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Online Real-time Monitoring of Milk Quality during Milking by Near-infrared Spectroscopy

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Abstract. *Recently, there has been a need by dairy farmers for a method to assess milk quality in real time during milking. We have constructed an on-line near-infrared (NIR) spectroscopic sensing system on an experimental basis. The NIR system can be used for real-time monitoring of milk quality items such as fat, protein, lactose, somatic cell count, and milk urea nitrogen during milking with sufficient precision and accuracy. We tried to improve the robustness of calibration (CAL) models for measurement of milk quality items using NIR spectrum data obtained from two dairy herds. When CAL models developed from data obtained from one herd were used for validation of data obtained from the same herd, the milk quality items could be measured with high levels of accuracy. On the other hand, when the CAL models were used for validation of data obtained from*

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the other herd, the levels of accuracy in measurements of all milk quality items except fat were low. The low levels of accuracy may be caused by factors such as differences in cow individuality, lactation stage, calving times, feeding stage and experimental period (temperatures in the dairy barn). To develop robust calibration models for measurement of milk quality items, therefore, data acquisition from various milk spectra caused by these factors is necessary.

Keywords. milk quality, somatic cell counts, milk urea nitrogen, robustness of calibration

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Introduction

Near-infrared spectroscopy (NIRS) is a new nondestructive method for obtaining qualitative information on foods and agricultural commodities. NIRS has already been put to practical use in automatic rice-quality inspection systems in Japan (Kawamura et al., 2002; Kawamura et al., 2003a). NIRS has also been used to assess milk quality (Sato et al., 1987; Tsenkova et al., 1999; Tsenkova 2001a; Tsenkova et al., 2001b; Tsenkova et al., 2001c; Natsuga et al., 2002), but it has been difficult to apply NIRS to real-time on-line monitoring of milk quality of individual cows during milking.

We have constructed an on-line near-infrared (NIR) spectroscopic sensing system on an experimental basis to assess milk quality, and we (Kawamura et al., 2003b) have reported that the NIR sensing system can be used for real-time assessment of milk quality during milking with sufficient precision and accuracy. However, in order to use the NIR sensing system for dairy farm management, robust calibration models for assessing milk quality items must be developed. The aim of this study was to improve the robustness of calibration models for measurement of milk quality items using NIR spectrum data obtained from two dairy herds.

Near-infrared spectroscopic sensing systems

An on-line near-infrared (NIR) spectroscopic sensing system for assessing milk quality of individual cows during milking was constructed on an experimental basis. The system consists of an NIR instrument, a milk flow meter, a milk sampler and a laptop computer (Table 1). The system was attached between a teatcup cluster and a milk bucket of a milking machine. Unhomogenized milk from the teatcup cluster continuously flowed into the milk chamber of the spectrum sensor and flowed out through an outlet pipe for surplus milk to the milk flow meter. The optical axes of a halogen lamp and optical fiber were set to the same levels (Figure 1). The volume of milk sample in the chamber was about 230 mL. The spectrum sensor acquired diffusion transmittance spectra through the milk. The spectra were recorded in the range of 600 to 1050 nm at 1-nm intervals every 10 seconds during milking. Six continuous spectra were averaged to obtain a spectrum for one minute. (Figure 2).

Cows and milk samples

Two herds of cattle, one belonging to Hokkaido University (herd A) and one belonging to the National Agricultural Research Center for Hokkaido Region (herd B) (Figures 3, 4) ,were used in this experiment (Table 2).

Herd A consisted of 14 Holstein cows. The cows were used in the experiment in the stage of early lactation to late lactation. Measurements were carried out in two consecutive milkings, i.e., milking in the evening and milking the next morning, every two weeks during the experimental period. A pipeline milking system was used in the cow shed at Hokkaido University.

Herd B consisted of 38 Holstein cows. The cows were used in the experiment in the stage of early lactation to late lactation. Measurements were carried out in every milking during the experimental period. A milking parlor system was used in the cow shed at the National Agricultural Research Center for Hokkaido Region.

