Development of a Near-infrared Spectroscopic Sensing System for Milk Quality Evaluation during Milking

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Abstract

This study was carried out on four Holstein cows with the objective of developing a near-infrared (NIR) spectroscopic sensing system for determining milk constituents during milking. We fabricated an NIR sensing system to determine three major milk constituents (fat, protein and lactose), milk urea nitrogen (MUN) and somatic cell count (SCC) of non-homogenized milk. Milk spectra with a wavelength range of 700 to 1050 nm and milk samples were obtained using the NIR sensing system. The three major milk constituents and MUN were analyzed for reference data using a MilkoScan instrument, while SCC was analyzed using a Fossomatic instrument. Calibration models were developed using partial least square (PLS) regression analysis, and accuracy of the models was validated. The coefficients of determination and standard errors of prediction were 0.99 and 0.17% for fat, 0.95 and 0.06% for protein, 0.91 and 0.06% for lactose, 0.94 and 0.88 mg/dL for MUN, 0.91 and 0.09 log SCC/mL for SCC, respectively. The results indicated that the newly developed NIR spectroscopic sensing system can be used to evaluate milk quality during milking with sufficient levels of precision and accuracy. The accuracy of the NIR spectroscopic sensing system was better than that of the previous NIR spectroscopic sensing system due to the fact that the new NIR sensing system had a higher signal-to-noise ratio and can thus be utilized for online real-time milk quality evaluation. This system can provide dairy farmers with information on milk quality and the physiological situation of each cow and can therefore aid the optimization of dairy farm management.

Keywords: Calibration models, Near-infrared Spectroscopy, Milk Constituents

1. Introduction

Dairy farming requires many tasks such as feeding, milking, livestock management feed crop production and manure treatment. Fat, protein and lactose are the three major milk constituents and are essential milk quality indicators. Extensive dairy farmers manage their livestocks in groups, which is a system known as herd management. However, an individual cow management system is important for monitoring the milk quality and physiological situation of each cow. This type of cow management is needed to upgrade the production of high-quality milk (Wathes *et al.*, 2008).

Near-infrared spectroscopy (NIRS) is a nondestructive system for obtaining qualitative information on foods and agricultural commodities. NIRS has already been used for evaluation of the physiochemical properties of rice and wheat (Kawamura *et al.*, 2003; Natsuga *et al.*, 2006). NIRS has also been used to determine milk quality (Sato *et al.*, 1987; Tsenkova *et al.*, 1999; Tsenkova *et al.*, 2001; Tsenkova *et al.*, 2001; Kawasaki *et al.*, 2008). However, Kawasaki *et al.* (2005) concluded that the reason for poor performance of calibration models is differences in various factors such as cow individuality, lactation stage, feeding stage, calving times, and environmental temperature, and this poor performance has made it difficult to use NIRS for real-time on-line monitoring of the milk quality of each cow during milking.

Kawamura *et al.* (2007) reported that an NIR spectroscopic sensing system can be used for real-time assessment of milk quality during milking with sufficient precision and accuracy. An empirical on-line NIR spectroscopic sensing system was therefore designed.

The objective of this study was to develop a near-infrared (NIR) spectroscopic sensing system for determining milk constituents during milking.

2. Materials and Methods

2.1. Near-Infrared Spectroscopic Sensing System

An empirical online near-infrared (NIR) spectroscopic sensing system was designed for analyzing milk quality of each cow during milking. The system consisted of an NIR spectrum sensor, NIR spectrometer, milk flow meter, milk sampler and a laptop computer (Fig. 1). The system was fixed between a teatcup cluster and a milk bucket of the milking system. Non-homogenized milk from the teatcup cluster flowed continuously across a bypass into the milk chamber of the NIR spectrum sensor. Excess raw milk flowed past the milk flow meter and was then released through a line tube into the bucket. The volume of a milk sample in the chamber was about 30 mL. The optical axes of halogen lamps A and B and the optical fiber were set at the same level, but the optical axis for halogen lamp C was set at 5 mm higher the optical fiber (Fig. 2). The spectrum sensor acquired absorbance spectra through the milk. Spectra were obtained in the range of 700 nm to 1050 nm at 1-nm intervals every 20 seconds during milking (Table 1). The milk flow rate was simultaneously recorded.

