Available online at www.sciencedirect.com
ScienceDirect
Livestock Science 116 (2008) 42–52
LIVESTOCK SCIENCE
www.elsevier.com/locate/livsci

Evaluation of retinal imaging technology for the biometric identification of bovine animals in Northern Ireland

A. Allen [a,*], B. Golden [b], M. Taylor [a], D. Patterson [c], D. Henriksen [b], R. Skuce [a]

[a] Agri-Food and Biosciences Institute (Stormont), Stoney Road, Belfast, Northern Ireland, BT4 3SD, UK
[b] Optibrand Ltd., 123 North College Avenue, Suite 240, Fort Collins, Colorado, CO 80524, USA
[c] Agri-Food and Biosciences Institute (Hillsborough), Hillsborough, County Down, Northern Ireland, BT26 6DR, UK

Received 22 May 2007; received in revised form 15 August 2007; accepted 18 August 2007

Abstract

Animal identification is a major requirement for government agricultural authorities, facilitating registration of animals, recording of authorised animal movements, national herd management, payment of appropriate grants and subsidies and as a vital tool in tracing diseases of public and animal health concern. Most schemes are based on a computer database of ear-tag numbers. A potential limitation of such systems has been their tracking of a device attached to the animal, rather than tracing the animal itself. This becomes problematic when accidental loss or fraudulent switching of tags occurs, as preserving correct identification is difficult. Biometric identification offers considerable advantages since the indices used to construct identifiers are unique, unalterable biological properties. We have evaluated a novel technology in bovine animals as a means of scientifically verifying tag-based identity. This system records the unique retinal vascular pattern at the back of an animal's eye as a means of corroborating ear-tag information. 869 animals were imaged to create a retinal identification. Each of these 1738 retinal patterns were compared computationally and visually against each of the remaining 1737, a total of 1,509,453 comparisons. None of these comparisons yielded an identical retinal pattern, indicative that each is unique within this dataset and that the chances of finding two different eyes with an identical pattern is at least 1 in 1.5 million. A further 2266 images taken from the registered animals at later dates were used for successful identification verification with 2227 (98.3%) being successfully computationally matched to the initial images. The remaining 39 (1.7%) were successfully matched by visual inspection. A simulated tag switch involving alteration of ear-tag number for 115 animals, after their initial imaging, was detected for all participants by subsequent imaging and computational comparison. These data indicate that this system could be deployed as a stand-alone technology for animal identity verification. It also has the potential to improve the performance of ear-tag-based identification systems in cattle and could be deployed in support of identification, registration and movement requirements and as a counter-fraud measure.

Keywords: Cattle; Identification; Retinal

1. Introduction

Accurate identification and registration of farm animals and recording of their authorised movements has been a major concern of national governments for many years, aiding control of diseases like bovine tuberculosis, grant

* Corresponding author. Agri-Food and Biosciences Institute (Stormont), Bacteriology Branch, Veterinary Sciences Division, Stoney Road, Belfast, BT4 3SD, UK. Tel.: +44 2 890519424; fax: +44 2890.
E-mail address: Adrian.Allen@dardni.gov.uk (A. Allen).

1871-1413/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.livsci.2007.08.018

and subsidy management and protecting public and animal health. Many countries have adopted national databases, based on numbered ear-tags, to monitor cattle movements (Houston, 2001; Buick, 2004).

Recent globalisation of trade and the formation of the European Common Market (McGrann and Wiseman, 2001) has strengthened the case for improved animal tracking systems. Consumers are presented with increased choice, but also increased risk from chemical/pathogenic contamination in foodstuffs (Caporale et al., 2001; McKean, 2001). The BSE crisis also demonstrated that the actions of one state can impact negatively on the public health of others (McGrann and Wiseman, 2001).

Consequently, European Union (EU) Council Directive 92/102/EEC dictated that all bovine animals in Member States should be identified with an ear-tag bearing a unique identification code shortly after birth (Ammendrup and Fussel, 2001). Council Regulation 1760/2000 (Commission of the European Communities, 2000–Commission Regulation No. 1760/2000), established the need for Member States to control registration and tracking of bovine animals through a computerised database based on a two ear-tag system.

In Northern Ireland, computer database monitoring of the national herd had been in existence since 1988. The original system was designed to facilitate the eradication of brucellosis and tuberculosis (Houston, 2001). However, in 1998 this system was superseded by the Animal and Public Health Information System (APHIS), which had increased functionality to manage identification, registration, movement and general traceability of animals. To date, APHIS facilitates the registration of all animal births, movements, test histories and slaughter, based on the two ear-tag system (Houston, 2001).

Future development of tag schemes may include the use of electronic identification devices such as radio frequency transmitter (RFID) ear-tags, ruminal boluses and injectable transponders which can improve existing practices by automating the reading of animal identifications and reducing transcription error (Ribo et al., 2001).

The EU recently funded a trial on the effectiveness of electronic identification called the 'Identification Électronique des Animaux' project. In total, this project investigated the application of RFID ear-tags, ruminal boulses and subcutaneous transponders to 370,000 cattle. The final report (Report from the Commission to the Council and the European Parliament, 2005) indicated that whilst boluses and transponders offered superior retention and read rates, recovery at time of slaughter was not as good as that observed for RFID ear-tags. Therefore, the report recommended that Member States should have the option of applying these ear-tags in place of the second conventional ear-tag required by EU law. Whilst lauding the ability of such a system to improve farm management, the report confirmed that RFID ear-tags still suffered from the same tag loss and switching problems which afflict conventional schemes. A recent study in intensively farmed buffalo has revealed mean conventional ear-tag retention time to be 272 days (Fosgate et al., 2006) and highlights the herd management and epidemiological problems this causes owing to difficulties in re-assigning correct identification.

