used, the reading rates are not sufficient (Burose, 2010). Additionally, LF and HF systems have a reading range of 1.0 respectively 1.5 m, which requires a small distance between reader and animal (Bauer et al., 2011; Caja et al., 2005; Thurner and Wendl, 2007). However, UHF-RFID benefits from a greater

* Corresponding author.
E-mail addresses: nora.hammer@uni-hohenheim.de (N. Hammer), felix.adrion@uni-hohenheim.de (F. Adrion).

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read range, the possibility of quasi-simultaneous reading by using anti-collision systems and a higher data transfer rate (Chawla and Ha, 2007). Ultra-high-frequency systems achieve a read range above 3.0 m with passive transponders (Baadsgaard, 2012; Clasen, 2007; Finkenzeller, 2012; Ruiz-Garcia and Lunadei, 2011; Umstatter et al., 2012). This results in a good suitability of UHF systems for animal husbandry by allowing simultaneous detection of larger groups of animal and the possible greater distance between reader and animal. Ultra-high-frequency systems should also be in a position to assume the application areas of LF and HF systems with shorter read ranges by reducing the reader output power. Ultra-high-frequency systems were previously considered as unsuitable for animal identification because of the high absorption potential of water in the UHF band, however, there have been further developments in terms of performance and robustness over time which partly bypass this problem (Adrion et al., 2015; Catarinucci et al., 2012; Finkenzeller, 2012; Stekeler et al., 2011b).

The farmer generally has many choices where to attach a transponder on an animal for on-farm identification. Passive systems are predominantly used in animal husbandry because of size and costs. Due to the light weight of the transponders, they are compatible with all mounting options. A collar is often used with dairy cattle. However, the collar is not a realistic option for pigs and fattening cattle, mainly because of the high costs and the risk of ingrowth with quickly growing animals. The use here of either an encapsulation for implantation or a transponder attached to an ear tag is more reasonable (Caja et al., 2005).

Encapsulation for implantation would not be the method of choice because of the potential high water absorption in the UHF band and the issue of fast removal from the carcass at the slaughter line (Merks and Lambooij, 1990). Using this operating frequency, an electronic ear tag seems to be the best choice for pig and cattle identification.

The legal foundation for pig and cattle identification in the European Union is currently based on a visual ear tag, but replacement of the latter with an electronic ear tag is already permitted for cattle (EC, 2000). Combining the official identification via an ear tag permitted already with the on-farm identification seems to be an obvious development.

1.1. Simultaneous individual animal identification with UHF-RFID

There have only been a few projects testing UHF ear tags for animal identification directly on the animals in practice. Cooke et al. (2010) used a UHF ear tag in their experiments for the simultaneous registration of deer, sheep and cattle on different farms. In the deer experiments, they achieved a reading rate between 75% and 100% with a gangway width of just above 2.0 m, depending on the reader position. The reading rate of the sheep experiments was between 94% and 100%, depending on the reader type, reader position and race width. They only obtained a reading rate of 72% in their cattle experiments at a race width of 2.6 m. However, an adjustment of the test conditions could not be performed here (Cooke et al., 2010). Further experiments with sheep were performed within a project called Rosei. Here, the authors achieved reading rates of 100% with a UHF transponder ear tag and two antennas in a metal race. They completed 2800 individual passes without a failure (European Commission, 2015). Stekeler et al. (2011b) attached a rigid UHF transponder to a pig ear tag and drove fattening pigs through a gate with two readers. They achieved a reading rate between 71.2% and 77.5%, while comparing different reader positions at a race width of 1.1 m. A UHF ear tag was developed for use in pigs in a project called “PigTracker”. A reading rate of $>95\%$ with a reading distance of 2.0 m was achieved in driving experiments with piglets (Baadsgaard, 2012; Swedberg, 2012). Hogewerf et al. (2013) carried out driving experiments with a button-type ear tag and five groups of pigs (10 or 11 pigs in each group) with a reader supplying four antennas. In a first trial in a 2.0 m broad hallway, they achieved a reading rate of 89.6% without a further adjustment of the experimental design. In conclusion, to the best of the authors' knowledge, the UHF technology has not been tested very often and a reading rate of 100% has seldom been reached.

1.2. Ear tag technology

There can be a general differentiation between rigid and flexible ear tags. The rigid ear tags are mostly button ear tags, and the transponder is inlaid into a round solid plastic ear tag. The surface available for the transponder antenna is very limited and the variability of the antenna structure of the transponder is restricted. Flexible ear tags, on the other hand, have a larger flat part where the transponder can be integrated. In general, the transponder has to be grouted into the ear tag to retain the size and not increase its weight. A professional grouting is very important to protect the transponder and to ensure durability.

The impedance of the transponder's antenna is changed depending on the material of the ear tag and its permittivity. This results in a shift of the transponder's resonance frequency. A reduction of the resonance frequency occurs usually (Rao et al., 2005). Consequently, the transponder must be adjusted to its surroundings (ear tag). The detuning of a transponder through the variation of its antenna length, label and antenna material, size and form are possibilities for a targeted adjustment and its successful use in animal husbandry (Adrion et al., 2015; Catarinucci et al., 2012; Lorenzo et al., 2011; Nikitin and Rao, 2006).

A few companies, for example, “definitive! business applications e.K., Münster, Germany”, “MS Schippers GmbH, Kerken, Germany” and “Simplum GmbH, Berlin, Germany”, currently sell rigid UHF ear tags for animals. Flexible UHF ear tags are also sold; “HANA micron Inc, Asan-si Chungnam, South Korea” can be mentioned here as an example.

1.3. Objectives

This study is part of a research project which is concerned with the development and testing of flexible UHF in-house developed ear tags for animal identification developed in-house. An optimal resonance frequency adjustment of the different transponder types developed to an animal's ear is the main aim. First systematic laboratory tests were carried out before testing the UHF ear tags in practice (Adrion et al., 2014, 2015; Hammer et al., 2013, 2014, 2015). According to the test bench results, different UHF ear tag types emerged as suitable for use in animal husbandry during the progress of the project.

Subsequently the test of these transponder ear tag types under practical conditions served the aim to identify the most suitable and durable one for simultaneous detection of cattle and pigs. Therefore, six different transponder ear tag types for cattle and three types for pigs were tested in driving experiments. The influence of the environment (indoors vs. outdoors), the reader orientation (sideways vs. above) and the reader output power (0.5 vs. 1.0 W) was also tested in the cattle experiments.

2. Materials and methods

2.1. Animals, UHF transponder ear tag types and UHF readers

All the experiments were conducted at the Agricultural Sciences Experimental Station of the University of Hohenheim. Unfortunately, it was not possible to test all transponder ear tag types

Table 1
Overview of transponder types (Hammer et al., 2015).

Transponder type	Number of ear tags	Characteristics	Species
B1	6	– Antenna sized for cattle ear tags	Cattle
B2	5	– Antenna design: Pif antenna	
B3	4	– Variation of antenna length and, thus, resonance frequency (higher from B1 to B3)	
		– Label and antenna material: layers of adhesive aluminium foil	
		– Grouted into a cattle ear tag	
B3-4	8	– Further development of B3	Cattle
B4-4	8	– Different label and antenna material: polyimide foil with aluminium cover	
B5	15	– Further development of transponder type B4-4	Cattle
		– Variation of antenna length and, thus, resonance frequency (higher for B5)	
		– Label and antenna material: polyimide foil with aluminium cover	
C1	7	– Antenna sized for pig ear tags	Pigs
		– Antenna design: Pif antenna	
		– Label material: layers of adhesive aluminium foil	
		– Grouted into a cattle ear tag	
C1-4	3	– Second generation of C1	Pigs
		– Different label and antenna material: polyimide foil with aluminium cover	
C2	10	– Further development of C1-4	Pigs
		– Variation of antenna length and, thus, resonance frequency (higher for C2)	
		– Label and antenna material: polyimide foil with aluminium cover	

at the same time because of the production process and their continued development during the project. This led to the implementation of a number of experiments per animal species. Three experiments were performed with cattle, incorporating 29 heifers of the Holstein-Frisian breed and two heifers of the Jersey breed. Two experiments also were performed with fattening pigs: 20 fattening pigs of the German Landrace × Pietrain breed and Swabian breed were used.