Milk samples were collected from the milk sampler every minute during milking. The experiment was conducted to cover variations in milk spectra caused by cow individuality, calving times, lactation stage, milking time and environmental temperature.

Table 1. Specifications of the near-infrared spectroscopic instrument constructed on an experimental basis.

Devices	Specifications
Spectrum sensor	Diffusion transmittance spectrum sensor
Light source	Halogen lamp
Optical fiber	Silica glass fiber, 0.6 mm
Milk chamber surface	Glass
Volume of milk sample	Approx 230 mL
Distance between optical axis and milk level	93 mm
Spectrometer	Diffraction grating spectrometer
Optical density	Transmittance
Wavelength range	600 - 1050 nm, 1-nm intervals
Wavelength resolution	Approx 5 nm
Photocell	Linear array CCD, 2048 pixels
Thermocontroller	Peltier cooling system
Data processing computer	DELL, Windows XP, Celelon 1.06GHz, RAM 384KB
A/D converter	12 bit
Spectrum data acquisition	Every 10 seconds

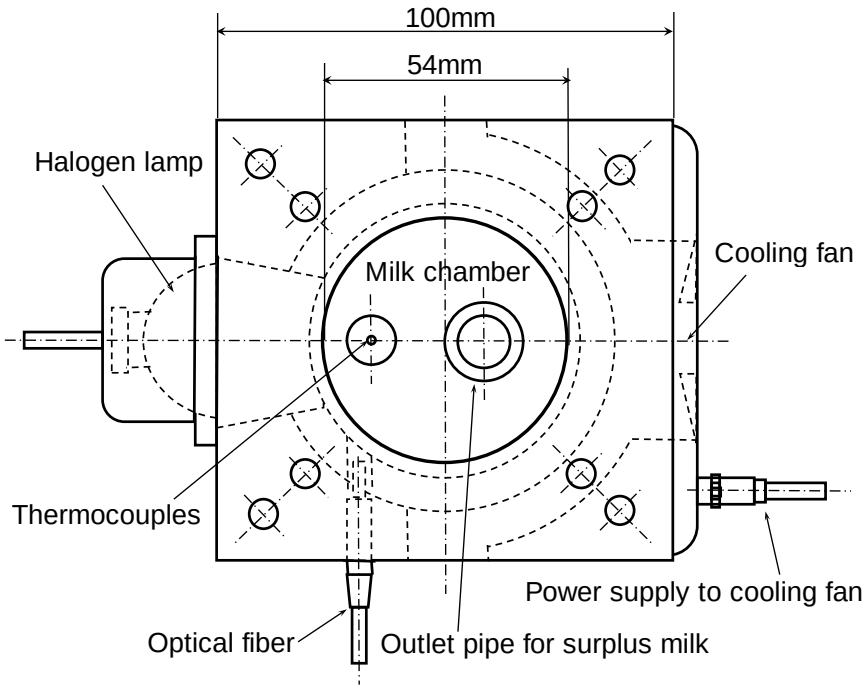


Figure 1. Plane view of the near-infrared spectrum sensor constructed on an experimental basis.

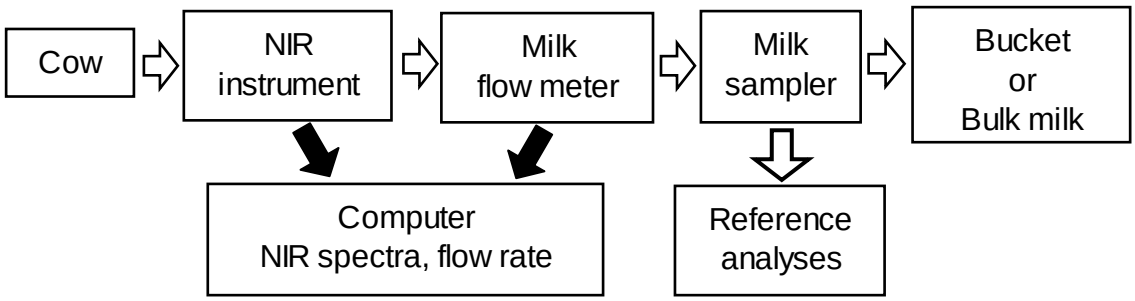


Figure 2. Flow chart of an on-line near-infrared spectroscopic sensing system for assessing milk quality.