Next-generation identification devices, such as RFID tags, boluses and transponder chips, whilst making animal management easier, still suffer many of the same constraints as conventional devices. Conventional and electronic identification systems rely on tracking devices (ear-tags, boluses, transponders etc), which are attached to animals, but not the animals themselves. However, biometric identification, which utilises unalterable biological properties of individual animals to produce a unique identifier, offers a potential solution.

Two biometric technologies, which can produce secure, unique identifiers are DNA profiling and retinal imaging (Pettitt, 2001). DNA profiling, whilst being a powerful tool for scientifically verifying animal identity, is currently limited by the fact that verification results cannot be generated in real-time i.e. beside animal, for most applications. It is unlikely therefore to become the primary identifier for live animals. It can be used effectively in retrospective audits, meat tracing and parentage verification (Caporale et al., 2001; Cunningham and Meghen, 2001; Houston, 2001; Raspor, 2004) as a traceability technology and counter-fraud measure.

Retinal vascular patterns (RVPs) appear to offer considerable advantages as biometric identifiers, not least because modern technology, such as the Optibrand system assessed in this study, is designed to facilitate the secure capture and analysis of RVP images beside the animal as a means of verifying identity. This function is linked, uniquely and securely, to GPS-based positioning.

The aims of this study were to assess:

1. The practicality of using the Optibrand system to capture and analyse good quality initial registration RVP images from bovine animals.
2. The capability of the system to capture and use subsequent RVPs from the same animals for the purposes of verifying correct APHIS identity and detect switched APHIS identity by comparison to initially captured images.

3. The error rates associated with verifying and refuting identity by the above methods and the usefulness of RVPs as unique biometric identifiers and their potential to quality assure the existing APHIS identification system.

2. Materials and methods

2.1. Retinal vascular pattern as a biometric identifier

Human eye biometric identifiers are common (Daugman, 2000), their informativity based on the analysis of patterns in the iris or ocular fundus. Golden (1998) proposed RVP images as a biometric identifier of cattle. These identifiers have the advantages of uniqueness, stability, high accuracy, speed, low cost, and no laboratory tracing. It has been shown that the patterns of RVPs are stable from birth and unchanging over an animal's life (Marchant, 2002), whilst Simon and Goldstein (1936) reported human eyes have a unique pattern of blood vessels that is different in each eye. This finding was substantiated by Huntzinger and Christian (1978) who studied retinal vasculature in identical human twins.

The retinal artery enters the inside of the eye along the optic nerve and then divides to supply the inner retina (Hogan and Zimmerman, 1962). The venous system drains from the inner retinal surface into the central retinal vein and exits the eye along the optic nerve. The geometric configuration of this vascular development occurs during fetal growth as vasculogenesis (Baldwin, 1996) and angiogenesis (Kinoshita and Honda, 1991) occur.

Retinal angiogenesis follows a Laplacian (Peterson, 2001) mathematical process, common in nature (Kinoshita and Honda, 1991). As with all Laplacian processes including tree branch formation, the pattern created by formation of the retinal vasculature appears to be a recursive process, influenced by random factors. Given the results of Simon and Goldstein (1936) and also Huntzinger and Christian (1978), there appears to be no evidence of genetic influence on the measured characteristics of the patterns. In normal, healthy eyes of post-natal animals, all of the factors influencing pattern formation appear to be pre-natal.

The RVP in domestic livestock has the following characteristics: 1) the presence of a large vascular network in the major portion of the light-sensitive portion of the retina; 2) blood vessels extend from the optic disk to the jagged margin between the light-sensitive and insensitive portions of the retina; 3) comprised of large and small vessels; with the large arterioles near 100 μm and large venules near 200 μm making them visible without magnification (De Schaepdrijver et al., 1989).

The mean and variance of vessel branching in bovine retina has been characterized (Whittier et al. (2003) as 12.8 total vessel branching points with a variance of 4.3 within the field of view of images collected, respectively. Therefore large orders of combinations to distinguish animals reliably can result from combining information about the relative positions of branch vessels, branch angles and branch size. A computational algorithm based on this premise is used in the Optibrand system to compare and match RVPs.

2.2. The Optibrand system

Optibrand have developed a hand-held device (Golden et al., 2004), called the OptiReader™, including a controlling computer and data-logger, digital video camera and a GPS receiver. Once the Optireader™ is switched on, the GPS aerial locates and logs its location to within 3 m. Image data recorded will be tied to this location at their exact time and date of capture. These data are securely linked to the RVPs imaged as an encrypted bundle known as a blob file, in a removable flash card connected to an internal docking point within the controlling computer.

Collation of all this information into a blob file provided continuity of evidence about each animal imaged. After the images were collected, they were transferred to a program called Data Management Software (DMS). DMS can be installed on any modern Windows PC or laptop with high speed internet access and permits the management of the image data and other data collected. The computational comparison of large numbers of images in a reasonable amount of time was impractical on personal computers. Therefore, a remotely accessible software Engine, based in Optibrand's headquarters is used for the analysis of RVP pair image data. These images pairs are analysed in real-time with results and matching scores presented to the sender within minutes. The current specification of the Engine software permits it to perform 20 pair matches per minute. The matching process utilised the matching algorithm, and depending on the degree of similarity in vessel size, vessel position and branch angles observed between pairs of RVPs, a score was assigned between zero and one hundred. The higher the score, the more likely the images in the pair were from the same eye. The recommended procedure for implementation of Optibrand's scoring procedure was to use it as a method of sorting large collections of images to identify candidates for visual inspection. The scoring procedure, whilst highly effective at resolving RVP features, was not intended to provide a definitive statement of whether image pairs were from the same individual or not, as visual matching is more powerful than computational. Visual inspection candidates would be selected by assigning an inspection threshold (IT) score value to the distribution of algorithm scores. For example, scores between pairs of images that should match but did not exceed the IT were visually inspected to make a final determination of match identity.