Six cattle-sized and three pig-sized transponder types were tested. Table 1 gives an overview of the transponder types and generations used per animal species. All of the transponder ear tag types presented here were transponder patterns developed and improved within the project period. The different transponder ear tag types and their characteristics are described in detail in Hammer et al. (2015), however, the transponder design is especially subject to patent protection and cannot be described in more detail. This is also the reason why more detailed information cannot be given for the resonance frequency.

All of these transponder types were two-dimensional Pif antennas with a similar antenna design. They differed basically in the length of the radiating part of the antenna. The cattle and the pig transponders resembled each other. Only the ground plane and the radiating part of the pig transponders were smaller and shorter compared to the cattle transponders. All of the transponder types had a relatively similar reading field. They were all equipped with an Impinj Monza 4® chip. The transponder samples were grouted into a traditional plastic cattle ear tag (Primaflex® 1/3, Caisley International GmbH, Bocholt). The transponders intended for use on pigs were also grouted into a cattle-sized ear tag because of technical restrictions at this stage of development. The dimensions of the ear tag are shown in Fig. 1. The transponder was grouted into the female part of the ear tag and, thus, lay on the inner side of the animal's ear for all experiments.

The animals were driven through a gate containing two UHF readers (TSU 200, deister electronics GmbH, Barsinghausen, Germany) to test the suitability of the transponder ear tags for simultaneous detection. Only a limited number of ear tags could be tested because of the time-consuming production process and its cost and the high rates of loss during the production.

The same UHF readers were used for all cattle and pig experiments. These readers were characterized by an internal antenna covered by a robust IP67 housing. They worked with an operating frequency of 868 MHz (EU), a circular polarised radiation and an opening angle of 90°. The readers adjusted themselves to their environment with an auto-tune function. An effective radiated power of a maximum of 1.0 W [W] was possible with these readers (antenna gain included). The antenna field was switched on and off manually or by software at the beginning and end of each repetition (cattle experiments: 1 repetition = 10 rounds; pig experiments: 1 repetition = 5 rounds). The transponder reset time (reset of the inventoried flag in the anti-collision procedure) was set at 100 ms. This implies that after a time of 100 ms, all

Fig. 1. Dimensions (mm) of the Primaflex® ear tag (left), pig with UHF transponder ear tag in its right ear (centre) and cattle ear with UHF transponder ear tag (ear tag 34) and standard visual ear tag (right).

transponders in the reading field can be read again. Because of the very short reading time (> 10 ms) of one transponder, all transponders present had the chance to be read in 100 ms. Thus, a number of readings per second are possible. The mounting of the readers depended on the experimental design and will be described in the following chapters.

2.2. Cattle experiments

The animals were tagged with an UHF ear tag at the beginning of the experiment. Each transponder ear tag was coded with an individual number. This number was linked to the individual number of the visual ear tag, and the animal's name, height and weight via a custom-built configuration software programme (Phenobyte GmbH und Co. KG, Ludwigsburg, Germany). The function of each transponder ear tag was checked on each test day before the driving experiments started. All animal- and test-related data were stored in a database (Phenobyte GmbH und Co. KG, Ludwigsburg).

The focus of experiment 1 was the comparison of the three different cattle transponder types, which differed strongly in their resonance frequency. Three transponder ear tag types (B1, B2, B3) were compared indoors with the reader orientation called 'sideways' in the first experiment (cf. Fig. 2). The different transponder types were assigned to an animal randomly. The UHF ear tag was tagged in the right or left ear of 15 animals (left=9; right=6) additional to and depending on the location of the visual ear tag in the ear.

The second experiment focused on the influence of the environment (indoors vs. outdoors), reader orientation (sideways vs. above) and reader output power (1.0 vs. 0.5 W) on the reading success of two transponder ear tag types developed further (B3-4, B4-4). Each of a group of 16 heifers was tagged with one of the two different types of UHF transponder ear tags randomly in the left ear in addition to the visual ear tag.

The third experiment was carried out after completion of the second experiment. In this experiment, each of 15 cattle was tagged with a UHF transponder ear tag of type B5 in their left ear next to the visual ear tag. All the parameters of the second experiment were tested for this transponder type except for the reader output power. Based on the results of cattle experiment 2, only a reader output power of 1.0 W was used in the third experiment. A comparative evaluation of the transponder types of experiment 1 and 2 was performed in this manuscript. In order not to falsify the comparison, the results of transponder types B3-4, B4-4 and B5 tested with 1.0 W were the basis of this evaluation.

The reader height and gate width were kept constant throughout all the cattle experiments. The cattle were driven through a gate containing two UHF readers for ten rounds per repetition in all trials. Several repetitions were performed on each test day. Table 2 gives an overview of all cattle experiments.

The experimental set-up indoors is shown in Fig. 2, while Fig. 3 shows the set-up for outdoors.

Only the reader orientation 'sideways' was tested in cattle experiment 1, while the reader orientation 'above' was added in experiment 2. Using the reader orientation 'sideways', one reader was located on the left side (in running direction, clockwise) of the gate, while the other was placed on the right side. When passing the gate, the right reader radiated from the front towards the animal's head and the left reader radiated from behind towards the back of the head. Both readers in all cattle experiments were mounted at a height of 230 cm. Thus, an undisturbed movement of the cows and the stuff in the barn was possible while the radiation angle of the readers radiated the whole width of the gateway. The inclination angle of both readers was 30°. Using the reader orientation 'above', both readers were installed horizontally and radiated towards the animal's head from above with an inclination angle of 90° (Figs. 2 and 3).