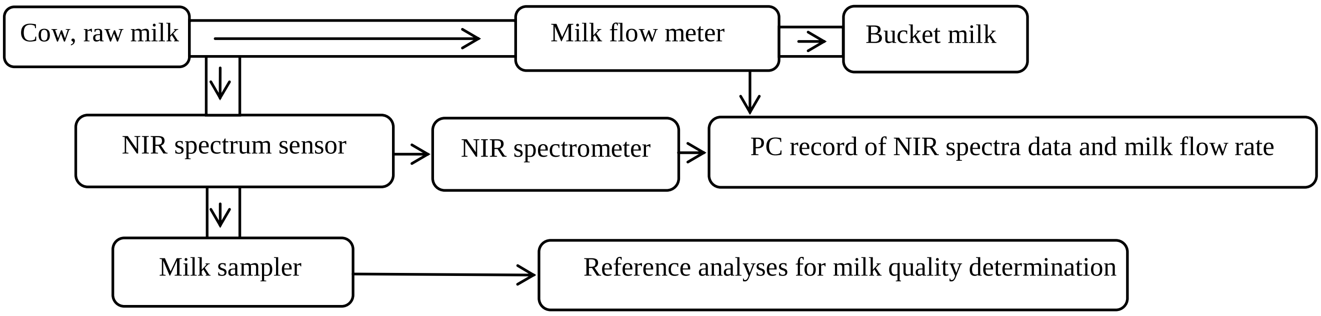

Fig. 1 Flow chart of the on-line near-infrared spectroscopic sensing system for assessing milk quality during milking

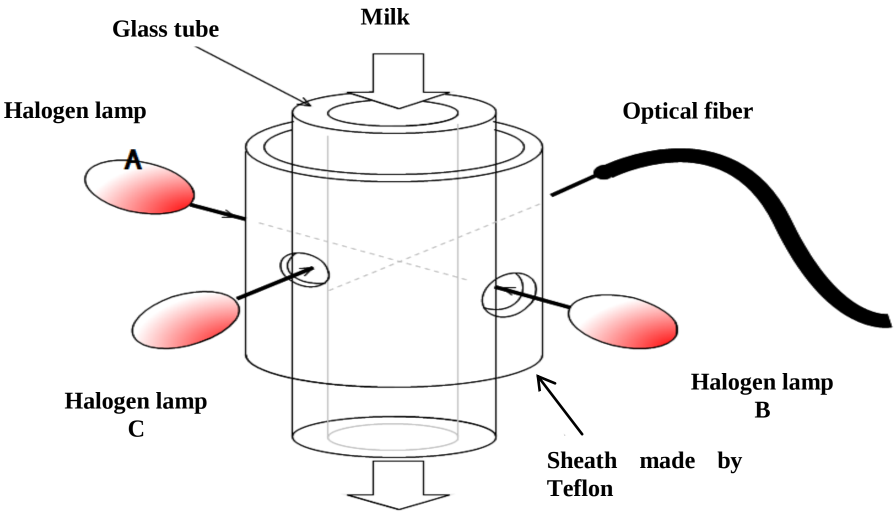

Fig. 2 Schematic diagram of the optical system of the NIR spectrum sensor

Table 1. Specifications of the near-infrared spectroscopic instrument

Devices	Specifications
NIR spectrum sensor	Absorbance spectrum sensor
Light source	Three halogen lamps
Optical fiber	Quartz Fiber
Milk chamber surface	Glass
Volume of milk sample	Approx. 30 mL
Distance between optical axis and milk level	55 mm
NIR spectrometer	Diffraction grating spectrometer
Optical density	Absorbance
Wavelength range	700 - 1050 nm, 1-nm internal
Wavelength resolution	Approx. 6.4 nm
Photocell	CMOS linear array, 512 pixels
Thermal controller	Heater and cooling fan
Data processing computer	Windows 7
A/D converter	16 bit
Spectrum data acquisition	Every 20 s