2.3. Animals

All animals were healthy and drawn from production research herds at AFBI Hillsborough and the Department of Agriculture and Rural Development's Greenmount Campus of the College of Agriculture Food and Rural Enterprise (CAFRE). All sampling was performed in accordance with the Animals (Scientific Procedures) Act 1986. Animals sampled, their breed, sex, age at time of sampling, range of occasions they were re-sampled and interval between initial and final samplings can be found in Table 1. Some animals were not available for secondary imaging.

AFBI staff with animal handling experience performed the imaging after 1 days training and a fortnight of practice. Cattle

Table 1
Herd level information and sampling details for animals sampled at AFBI Hillsborough and CAFRE

No. of animals initially sampled for registration	Breed	Sex ratio	Age range at time of initial sampling (years)	Range of repeat samplings per animal	Range of time interval between initial and final samplings (days)	No. of animals initially sampled but lacking subsequent sampling
869	31 Aberdeen Angus 32 Belgian Blue 3 Blonde D'Acquitane 174 Charolais 9 Friesian 371 Holstein 3 Jersey 180 Limousin 2 Meuse Rhine Issel 43 Norwegian Red 21 Simmental	492 Female 377 Male	0.1–9.1	1–14	0.5–255	93

were restrained by single and double-gated Morris Cattlemaster crushes which closed just behind the animals' heads but permitted limited vertical and horizontal movement. All animals were imaged indoors/under cover to avoid the effects of outdoor light which narrowed the animals' pupils and restricted the view of the retina. To obtain RVP images in this study, cattle were worked through a race with a crush at one end. Once animals were restrained by the crush, the keypad on the OptiReader™ was used to manually enter each animal's ear-tag identification number. The user then approached the animal's head and directed the camera into its eye whereupon a light source illuminated the ocular fundus and a live feed of the retinal image appeared on the controlling computer's screen. Software analyses each frame of the video stream looking for an image with the characteristics of a bovine RVP. The software also determines quality attributes of the image including detecting the presence of glare and proper focus. When a single frame meets the software's acceptability criteria, the device presents the frame to the operator for final acceptance. As well as collecting retinal images, the OptiReader™ devices were also used to collect images of ear-tags and electronic ear-tag information via a wireless connection to an RFID reader.

869 cattle were imaged in both eyes as described to create retinal identifications. These 1738 RVP identifications were linked to each animal's APHIS ear-tag number and termed as Initial Registration RVPs (IR RVPs). A further 2266 images were collected from the same animals, again linked to individual ear-tag numbers and termed as Secondary identification Verification RVPs (SIV RVPs).

To simulate cattle identity switching, single eye images from 115 animals, selected at random, were deliberately, incorrectly labelled with the ear-tag number of another animal from the initial registration sampling of 869.

2.4. Data analysis

In order to evaluate the distributions of Engine scores comparisons were made for two types of image pairs. 1) Scores were

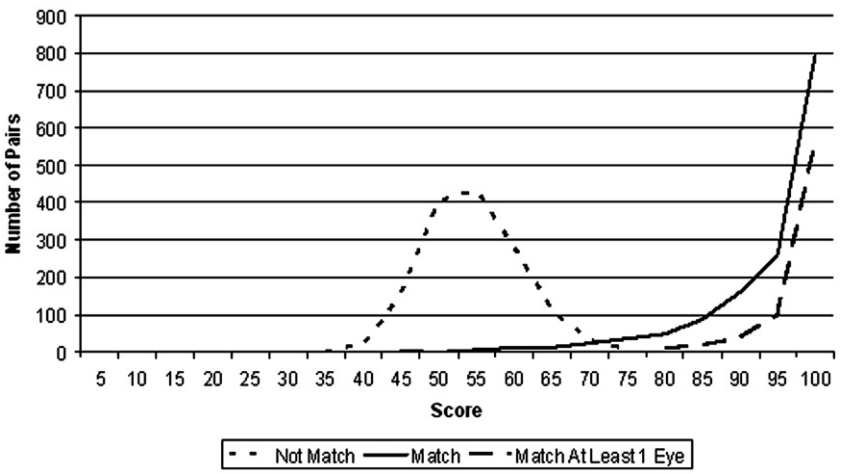

Fig. 1. The distributions of scores for pairs of images that should not match (Image pairs from different eyes), should match (image pairs from the same eye), and the highest score from two eyes. Using the highest score from both left and right eye comparisons is a method used to evaluate a confirmation of identity.

determined for images of the same eye taken at consecutive data collection times. 2) Scores were also determined by comparing an image of an eye to a subsequent image taken of the same animal's other eye. This was done to create an equal number of comparisons that should match and that should not match and to determine an IT value that would effectively discriminate between true matches and true non-matches.

In all subsequent testing, the term 'match' is used to convey the fact that SIV RVPs visually and/or computationally matched the IR RVP obtained from the same eye of the same animal on a previous occasion and was sufficient to verify the APHIS identification of that animal. Individual SIV RVPs were expected to match only one of the IR RVPs per animal initially enrolled. 'Non-match' is defined as a failure to visually and/or computationally match an SIV RVP to either of the two IR RVPs taken from the animal, which the SIV RVP is labelled to represent.

All 2266 SIV RVPs were initially visually compared to both IR RVPs obtained from animals with the same APHIS ear-tag identifier. A 'match' result was assigned to each individual SIV RVP if they visually matched the IR RVP obtained from the same eye of the animal bearing the same APHIS identifier. It was necessary to perform this visual match prior to computational comparison of all image pairs so as to confirm matching between all same eye RVP pairs. The latter would then make it easier to assess the number of true matches which the computational algorithm failed to detect by virtue of their match score not exceeding the IT.