Table 2. Two herds used in the experiment.

herd	Experiment site (Milking system)	Experimental period	Number of cows	Milking time	Number of samples			
					Fat Protein Lactose	SCC	MUN	
A	Hokkaido University (Pipeline milking system)	23 Jan. 01 - 23 Jul. 23	14	135	1468	945	488	
B	National Agricultural Research Center for Hokkaido Region (Milking parlor system)	13 Oct. 02 - 29 Oct. 02 25 Jun. 03 - 10 Jul. 03	38	27	865	808	820	

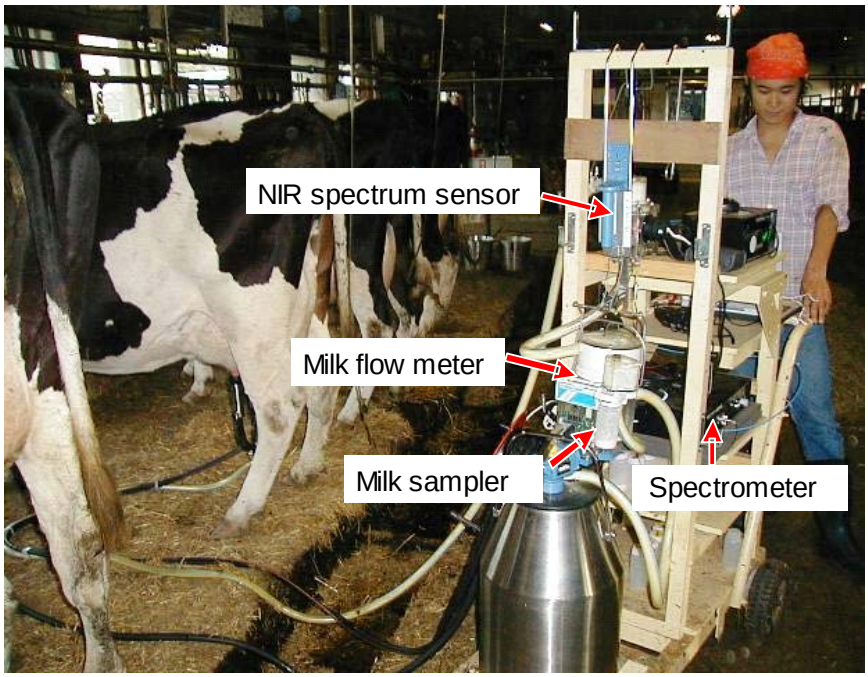


Figure 3. On-line near-infrared spectroscopic sensing system (Hokkaido University).



Figure 4. On-line near-infrared spectroscopic sensing system (National Agricultural Research Center for Hokkaido Region).

Reference analyses

We measured three major milk constituents (fat, protein and lactose), somatic cell count (SCC) and milk urea nitrogen (MUN) of unhomogenized milk as indices of milk quality in this study. The milk constituents were determined using a Milkoscan S54A (Foss Electric, Hillerod, Denmark). SCC was determined using a Fossomatic 5000 (Foss Electric), and MUN was determined using a Milkoscan 4000 (Foss Electric, Hillerod, Denmark).

Calibration and validation

Three data sets were obtained from the two experiments using herd A and herd B: one data set from herd A (data set A), one data set from herd B (data set B) and one data set from herds A and B (data set A+B). Each data set was randomly divided into two subsets, i.e., a calibration subset containing two-thirds of all data and a validation subset containing the remaining data (one-third).