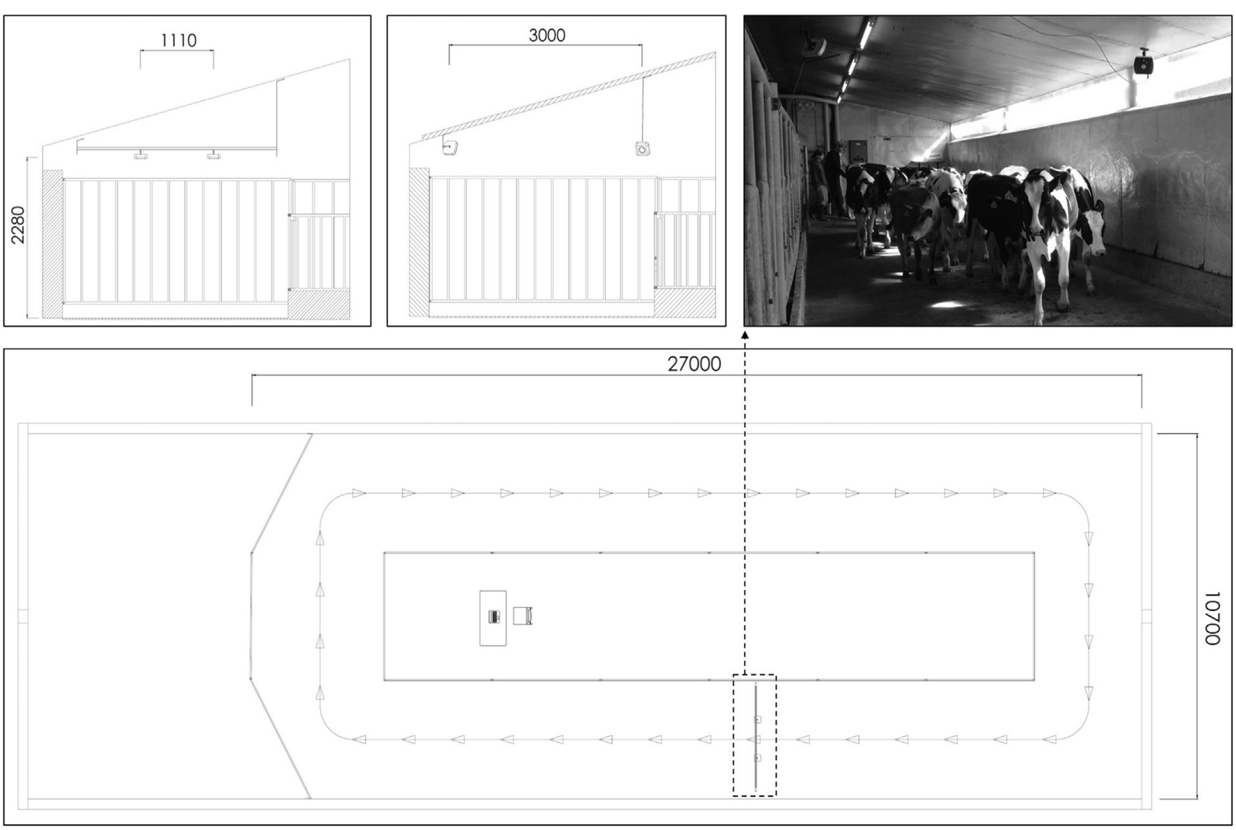

Fig. 2. Experimental set-up for the cattle experiments indoors (dimension in mm).

Table 2
Overview of cattle experiments.

Experiment	Transponder type	Number of animals	Repetitions
1	B1	6	8
	B2	5	8
	B3	4	8
2	B3-4	8	80
	B4-4	8	80
3	B5	15	40

2.3. *Pig experiments*

The experimental set-up of the pig experiments was similar to the cattle experiments and oriented towards Stekeler et al. (2011b).

After all the animal- and test-related data were collected, the pigs were driven through a gate with two UHF readers for five rounds (5 rounds=1 repetition). After a break of at least 45 min, the procedure was repeated. Two repetitions were performed on each test day and an effective radiated power of 1.0 W was used. Three transponder ear tag types were tested in two experiments.

In the first experiment, two transponder ear tag types (C1; C1-4) were randomly spread through three pig groups (10 pigs each). Only a very limited number of transponder ear tags could be tested here (C1=7 ear tags; C1-4=3 ear tags). The remaining animals were not part of this experiment. These two transponder types were tested over a period of about eight weeks.

In the second experiment, an improved transponder type (C2) was examined. One group (10 pigs) was tagged with this transponder type. These pigs were driven through the gate on two test days within two weeks.

All pigs of both experiments were tagged in the right ear. Because of the very low sample size of the two experiments, the results of the three pig transponder types will be presented in parallel within the frame of this manuscript. These results should be seen more as an outlook that a good simultaneous reading of the pig transponder types is also possible.

The experimental set-up and the exact dimensions of the pig experiments are shown in Fig. 4.

Both readers were mounted at a height of 167 cm. The gate width was 166 cm. One reader was located on the left side (direction of movement, clockwise) of the gate, while the other was placed on the right side. When passing the gate, the right reader radiated from the front towards the pig's head and the left reader

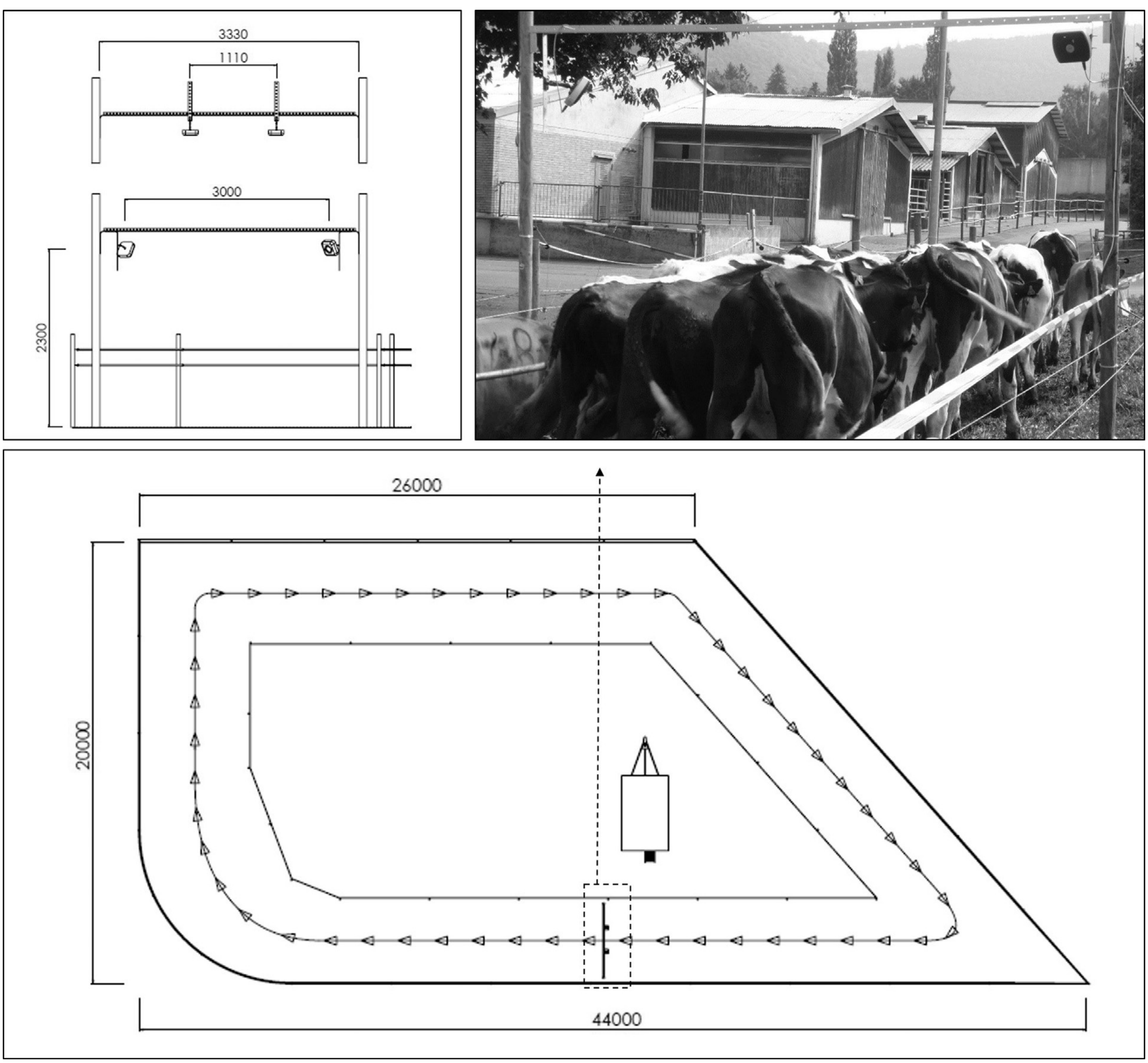

Fig. 3. Experimental set-up for the cattle experiments outdoors (dimensions in mm).