All 2266 SIV RVPs were computationally compared to both IR RVPs from animals with the same APHIS identifier. A

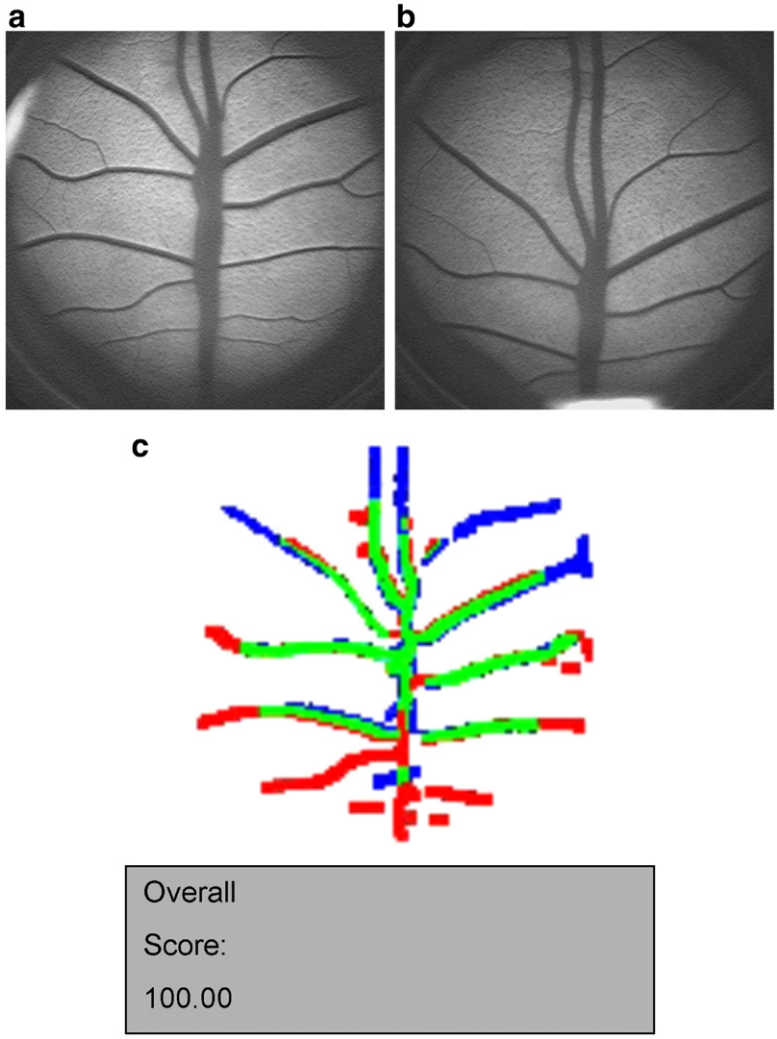

Fig. 2. Example of a matching pair of RVPs from the same eye of the same animal, sampled on separate occasions, which were correctly computationally matched (score>75) by the Optibrand Matching Engine. (a) Initial registration RVP taken at time of first sampling, (b) Secondary identification verification RVP of the same eye taken on a subsequent occasion, (c) Overlap of RVP patterns and Engine assigned match score.

'match' result was assigned to each individual SIV RVP if they exhibited an IT larger than the determined threshold when compared to the IR RVPs obtained from the same eye of the animal bearing the same APHIS identifier. Those exhibiting a lower score were noted as requiring another visual inspection using the process described above.

The 115 deliberately, incorrectly labelled SIV RVPs were also visually and subsequently computationally compared to both IR RVPs of the animals they were falsely labelled to represent. Failure to visually or computationally match these RVPs to either of the two IR RVPs resulted in a 'non-match' result being assigned.

Finally, as a measure of the uniqueness of individual RVPs, and in support of their use as a stable identifier in this data set, each individual IR RVP was computationally compared to each of the other 1737 IR RVPs which they should not match. This set of 1,509,453 individual comparisons was expected to result in some spurious computational matches exhibiting scores above the selected IT threshold. These spurious matches were then visually inspected to make a final judgement as to whether they truly matched or not.

3. Results

Fig. 1 shows the distributions of scores for pairs of images of the same eye and when pairs of images are of different eyes. These data indicate that the score ranges necessary to detect true and false matches are distinct and exhibit very little overlap. Because the degree of