The statistical method of partial least squares (PLS) was used to develop calibration models from the transmittance spectra and reference data. Pretreatment of the spectra such as smoothing or derivatives was not performed. Spectral data analysis software (The Unscrambler, Camo AS, Trondheim, Norway) was used for the analyses.

To confirm robustness of the calibration models, the following combinations of calibration sets and validation sets were used:

1) Each calibration model developed from each calibration set was used for validation of the same data set, i.e., A→A, B→B, and A+B→A+B.

2) The calibration model developed from calibration set A was used for validation of validation set B, i.e., A→B.

3) The calibration model developed from calibration set A+B was used for validation of validation set A or B, i.e., A+B→A and A+B→B.

Results and discussion

Near-infrared spectra

Figure 5 shows an example of an original NIR spectra set of unhomogenized milk from a cow. The deep dip of the spectra in the wavelength range of 970 to 990 nm in Figure 5 indicates second-overtone absorption by water molecules. The two dips in the spectra around 740 nm and 840 nm indicate overtone absorptions by C-H strings and C-C strings.

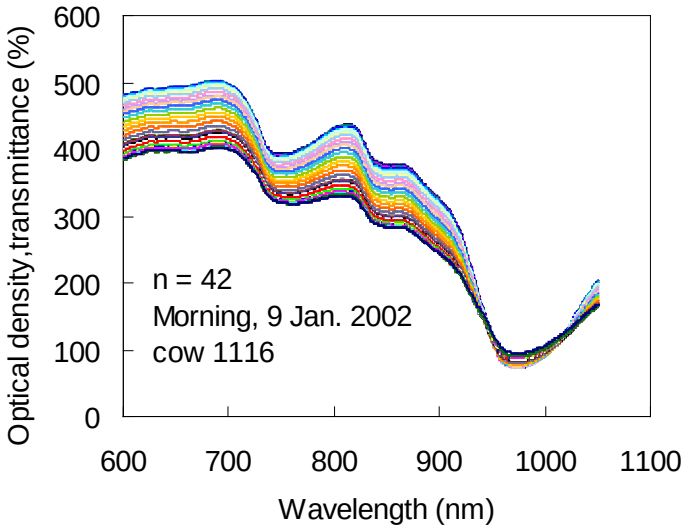


Figure 5. Original spectra of unhomogenized milk from cow number 1116 during milking on January 9, 2002.

Precision and accuracy of calibration models

The validation statistics of the calibration models of milk quality items are summarized in Table 3.

When the calibration models were used for validation of the same data set, e.g., A→A and B→B, the precision and accuracy levels of the models were sufficiently high. In the case of calibration set B and validation set B (B→B) , the coefficient of determination (r^2), standard error of prediction (SEP) and bias of the validation set for fat were 0.92, 0.47% and 0.04%, respectively (Figure 6). The values of r^2, SEP and bias for protein were 0.76, 0.16% and 0.00%, respectively. The values of r^2, SEP and bias for lactose were 0.89, 0.10% and -0.01%, respectively. The values of r^2, SEP and bias for SCC were 0.64, 0.29 logSCC/mL and -0.01 logSCC/mL, respectively (Figure 7), and the values of r^2, SEP and bias for MUN were 0.70, 2.01 mg/dL and 0.01 mg/dL, respectively. These results indicate that the NIR sensing system developed in this study can be used for online real-time monitoring of milk quality during milking.

However, when the calibration models developed from calibration set A were used for validation of a different data set, e.g., A→B, the performance of the calibration models was poor except for

fat content (Figure 8). The reason for the poor performance was thought to be differences in various factors such as cow individuality, lactation stage, calving times, milking system, feeding stage and experimental period.