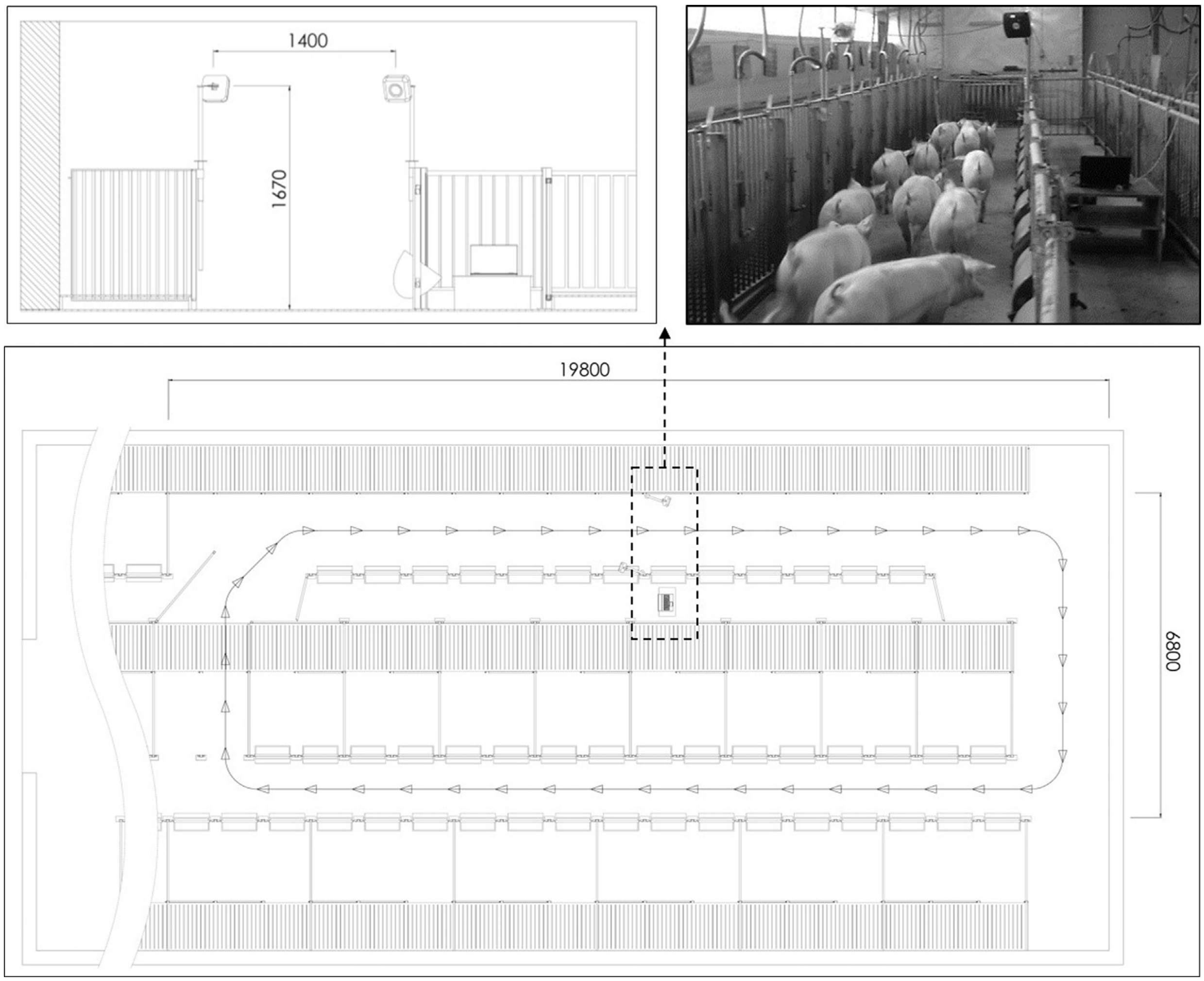

Fig. 4. Experimental set-up of the pig experiment (dimensions in mm).

radiated from behind, towards the back of the head. The inclination angle of both readers was 20°. Both readers were also rotated by 20° to the centre of the gateway.

2.4. Data preparation

Two parameters were taken into account to evaluate the quality of the different transponder types for all experiments performed. The 'number of readings per round' achieved by each transponder ear tag was recorded for each round. Consequently, an 'average number of readings per round' could be constructed for each transponder ear tag (Eq. (1)). This was carried out for every repetition.

$$\text{Average of readings per round} = \frac{\sum \text{Number of readings}}{\sum \text{Number of rounds}} \quad (1)$$

Furthermore, the reading rate of an individual transponder ear tag was calculated for every repetition. Therefore, a 'number of readings' equal to zero was listed as zero, and a 'number of readings' greater than zero was listed as one for one round. Subsequently, a proportional analysis was performed. The reading rate of an ear tag was calculated by the following formula (Eq. (2)):

$$\text{Reading rate [\%]} = \frac{\sum \text{rounds, where number of readings} \geq 1}{\sum \text{Number of rounds}} * 100 \quad (2)$$

A comparison of the transponder types was performed in cattle experiment 1 and a mixed model (SAS® 9.4 proc mixed) could be calculated. The model creation was started with the full model with all interactions (2-fold to 4-fold). The random effects for the 'number of readings' were the repetition and the ear tags. When calculating the mixed model for the 'reading rates', only the ear tag was used as the random effect. The normal distribution within the calculation was examined and the data was transformed. A $\text{Log}_{10}\,(y+1)$ transformation for the 'number of readings' and an arcsin $(\sqrt{y}/100)$ transformation for the 'reading rates' were used. The normal distribution was determined via Q–Q plots graphic analysis. Firstly, no variance homogeneity was given. Therefore, the transponder types were determined as a grouping variable in the analysis and the variance component per transponder type estimated. Comparisons of means were conducted with t-tests. A simulate adjustment for multiple comparisons of means followed. Unfortunately, no randomised implementation of the test procedure was possible because of operational processes on the experimental station for cattle experiment 2 and 3. A mixed model was also calculated for cattle experiment 2 because the data set met all other requirements of the model. The repetition and the ear tag were used here as random effects in both models. The same data transformations as those of cattle experiment 1 were used. Because transponder type B5 was tested in another experiment (experiment 3), this transponder ear tag type could not be integrated into the mixed model of cattle experiment 2.

Table 3 shows an overview of the fixed effects and the final

Table 3
Overview of fixed effects and final mixed model used in cattle experiments 1 and 2.

	Cattle 1	Cattle 2
Fixed effects	transponder type (T)	Transponder type (T), performance (P), reader orientation (O), place (PL), all interactions (AL)
Final model	Number of readings:	Number of readings:
	y=T+R+E+e	Y=T+P+O+PL + AL+ R+E+e
	reading rates:	Reading rates:
	y=T+E+e	y=T+P+O+PL + AL + R+E+e

R=repetition; E=ear tag; e=residual error.

model, after eventual withdrawal of non-significant effects or interactions.

A graphic representation with the types of experiment 2 was chosen to classify cattle transponder ear tag type B5. The same applied to the pig transponder types, because of the very low sample size.

3. Results

3.1. Cattle experiments

3.1.1. Experiment 1 (Comparison of transponder types B1, B2 and B3)

Fig. 5 shows the results of experiment 1 in cattle, where different transponder types (B1, B2 and B3) were compared. A different number of ear tags was available for every transponder type. Six ear tags of type B1, five of type B2 and four of type B3 were tested in this experiment. The three different transponder types showed distinct differences.

With regard to the overall mean of readings per round and the average reading rates for all test days, transponder type B1 performed worst (2.1; 30.4%), while transponder type B3 performed best (28.7; 94.4%). B2, with 16.5 readings per round and 78.8% average reading rate, lay in between the two other transponder types. The average number of readings per round and the reading rates showed a clear increase from B1 to B3. The statistical analysis of both parameters showed a significant difference between transponder type B1 and B2 and between B1 and B3. However, no significant difference was obtained between B2 and B3. It should also be mentioned that transponder type B3 showed the greatest variance in the average of readings per round, but the smallest variance in the reading rates. No lost or broken ear tags were recorded within this test period.

3.1.2. Experiment 2 (influence of environment, reader output power and reader orientation on the performance of transponder types B3-4 and B4-4)

With two transponder types developed further (B3-4, B4-4), the influence of a different environment (outdoors vs. indoors), reader output power (0.5 W vs. 1.0 W) and reader orientation (above vs. sideways) on the average of readings per round and the reading rates was tested. Fig. 6 shows the results of the different environments.