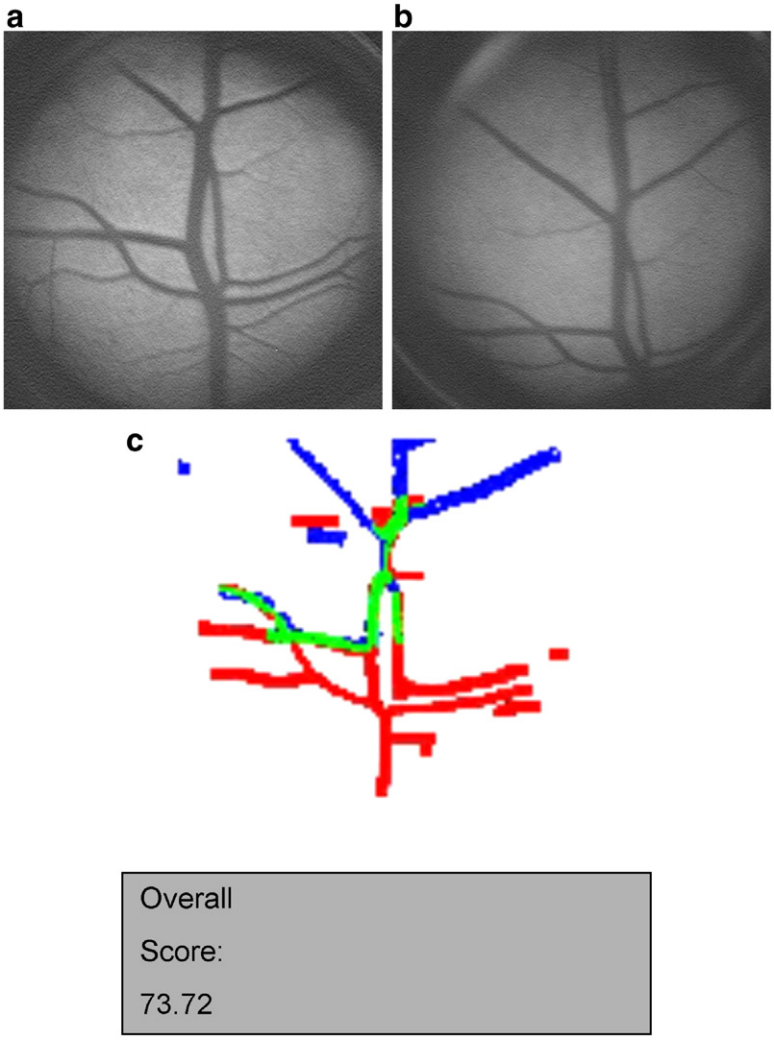

Fig. 3. Example of a matching pair of RVPs from the same eye of the same animal, sampled on separate occasions, which were not computationally matched (score<75) but were visually matched. (a) Initial Registration RVP taken at time of first sampling, (b) Secondary identification Verification RVP of the same eye taken on a subsequent occasion, (c) Overlap of RVP patterns and Engine assigned match score.

relatedness between animals was unknown, making comparisons within animal, within and between eyes would include all common genetic and permanent environmental influence on the score, if it existed.

From the data described above, it was decided that an IT of 75 was deemed suitable for the matching of image pairs in this study —see Discussion below. Of the 2266 images collected in the secondary imaging sessions of the initially enrolled 869 animals, 2227 (98.3%), exhibited match scores of 75 or greater when compared to IR RVPs of the same eye from the animal bearing the same APHIS identifier. All of these pairs were also assigned a match result after visual inspection. An example of one such pair can be seen in Fig. 2 where the score was 100.

The remaining 39 SIV RVPs (1.7%) exhibited match scores of less than 75 and were subsequently short-listed for visual inspection. By visual inspection, it was determined that all 39 SIV RVPs matched the IR RVPs taken from the same eye of the same animals. An example of a pair of RVPs which required visual matching can be seen in Fig. 3.

All 115 images (100%) from the identification switch trial when subjected to computational analysis by the matching algorithm failed to result in scores above the IT