On the other hand, when the calibration models developed from calibration sets A and B were used for validation of data set A or B, e.g., A+B→A and A+B→B, the precision and accuracy levels of the models were sufficiently high (Figure 9). These results indicate that collection of NIR spectra data, including data on factors affecting model performance, is needed to develop robust calibration models.

For the development of a robust calibration model, it is therefore necessary to use a combined sample set that covers milk spectra with variations caused by these factors such as cow individuality, lactation stage and so on.

Table 3. Validation statistics of the near-infrared sensing system for determination of milk quality.

Milk quality items	CS	VS	n	Range	r^2	SEP	Bias	Regression Line
Fat (%)	A	A	484	0.51 - 9.85	0.94	0.47	0.01	y = 0.98 x + 0.08
Protein (%)			488	2.23 - 4.17	0.71	0.21	0.02	y = 0.95 x + 0.18
Lactose (%)			485	4.35 - 5.49	0.83	0.10	0.00	y = 1.02 x - 0.08
SCC (log SCC/mL)			311	3.18 - 5.78	0.72	0.27	-0.01	y = 1.00 x - 0.01
MUN (mg/dL)			161	1.40 - 22.10	0.75	2.17	0.19	y = 1.06 x - 0.45
Fat (%)	A	B	865	0.66 - 9.59	0.88	0.53	-0.06	y = 1.17 x - 0.79
Protein (%)			865	2.23 - 4.08	0.10	0.30	0.12	y = 0.39 x + 1.94
Lactose (%)			865	4.18 - 5.44	0.39	0.23	-0.18	y = 1.12 x - 0.78
SCC (log SCC/mL)			808	3.70 - 6.46	0.00	0.50	0.02	y = -0.10 x + 5.03
MUN (mg/dL)			820	3.00 - 22.50	0.00	3.42	1.36	y = -0.05 x + 14.63
Fat (%)	B	B	289	0.90 - 8.83	0.92	0.47	0.04	y = 1.02 x - 0.04
Protein (%)			288	2.29 - 3.97	0.76	0.16	0.00	y = 0.95 x + 0.15
Lactose (%)			287	4.18 - 5.44	0.89	0.10	-0.01	y = 1.01 x - 0.07
SCC (log SCC/mL)			287	3.70 - 6.09	0.64	0.29	-0.01	y = 1.09 x - 0.40
MUN (mg/dL)			272	3.40 - 22.10	0.70	2.01	0.01	y = 1.04 x - 0.58
Fat (%)	A+B	A+B	787	0.51 - 11.17	0.91	0.53	-0.03	y = 0.98 x + 0.05
Protein (%)			784	2.11 - 4.18	0.64	0.22	-0.01	y = 1.02 x - 0.06
Lactose (%)			781	4.18 - 5.54	0.74	0.14	-0.01	y = 1.00 x - 0.01
SCC (log SCC/mL)			578	3.30 - 5.78	0.57	0.31	-0.01	y = 0.94 x + 0.26
MUN (mg/dL)			428	1.70 - 22.10	0.60	2.58	-0.15	y = 0.99 x - 0.04
Fat (%)	A+B	A	499	0.51 - 11.17	0.92	0.53	-0.03	y = 0.95 x + 0.21
Protein (%)			509	2.11 - 4.18	0.71	0.21	0.00	y = 1.02 x - 0.07
Lactose (%)			500	4.18 - 5.54	0.73	0.14	-0.01	y = 0.93 x + 0.35
SCC (log SCC/mL)			323	3.30 - 5.78	0.54	0.31	-0.01	y = 0.83 x + 0.79
MUN (mg/dL)			159	1.70 - 21.20	0.57	2.83	-0.02	y = 1.08 x - 0.88
Fat (%)	A+B	B	288	0.90 - 8.24	0.89	0.51	-0.36	y = 1.10 x - 0.46
Protein (%)			275	2.28 - 4.08	0.46	0.23	-0.01	y = 1.00 x - 0.01
Lactose (%)			281	4.18 - 5.44	0.78	0.13	-0.01	y = 1.16 x - 0.75
SCC (log SCC/mL)			255	3.70 - 5.74	0.61	0.28	-0.01	y = 1.21 x - 0.98
MUN (mg/dL)			269	3.40 - 22.10	0.54	2.42	-0.23	y = 0.96 x + 0.39

CS: Calibration Set VS: Validation Set n: number of validation samples

r^2: coefficient of determination. SEP: standard error of prediction.