It can be seen in Fig. 6 that the overall mean of readings per round and the average reading rates were higher indoors (22.3; 77%) than outdoors (9.3; 66.1%). The statistical analysis also showed a significant difference between the two environments. Additionally, it can be seen that the variance in the average of readings per round indoors is higher than outdoors. This is the opposite of the situation regarding the reading rates.

Fig. 7 presents the results of the different reader output power (0.5 W, 1.0 W). It can be seen that a reader output power of 1.0 W achieved a greater mean of overall readings (21.5) and higher reading rates (81%) compared to the output power of 0.5 W (10.2; 62%). The statistical analysis again confirmed the graphic evaluation and a significant difference between the two output powers was observed.

Similar to the results for the environment, a higher variance for the better variant was seen in the reading rates in contrast to the average of readings per round. The results for the different reader orientations are presented in Fig. 8. A difference was made here between readers mounted on top of the gate ('above') and readers mounted on each side of the gate ('sideways').

It could be shown that significant differences in the average of readings per round and in the average reading rates also existed in terms of the reader orientation. The overall mean of readings per round and the average reading rates were significantly higher for the reader orientation 'above' (18.4; 78.7%) compared to 'sideways' (13.3; 64.3%). Similar to the other parameters, the variant with the

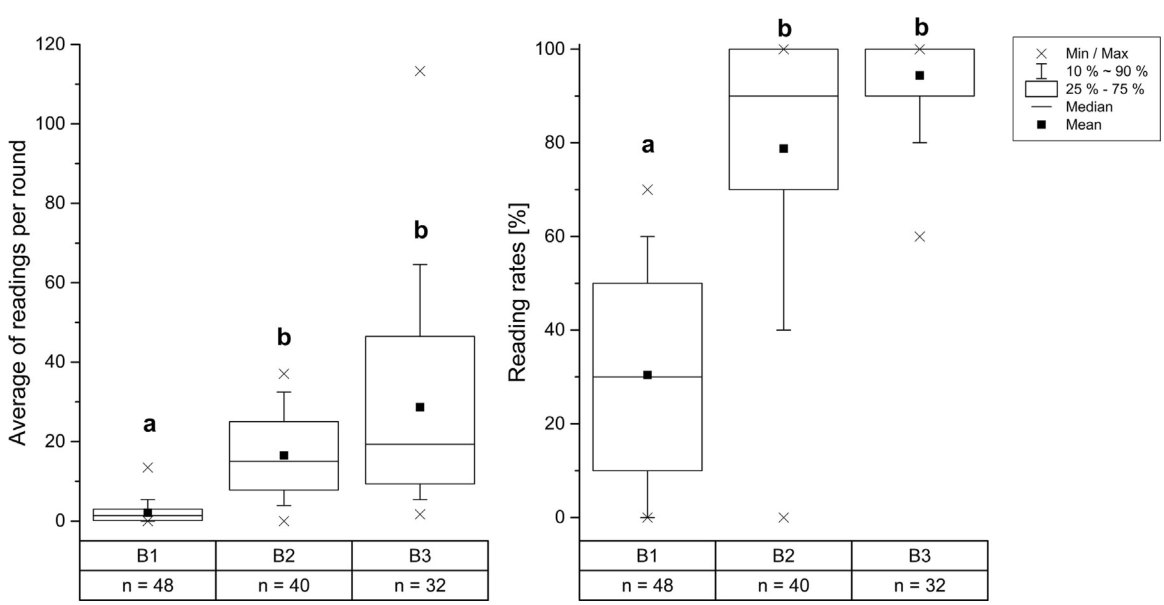

Fig. 5. Average of readings per round (left) and reading rates (right) of cattle transponder types B1, B2 and B3; n: sample size (number of ear tag * repetitions); a, b: different letters indicate that values diverge significantly ($P < 0.05$).

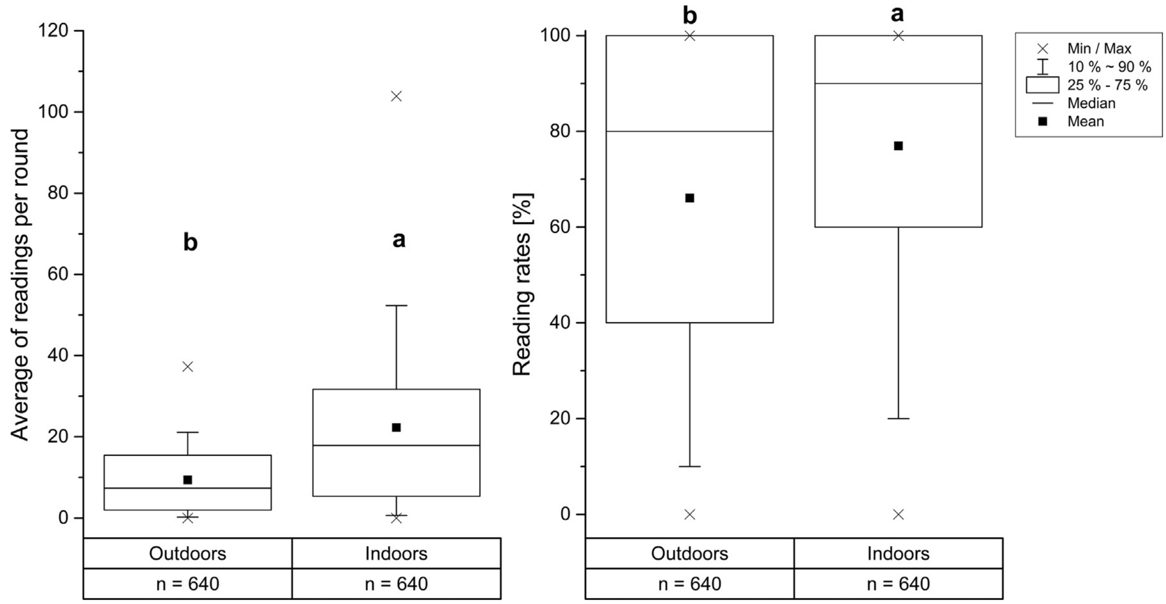

Fig. 6. Average of readings per round (left) and reading rates (right) of cattle transponder types B3-4 and B4-4 indoors and outdoors; n: sample size (number of ear tag * repetitions); a, b: different letters indicate that values diverge significantly ($P < 0.05$).

lower variance of the average of readings per round again had a higher variance than the reading rates. Again in general the reading rates show greater variances for both variants.

All ear tags with these transponder types (B3-4, B4-4) stayed functional over the entire period of experiment, and no losses were recorded.

3.1.3. *Comparison of transponder types B3-4, B4-4 and B5*

The results of the statistical comparison of transponder types B3-4 and B4-4 are shown in Fig. 9. The results of transponder type B5 are also presented in this figure to show them in relation to the results of the two other transponder types.

The differences in the overall mean of readings per round (19.7; 23.2) and the average reading rates (73.8%; 88.3%) between transponder type B3-4 and B4-4 are small, as can be seen in Fig. 9. No significant difference was found for the average of readings per round or for the reading rates. In comparison to these transponder types, type B5 achieved a higher overall mean of readings (27.4), but lower average reading rates (86.8%).

No transponder ear tag broke or was lost on any test day. No decline of the transponder performance over time was observed.

Furthermore, it was remarkable that the reading rates of the individual ear tags differed so greatly. Fig. 10 shows the reading rates of the individual ear tags. Regardless of the environment, the ear tags of transponder type B3-4 varied between 20.3% and 99%, while the values of type B4-4 were between 74.6% and 100%. When considering the ear tags of transponder type B3-4 closer, it should be noted that two particular ear tags (17, 26) showed the poorest average reading rates. The ear tags of transponder type B4-4 ranged more homogeneous.