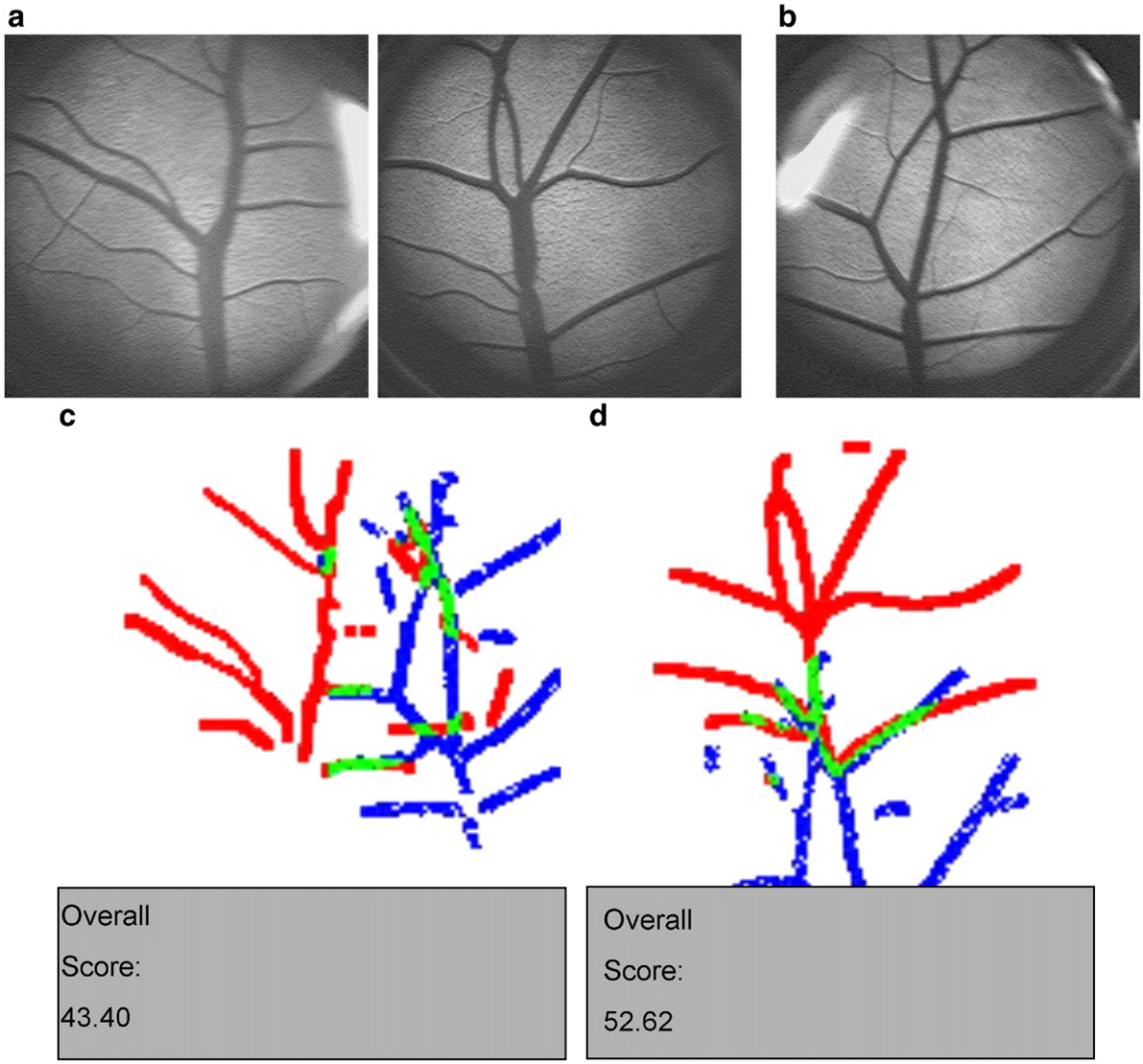

Fig. 4. Example of Simulated Cattle identification switch detected by the Optibrand Matching Engine (score<75). (ai) and (aii) Initial Registration RVPs from left and right eyes of AFBI Hillsborough dairy animal number 144, (b) Secondary identification Verification RVP taken from AFBI Hillsborough dairy animal 236, but falsely labelled as animal 144, (c) Overlap of RVP patterns and Engine assigned match score for RVP (b) against RVP (ai), (d) Overlap of RVP patterns and Engine assigned match score for RVP (b) against RVP (aii).

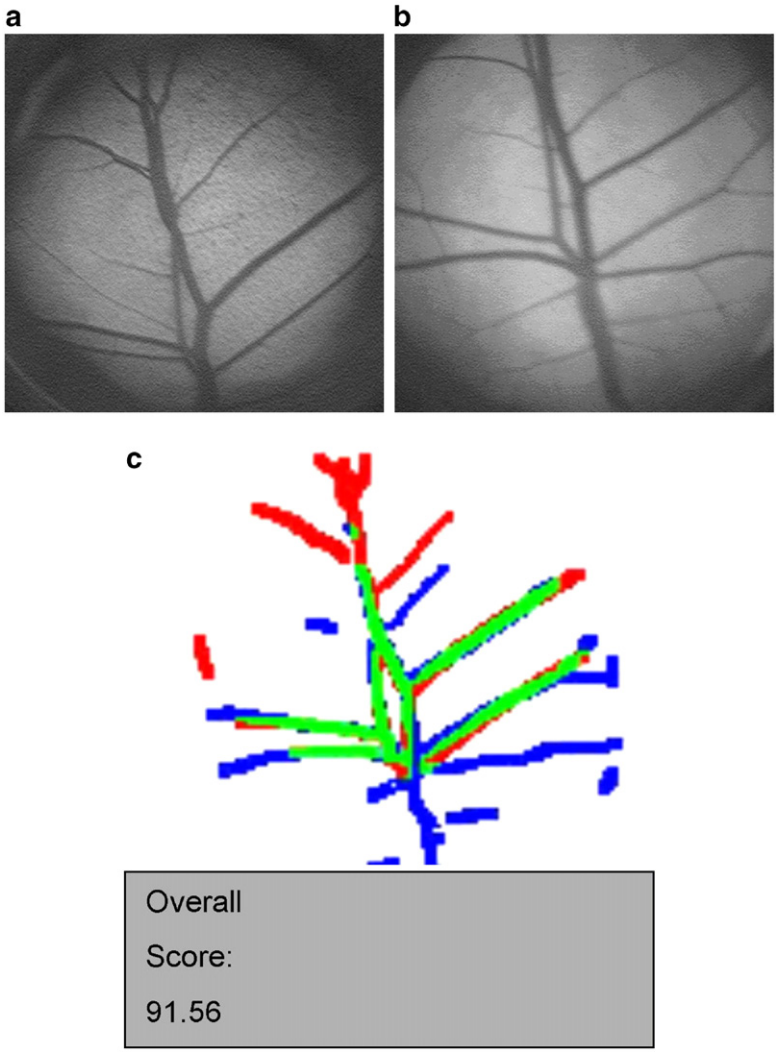

Fig. 5. Example of computational false match IR RVP pair exhibiting highest score over IT (>75). (a) IR RVP from animal 506, (b) IR RVP from animal 1146, (c) Overlap of RVP patterns and Engine assigned match score.

when compared to both IR RVPs of the animals they were falsely labelled to represent. Visual inspection also showed this to be the case. An example of such an identification switch and its detection by the system can be seen in Fig. 4.

The computational comparison of all single IR RVPs against all other IR RVPs resulted in 5680 spurious matches (0.38% computational false positive rate) which exhibited IT values above the selected threshold of 75. Upon visual inspection, all of these computational matches were determined to be false positive and assigned a non-match result. The spurious match pair exhibiting the highest score above the IT can be seen and visually inspected in Fig. 5.

4. Discussion

Operators were trained to use of the OptiReader ™ system. After one day of training, operators were proficient in acquiring RVP images. Further practice over the ensuing fortnight increased operator proficiency and image quality whilst decreasing time taken to acquire images. On average, an animal could be run through a race, restrained by a single or double-gated crush and have both eyes imaged in approximately 2 min.

The level of restraint required for imaging was best achieved using a double-gated crush which extended the neck and minimised both horizontal and vertical head movement. Operators trained using higher specification

crushes easily adapted to single-gated crushes without any detrimental effects on image quality. Also, the OptiReader™ camera produces a live feed of video at a speed of 19 frames per second, even with disruption caused by head movement, this speed is sufficient to capture one frame of video containing an RVP that passes image capture software criteria.

Strong ambient light compromises the effectiveness of the OptiReader™ in acquiring good quality RVPs. For this reason, virtually all of the animals in this study were imaged indoors. However, at some of the locations, crushes were located outdoors or in byres open to daylight. With portable shading in place, we observed that imaging resulted in quick capture of good RVPs. The OptiReader™ can be used to capture RVPs after minimal training in a variety of farm conditions provided there is sufficient animal restraint. This flexibility of approach is essential when one considers that not all commercial farms will have the same facilities.