Regression line: Regression line from predicted value (x) to reference value (y).

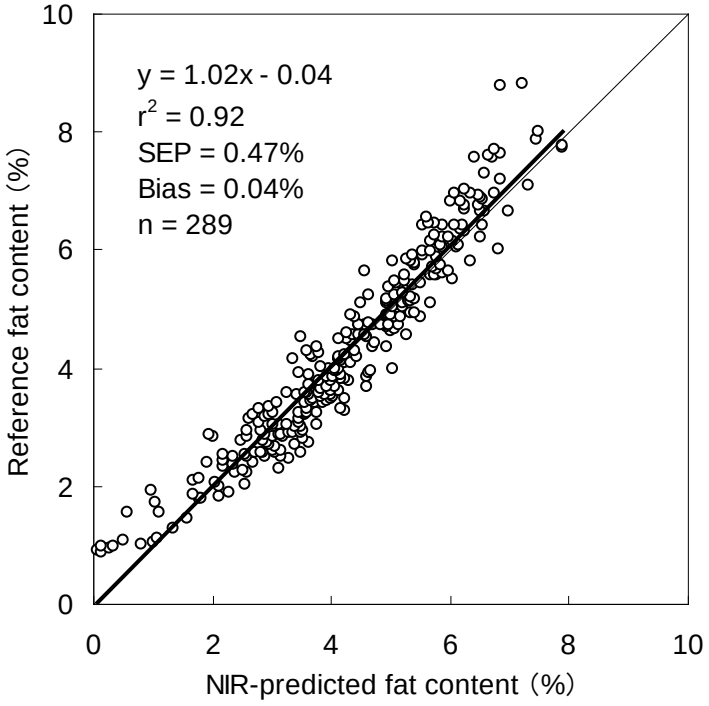


Figure 6. Correlation between reference fat content and NIR-predicted fat content (B→B).

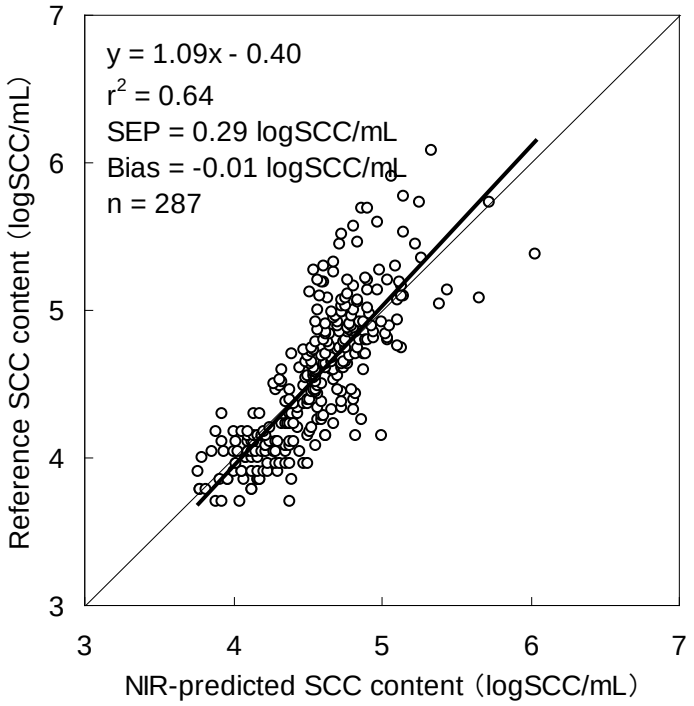


Figure 7. Correlation between reference SCC content and NIR-predicted SCC content (B→B).