The average reading rates of the ear tags of transponder type B5 ranged between 28 and 100%. The reading rates of two ear tags

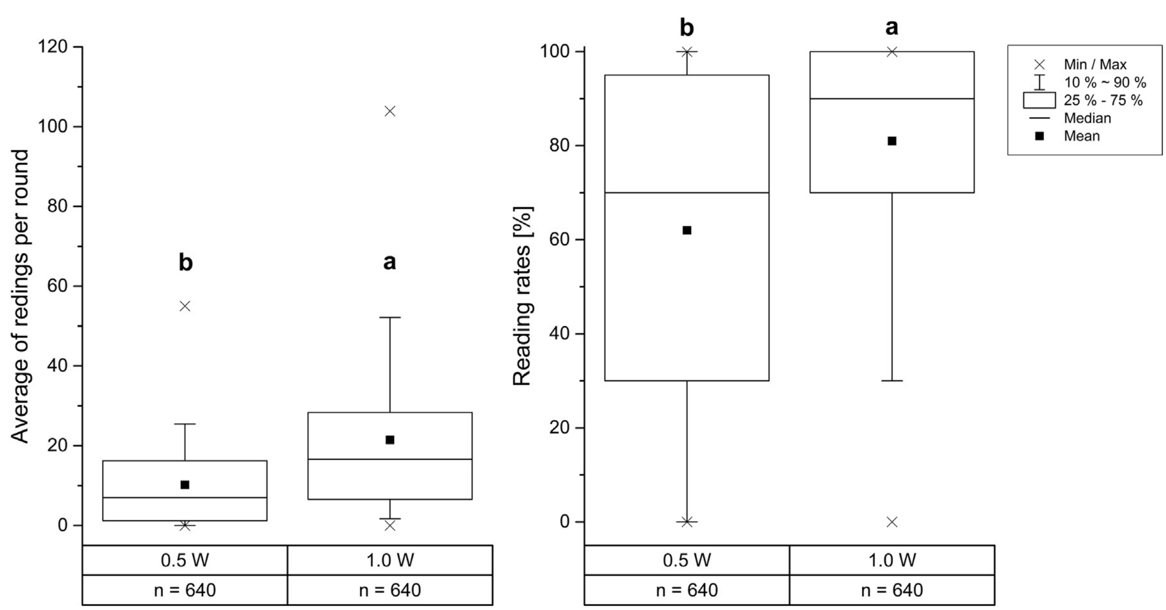

Fig. 7. Average of readings per round (left) and reading rates (right) of cattle transponder types B3-4 and B4-4 with a reader output power of 0.5 W and 1.0 W; n: sample size (number of ear tag * repetitions); a, b: different letters indicate that values diverge significantly ($P < 0.05$).

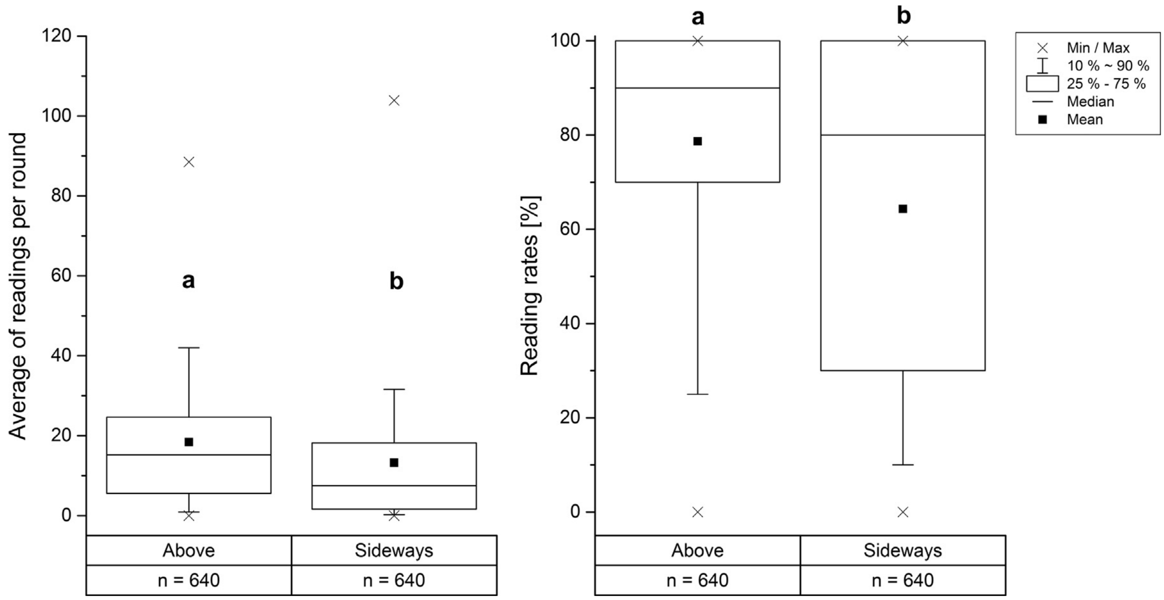

Fig. 8. Average of readings per round (left) and reading rates (right) of cattle transponder types B3-4 and B4-4 in reader orientation 'above' and 'sideways' n: sample size (number of ear tag * repetitions); a, b: different letters indicate that values diverge significantly ($P < 0.05$).

were again considerably worse (7; 17) than the others. The average reading rates without including these two ear tags were between 85 and 100% and, thus, even better and more homogeneous than B4-4.

3.2. Pig experiments

Three transponder types (C1, C1-4 and C2) provided for use on pigs were developed within the project. All ear tags of transponder type C1 were lost or broken in the sixth week of the experiment. Only two ear tags of transponder type C1-4 remained functional until the end of the testing period. Ten ear tags of a third transponder type (C2) were tested in a further experiment. All transponder ear tags were lost or broken within two weeks.

No statistical analysis could be performed for the pig experiments because of the very limited number of ear tags.

The results of performance of the different transponder types can be seen in Fig. 11.

Transponder type C1 performed worse (3.2; 68.5%) compared to type C1-4 (19; 96.5%) in terms of the overall mean of readings per round and the average reading rates. It is also noticeable that the variance of the reading rates for transponder type C1 was quite large. When looking at the averages of transponder type C2, it is conspicuous that the overall mean of readings per round is lower (14.1), but the average reading rate is higher (100%) compared to transponder type C1-4. Within the testing period of transponder type C2, every transponder ear tag was read in every round of the experiment. However, rounds with no readings existed for transponder types C1 and C1-4. Furthermore, it can be seen that the variance within the reading rates is much lower for C1-4 and C2 than for C1.

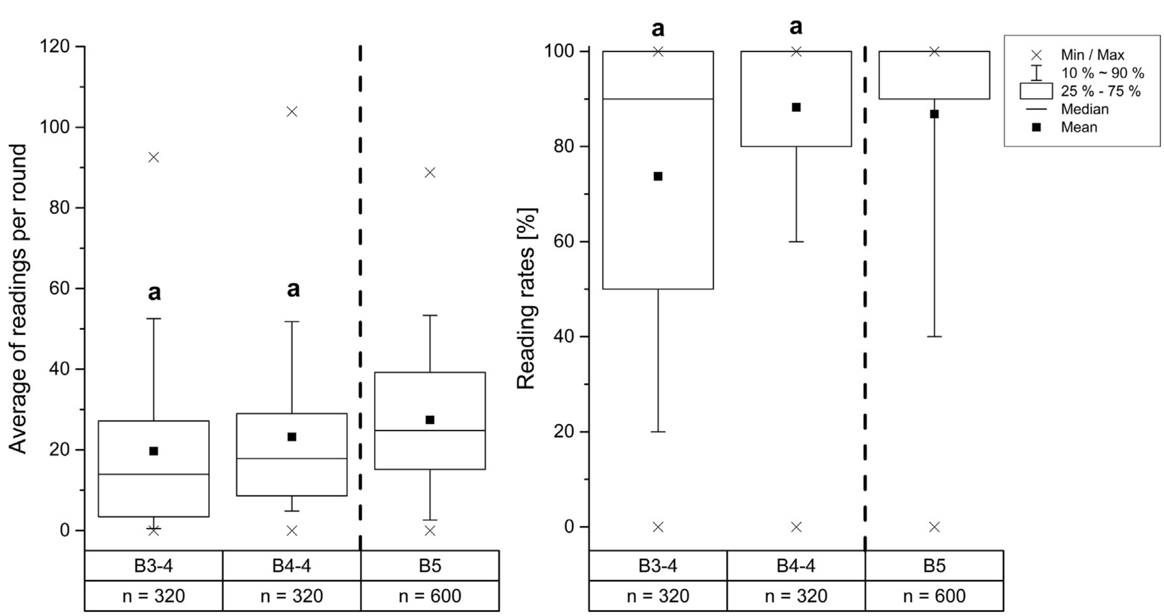

Fig. 9. Average of readings per round (left) and reading rates (right) of cattle transponder types B3-4, B4-4 and B5; n: sample size (number of ear tag * repetitions); a, b: different letters within a transponder type indicate that values diverge significantly ($P < 0.05$); no statistical evaluation for transponder type B5 was performed, as data belong to different experiments.