With regard to the evaluation of the usefulness of RVPs in verifying or refuting cattle identity, the results of this study are very favourable and suggest that the technology could have applications in improving the performance of tag-based identity schemes and cattle forensics. Smith et al. (2005) described ten potential applications for animal traceability systems, seven of which involved forensic considerations, including the control of movement of animals, confirmation of animal identification for subsidy payments (Rusk et al., 2006), source verification of animals for contractual supply agreements. Depending on the nature of the forensic application chosen, one has the flexibility of assigning a suitable IT. Setting the IT for either a higher or lower score value created a trade off between visually inspecting pairs of images that should not match but the score was above the IT, or inspecting more images between pairs of images that should match but the score was below the IT.

The data shown in the bi-modal distribution in Fig. 1 demonstrated that to maximise the detection of false RVP matches, it would be best to opt for an IT of 75 or greater. Minimising the number of true matches requiring visual inspection would be beneficial in assessing the system's ability to verify correct animal identity. For this reason, an IT of 75 was chosen since it serves to discriminate between true and false matches at a stringent level (Fig. 1). This hypothesis was supported by the observation that 2227 of the 2266 SIV RVPs collected in the study were matched computationally by the Engine to their corresponding IR RVPs from the same animals (see Fig. 1) with only 39 SIV RVPs (1.7%) short-listed for visual inspection. For these 39 images, it was obvious that a poor matching score had arisen from at least one image of the pair being very low quality or purely from the capture of mostly different areas of the same retina during different imaging sessions (see Fig. 2). This resulted in RVPs which did not exhibit sufficient areas of overlap, hence the scores did not exceed the IT. However, in all image pairs there were elements of the RVP that were visible in both images such that conclusive identification was possible. Hence, these 39 RVPs were designated as false non-matches.

The finding that the Matching Engine flagged all 115 incidents of simulated identity switching by assigning a score lower than the IT when compared to both IR RVPs of the animals they were falsely labelled to represent (see Fig. 4), illustrates the power of this system to detect identity changes. Confirmation of this finding by visual inspection served to distinguish these true non-matches from the 39 false non-matches mentioned above.

From the comparison of all 1,509,453 IR RVP pairs, the fact that 5680 pairs which did not visually match, computationally exceeded the IT threshold is indicative of a computational false positive match rate of 0.4%. These data indicate that for identification verification purposes, computational matching has a sensitivity of 98.3%, (1.7% false non-match rate) and a specificity of 99.6% (0.4% false match rate). This demonstrates the usefulness of the matching engine algorithm's ability to effectively sort through large sets of RVPs. When combined with visual inspection, as in this study, it is possible to verify correct identification in 100% of occasions. Detection of identification switches by the matching engine is also highly effective with only a 0.4% chance of a false positive result being assigned. However, this small chance of an incorrect identity not being detected is also overcome by visual inspection. This type of procedure has been used in all forms of automated biometric identification including DNA and fingerprint analysis, where final outcome is determined by an operator.

In forensic applications of biometric identification using DNA, it is necessary to estimate the rate at which a randomly drawn individual matches some other randomly drawn individual. An equivalent rate for the procedure used in this study is useful in a variety of forensic applications. A point estimate of the rate is more difficult for the retinal identification procedure than for DNA, because the variation of the features of RVPs cannot be codified into specific classes like alleles. However, using the results of the current study it is possible to estimate an upper limit for this rate. The probability that an RVP from one eye in a randomly drawn animal matches another randomly drawn animal RVP is equal to the frequency of pairs of images from

different eyes matching when all possible comparisons are made. This was performed in the computational comparison analysis of all possible IR RVP pairs. The fact that the 5680 spurious match pairs were visually confirmed to be non-matches indicates that the rate of pairs that matched among all comparisons was zero, and therefore an upper limit could be estimated for false match rate. The limit was estimated by evaluating the point estimate resulting if one comparison among the 1,509,453 resulted in a false match. The true value was likely to be below this limit:

$$P(I_i)P(I_j|I_i) = \frac{2}{1738} \times \frac{1}{1737} = \frac{1}{1,509,453} = 6.62492 \times 10^{-7}$$

$P(I_i)$ was the probability of randomly drawing one of the two images involved in the false match; $P(I_j|I_i)$ was the probability of randomly drawing the second image from the remaining images. Thus, the frequency of an image from a single eye of a randomly drawn individual matching another image of a single eye from a different randomly drawn individual was estimated to be less then 6.62492×10^{-7}. Then if the second eye on each individual is considered, the frequency of both eyes matching was estimated to be less then $(6.764344 \times 10^{-7})^2 = 4.38895 \times 10^{-13}$, a very small number.

These data illustrate the diversity and complexity of vascular patterns observed in bovine animals and add further weight to their use as a means of uniquely identifying individuals.

In this study, the Optibrand system was applied as a means of identity verification, defined as confirming or refuting identification by comparing SIV RVPs, against existing IR RVPs supposed to come from the same animal. An alternative application not tested in this study was that of a biometric database search. In this scenario, if identification could not be verified by the method detailed above — perhaps because of an identity switch, one could compare the unmatched RVP against all other RVPs from all animals in the dataset in the hope of finding a match to the real animal of origin. Obviously this would entail that the database should contain RVPs from all animals that the unmatched animal's RVP could conceivably have come from. On a national scale, this would imply imaging most if not all of the national herd. Whilst entirely possible to achieve, such a strategy would be harder to finance and also logistically more difficult to perform. The verification application would allow for targeted identification confirmation and refutation suitable for a number of regulatory applications. Such a system could be used for the quality assurance of national cattle registers, using RVP and GPS information to scientifically confirm ear-tag identification and confirm movements from farm to farm/farm to mart/farm to abattoir. RVP identification verification would also be a powerful tool in scientifically quality assuring the removal of diseased animals from the national herd and in detecting breaches of such schemes for the purposes of fraudulent financial subsidy gain.