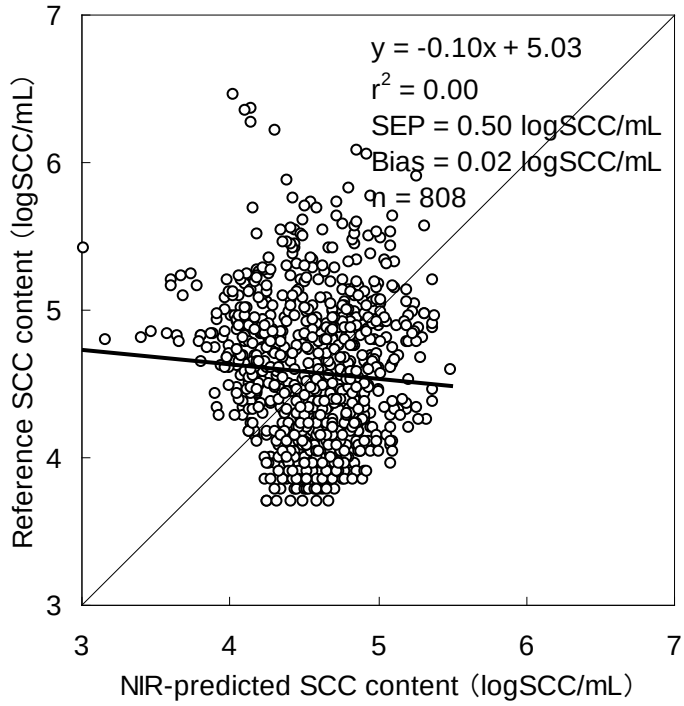


Figure 8. Correlation between reference SCC content and NIR-predicted SCC content (A→B).

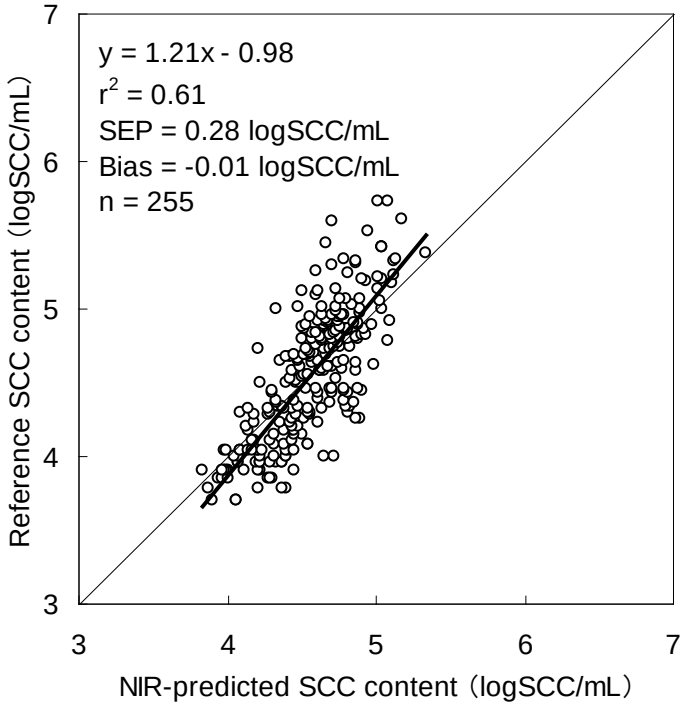


Figure 9. Correlation between reference SCC content and NIR-predicted SCC content (A+B→B).

Conclusion

The on-line NIR spectroscopic sensing system developed in this study can be used for real-time on-line monitoring of fat, protein, lactose, SCC and MUN during milking with sufficient precision and accuracy. Robust calibration models can be developed using NIR spectra including many factors affecting the performance of calibration models.

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