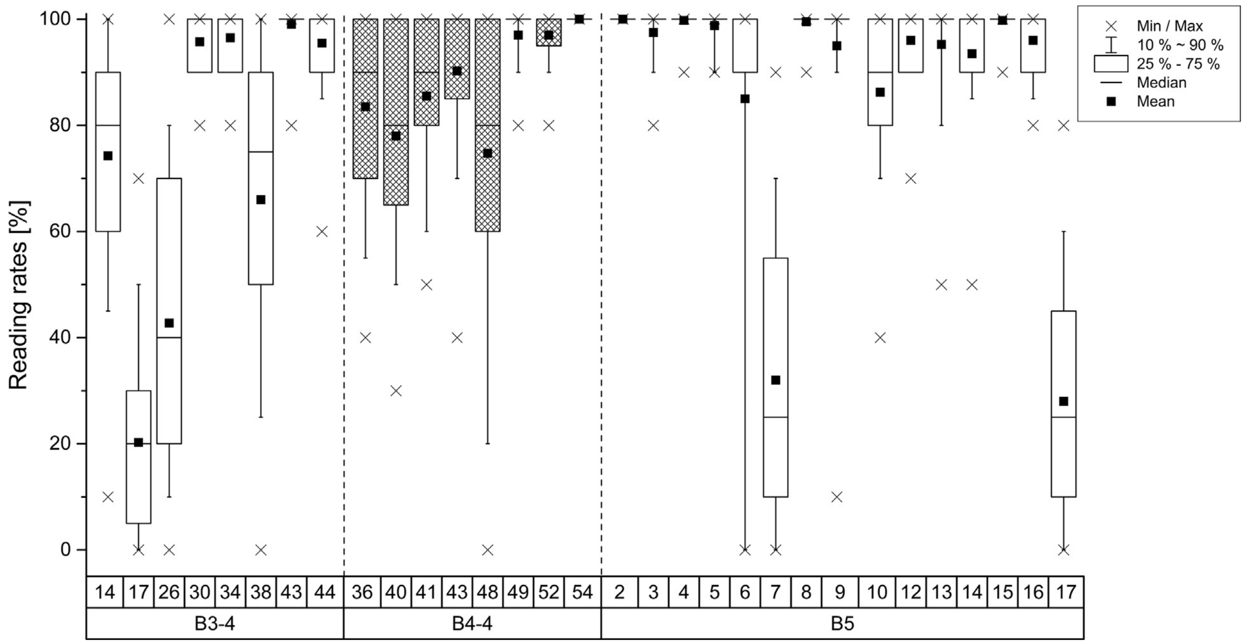

Fig. 10. Reading rates of the individual ear tags named by individual numerals of transponder types B3-4, B4-4 and B5; sample size = 40 (repetitions with 1.0 W).

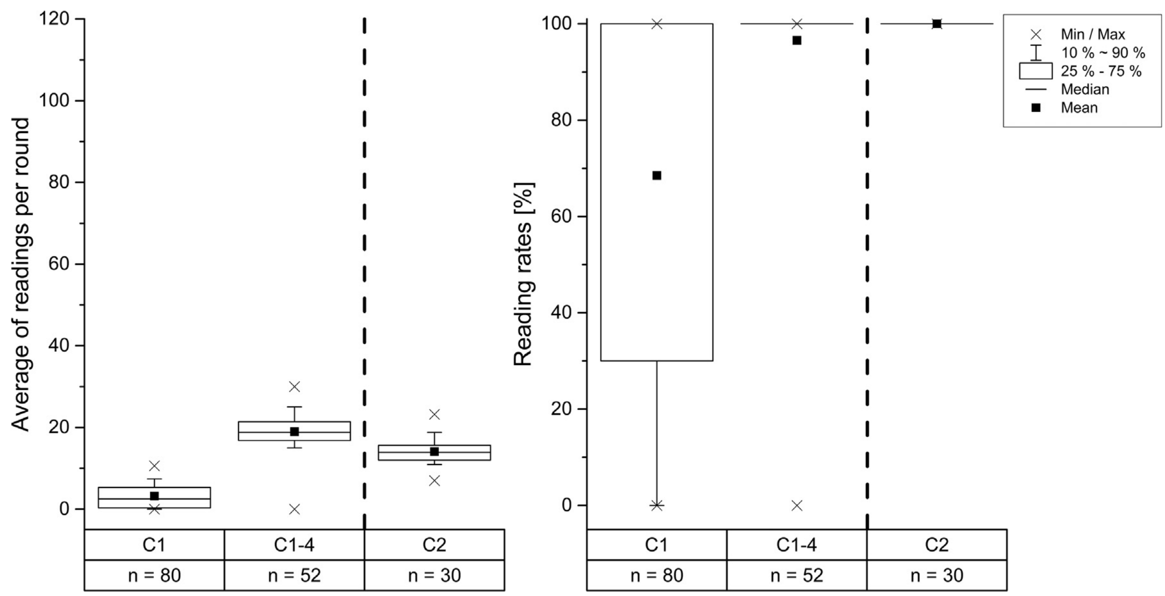

Fig. 11. Average of readings per round (left) and reading rates (right) of pig transponder types C1, C1-4 and C2; n: sample size (number of ear tag * repetitions).

4. Discussion

4.1. Cattle experiments

4.1.1. Cattle experiment 1

Three transponder types for cattle (B1, B2 and B3) developed within the project were compared in the first cattle experiment. Transponder type B3 achieved the highest average reading rate with 94.4%, which is a promising result for the simultaneous detection of cattle. The increasing number of readings per round and the reading rates from type B1 to type B3 can be explained by the adjustment of the resonance frequency. The latter was increased to compensate for the detrimental effects of surrounding materials (plastic ear tag and animal's ear (Table 1)). Transponder type B3 had the highest resonance frequency. The adjustment of the transponders for use in an ear tag seemed to work and an improvement from type B1 to type B3 could be recognised.

4.1.2. Cattle experiment 2

When comparing the two environments, indoors and outdoors, it was remarkable that the overall mean of readings per round and the average reading rates indoors were significantly higher (cf. Fig. 6). This is probably caused by reflections. Indoors, the electromagnetic radiation is reflected by the metallic surface of the barn equipment. In this way, the possibility of a transponder being read by at least one of the two readers is increased. Almost no reflections are present on pastureland (outdoors), thus, the reader–transponder communication has to work in a direct way. If organic material (such as a cow's head) absorbs the electromagnetic radiation, the possibility of reliable reading decreases. This circumstance is also probably the reason for the higher average of readings per round and average reading rate using the reader orientation above. Here again, a significant difference between the two orientations was obtained (cf. Fig. 8). Using reader orientation 'above', the readers radiated from above to the animal's head and the ear tag was covered less by organic material (such as the nose or back of the head of the animal) and could be read more reliably in contrast to the reader orientation 'sideways'. Additionally, with an opening angle of 90°, the distance from the reader to the transponder ear tag was, on average, shorter with this reader orientation. Thus, a higher radiative power of the reader was available for the transponder to send a response signal. A significant difference was found for the parameter 'reader output power'. The overall mean of readings per round and the average reading rates here were significantly higher using a reader output power of 1.0 W (cf. Fig. 7). Again, with 1.0 W, a higher radiative power of the reader is available for the transponder to send a response signal. This is the reason for the difference between the two output powers.