Acknowledgements

This project was funded by The Department of Agriculture and Rural Development for Northern Ireland, under its 'Vision for the future of the Agri-Food Industry' research programme. All imaging was performed by Mr Stephen Gilkinson, Mr Ken Clarke, Mr Alistair Thompson and Mr Brian Dawson of AFBI Hillsborough. Sampling was arranged and facilitated by Mr Brian Gourley of AFBI Stormont. Thanks to Mr Charlie Kilpatrick and Mr Victor Woods of CAFRE Greenmount for arranging sampling of CAFRE animals. Thanks to Dr Stanley McDowell of AFBI Stormont for his advice on data analysis.

References

Ammendrup, S., Fussel, A.E., 2001. Legislative requirements for the identification and traceability of farm animals within the European Union. Revue Scientifique et Technique 20, 437–444.

Baldwin, H.S., 1996. Early embryonic vascular development: review. Cardiovascular Research 31, E34–E45.

Buick, W., 2004. Animal Passports and Identification. Defra Veterinary Journal 15, 20–26. http://www.defra.gov.uk/animalh/svj/vol1501/chap4.pdf. Accessed December 2, 2005.

Caporale, V., Giovannini, A., Di Francesco, C., Calistri, P., 2001. Importance of the traceability of animal products in epidemiology. Revue Scientifique et Technique 20, 372–378.

Commission of the European Communities, 2000. Regulation (EC) No. 1760/2000 of the European Parliament and of the Council of 17 July 2000: establishing a system for the identification and registration of bovine animals and regarding the labelling of beef and beef products and repealing Council Regulation (EC) No. 820/97. Official Journal of the European Communities. L. Legislation 204, 1–10.

Cunningham, E.P., Meghen, C.M., 2001. Biological identification systems: genetic markers. Revue Scientifique et Technique 20, 491–499.

Daugman, J., 2000. Biometric Personal Identification System Based on Iris Analysis. U.S. Patent No. 5,291,560.

De Schaepdrijver, Simoens, L.P., Lauwers, H., De Geest, J.P., 1989. Retinal vascular patterns in domestic animals. Research in Veterinary Science 47, 34–42.

Fosgate, G.T., Adesiyun, A.A., Hird, D.W., 2006. Ear-tag retention and identification methods for extensively managed water buffalo (*Bubalus bubalis*) in Trinidad. Preventive Veterinary Medicine 73, 287–296.

Golden, B.L., 1998. Retinal imaging: an unalterable livestock biometric identification method. Proceedings of the National Farm Animal Identification Symposium. St Louis, MO, Nov 8–10, 1998.

Golden, B.L., Rollin, B.E., Switzer, R.V., Comstock, C.R., 2004. Retinal vasculature image acquisition apparatus and method. U.S. Patent No. 6,766,041.

Hogan, M.J., Zimmerman, L.E., 1962. Retina. In: Opthalmic Pathology, An Atlas and Textbook. 2nd edn. Eds W.B. Saunders. p.475

Houston, R., 2001. A computerised database system for bovine traceability. Revue Scientifique et Technique 20, 652–661.

Huntzinger, R.S., Christian, J.C., 1978. The retinal blood vessel pattern in twins. Progress in Clinical and Biological Research 24, 241–246.

Kinoshita, M., Honda, Y., 1991. The fractal property of retinal vascular pattern. Investigative Opthalmology and Visual Science 32, 1082.

Marchant, J., 2002. Secure Animal Identification and Source Verification. JM Communications UK. Copyright Optibrand Ltd., LLC.

McGrann, J., Wiseman, H., 2001. Animal traceability across national frontiers in the European Union. Revue Scientifique et Technique 20, 406–412.

McKean, J.D., 2001. The importance of traceability for public health and consumer protection. Revue Scientifique et Technique 20, 363–371.

Peterson, M.A., 2001. Mathematical Meristems: The Singularities of Laplacian Growth. In: Branching in nature: dynamics and morphogenesis of branching structures, from cell to river networks. Les Houches School, October 11–15, 1999/Eds, V. Fleury, Gouyet, J.F., Leonetti, M. Berlin; New York: Springer; Les Ulis: EDP Sciences, c2001.

Pettitt, R.G., 2001. Traceability in the food animal industry and supermarket chains. Revue Scientifique et Technique 20, 584–597.

Raspor, P., 2004. Bio-markers: traceability in food safety issues. Acta Biochimica Polonica 52, 659–664.

Report From the Commission to the Council and The European Parliament: On the possibility of introduction of electronic identification for bovine animals, 2005. http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/com/2005/com2005_0009en01.pdf. Accessed January 13, 2006.

Ribo, O., Korn, C., Meloni, U., Cropper, M., De Winne, P., Cuypers, M., 2001. IDEA: a large scale project on electronic identification of livestock. Revue Scientifique et Technique 20, 426–436.

Rusk, C.P., Blomeke, C.R., Balschweid, M.A., Elliot, S.J., Baker, D., 2006. An evaluation of retinal imaging technology for 4-H beef and sheep identification. Journal of Extension 44 (5), http://www.joe.org/joe/2006october/a7.shtml.

Simon, C., Goldstein, I., 1936. Eye disease and patterns of blood vessels of the eye. New York State Journal of Medicine (Sept 15th 1936).

Smith, G.C., Tatum, J.D., Belk, K.E., Scanga, J.A., Grandin, T., Sofos, J.N., 2005. Traceability from a US perspective. Elsevier Meat Science 71, 174–193.

Whittier, J.C., Shadduck, J.A., Golden, B.L., 2003. Secure identification and source verification of livestock — the value of retinal images and GPS. Proceedings of the First European Conference on Precision Livestock Farming. Berlin, Germany, June 16–19, 2003, pp. 167–172.