4.1.3. Comparison of transponder types B3-4, B4-4 and B5

An increased number of ear tags would also have assured more reliable results, but a higher number of ear tags was not feasible because of the development process in the project.

Transponder type B4-4 showed a higher average reading rate compared to transponder type B5, but a smaller overall mean of readings per round. Even though no statistical comparison with type B5 was performed, it can be inferred that a further improvement of the adjustment of the cattle transponder was achieved. The average of readings per round and the reading rates improved along the development chain (from experiment 1 to experiment 3). In conclusion, the average reading rates $>86\%$ indoors and outdoors with a reader output power of 1.0 W and the reader orientation 'above' can be declared as a very good result (transponder types B4-4 and B5). These can be compared with the reading rate achieved by Cooke et al. (2010) of about 72% in cattle trials.

Regarding the comparison of the individual ear tags, it was noticeable that the variability between the single ear tags was not as great for B5 as for B3-4 and B4-4. The ear tags especially of type B3-4 showed great differences. The ear tags of type B5 were generally much more homogeneous, except for two ear tags. One reason for the variability in the reading rates could be the individual animals. The shape of the ear and, thus, the position of the ear tag in the animal's ear, the speed of the animal while passing the gate, the position of the animal in the herd and the head posture might have had an influence on the reading success. All of these parameters influence the absorption of the electromagnetic radiation and the power of the response signal of the transponder more or less. Unfortunately, these parameters were not examined in closer detail in this experiment. Small differences in the single transponders themselves could be another reason. Minimal variations in antenna length or structure at this stage of the project could not be excluded. This could also result in a slightly shifted resonance frequency.

4.2. Pig experiment

This experiment with three pig transponder types (C1, C1-4 and C2) can be better described as a first test with a perspective for further pig transponder development because of the very limited number of ear tags due to this early stage of development and a missing statistical analysis. With respect to the reading performance an improvement with the development of the transponder types could be graphically observed. Transponder type C1-4 achieved a good overall mean of readings per round, while type C2 achieved a very good average reading rate of 100%. Such a high reading rate has not been achieved by any other UHF project with pigs (Baadsgaard, 2012; Hogewerf et al., 2013; Stekeler et al., 2011b).

The durability of the pig ear tags has not turned out satisfactory. All ear tags of transponder type C1 were lost or broken within a relatively short time (42 days with already 30% of this type non-functional after 24 days). However, two out of three ear tags of transponder type C1-4 remained functional until the end of the experiment. The ear tags of type C2 again only stayed functional for approximately two weeks.

It was shown that the label material of C1-4 (polyimide foil with aluminium cover) contributes to a better durability of the ear tags through a more effective grouting process. Unfortunately, a better durability of type C1-4 through the polyimide foil, which was clearly visible, could not be proved by the results of transponder type C2.

4.3. Readings per round vs. reading rate

It should be pointed out again that a higher number of readings per round is not synonymous with a higher reading rate. One reading per round is sufficient to be classified as a 100% reading rate. Calculating the reading rates, it makes no difference if an animal stops right under the readers and is read many times or if it runs through the gate fast and is read only once. The reading rate is the decisive factor for the application in practice. A reading rate of 100% should always be the aim for a practical use of the transponder ear tags.

The number of readings per round is suitable to indicate quality differences between the several transponder types. The more readings per round a transponder type achieves, the better its performance potential is and the higher the probability of being actually read in practical applications is. A better performing transponder is also read at a greater distance in front of and behind the gate. This is why the readings per round is more important than the reading rates for the further development with fine tuning of the transponder types.

4.4. Improvement of gate and reader settings

Even though transponder types B4-4 and B5 constitute suitable transponders for simultaneous cattle detection, a further adjustment of the gate should be carried out to ensure an average reading rate of 100%. One possibility would be a further adjustment of the transponder-reader communication by using the so-called 'inventoried flags'. During the anti-collision process, these inventoried flags can be changed by a reader after a successful reading. Afterwards, the transponder is insensitive to further commands from the reader for a certain time period. Consequently, multiple readings of transponders passing the gate could be prevented, resulting in a reduction of data traffic on the air interface. After a predefined time, the inventoried flag of the transponder is reset and the transponder can again be read. This setting is sensible to ensure a high reading rate in practical applications because a single reading per transponder is sufficient to register an animal.

Another adjustment could be made by modifying the reader orientations. The reader orientation 'above' (inclination angle 90°) in the cattle experiments generally achieved better reading rates than the reader orientation 'sideways'. However, the readers could be slightly tipped in the direction of the gateway (change of inclination angle) to further improve this reader orientation and to improve the reading success of the individual transponders. The expected advantage of this adjustment would be the radiance of a greater area in front of and behind the gate. Additionally, an overlap of the reading fields of the two readers (opening angle 90°) would be completely prevented, which would also prevent the simultaneous accessing of a transponder by two readers. In the worst case, a multi-accessed transponder does not get the chance to send a response signal back to the reader and will not be read.

A further option would be the use of more than two antennas. These other antennas could be installed at ground level. Animals walking with hanging heads could be detected more easily. Ultra-high-frequency gates with more than two antennas have already been used for pigs in the project called "PigTracker" (Swedberg, 2012) and for cattle by the company "Hana micron Inc." (Anonymous, 2015).

The ear tag losses in the pig experiment can also be declared as too high.

4.5. Durability and size of the pig transponder ear tags

An improvement in the durability of the pig transponder ear tags is essential for their further use in practice. Reducing the size of the ear tag to a real pig-sized ear tag is the first step to diminish the chewing of the ear tag by other pigs, because the ear tag is more difficult to access. A change in the chip location within the transponder design more in the top-centre of the ear tag is a possibility to optimise the durability of the transponder ear tag. If the transponder chip is bitten, the transponder loses its function immediately, while the transponder antenna can keep its function after being deformed. In the meantime ongoing tests with such modified and smaller pig ear tags show promising results with improved transponder performance and durability (unpublished results).

5. Conclusions

It was demonstrated in several driving experiments with cattle and pigs that flexible UHF transponder ear tags are generally suitable for use in simultaneous detection of transponders in cattle and pigs. Furthermore, it could be proved that driving experiments are suitable and necessary to test UHF transponder ear tags in practice. Suitable and durable UHF transponder ear tags were found in the cattle experiments. Regarding the further development of the transponder ear tag types, it was shown that the correct detuning of a transponder results in a clear improvement in the results and an improvement in the detection reliability. A reading rate of 100% could be reached in the pig experiments, but the transponder ear tags need to be reduced in size and improved in robustness and durability to keep their functionality during the whole lifetime of the pigs. The label and antenna material is a decisive factor for the success of the grouting process of the ear tag. Since the grouting directly influences the protection of the transponder by the ear tag material, the durability of the ear tag also depends on the foil material which has to be chosen carefully. In the present experiments, polyimide foil seems promising.

However, a poor reading performance of individual transponder ear tags, caused by absorption of the electromagnetic radiation by animal body tissue, can occur frequently. This makes it all the more important to optimise the reader gate in different environments to guarantee reliable animal detection, and for administrative purposes. In general, an adjustment of the reader settings and the reader orientation seems sensible to further improve the reading rates.

This study has provided an outlook on the potential of UHF transponder ear tags and shows that a development of special transponders for this scope of application is necessary and promising.

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