2.2. Cows and Milk Samples

Four Holstein cows belonging to Hokkaido University were used in this study. The cows were used in the experiment during different lactation periods. Measurements were performed in two consecutive milkings, milking in the evening and milking the following morning, for about two weeks during the experiment. A pipeline milking system was used for milking the cows at the Hokkaido University cow barn. Two cows were milked at the same time and each was measured for about four milking times. Milk spectra data were recorded and then milk samples were collected from the milk sampler every 20 seconds during milking. The experiment was conducted to cover variation in milk spectra caused by cow individuality, calving times and lactation stage (Table 2).

Table 2 Information on cows used in the experiment

Cow number	Date of birth	Date of latest calving	Calving times
1221	Oct 22, 2006	Dec 16, 2014	6
1230	Nov 01, 2010	Oct 22, 2015	3
1236	Jul 11, 2011	Jan 28, 2015	2
1237	Jul 24, 2011	Feb 15, 2015	2

2.3. Reference Analyses

In this work, we measured three major milk constituents (fat, protein and lactose), MUN and SCC of non-homogenized milk as milk quality indicators. The milk constituents and MUN were determined using a MilkoScan instrument (Foss Electric, Hillerod, Denmark) and SCC was determined using a Fossamatic instrument (Foss Electric, Hillerod, Denmark).

2.4. Chemometric Analyses

Chemometric analyses were carried out to develop calibration models for each milk quality indicator and to validate the precision and accuracy of the models. One data set was obtained from the experiment conducted using four cows. The data set from the four cows was used to develop calibration models and the same data set from the four cows was used for validation of the calibration models. Full cross validation was used to validate the calibration models. Spectra data analysis software (The Unscrambler ver. 10.3, Camo AS, Trondheim, Norway) was used for the analyses. The statistical method of partial least squares (PLS) was used to develop calibration models from the absorbance spectra and reference data. Pretreatment of the spectra such as multiplicative scatter correction and smoothing were not performed.

3. Results and Discussion

3.1. Near-Infrared Spectra

Figure 3 shows an example of an original spectra set for non-homogenized milk from a cow. The two peaks in the spectrum around 740 nm and 840 nm indicate the overtone absorption by C-H strings and C-C strings that are related to the typical absorption band of fat content in raw milk. The peak of the absorbance spectrum in the wavelength of about 960 nm indicates the second-overtone absorption by water molecules.

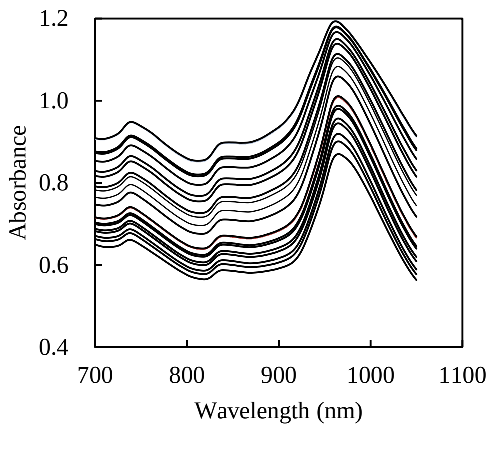

Fig. 3 Original spectra of non-homogenized milk from cow number 1230 during milking on November 3, 2015

3.2. Precision and Accuracy of Calibration Models

The validation statistics of the NIR sensing system for determination of milk quality are summarized in Table 3. The correlations between reference and NIRS-predicted values of fat, lactose, protein, MUN and SCC are shown in Figs. 4 to 8 respectively.

The three major milk constituents are the main determinants of milk quality. The milk constituents can be influenced by the physical condition of each cow and their feed composition. Everyday checking of milk constituents while milking can be utilized for individual cow management and nutritional intake of the cow. The coefficient of determination (r^2), standard error of prediction (SEP) and bias of the validation set for fat were 0.99, 0.17% and 0.00% respectively. The values of r^2, SEP and bias were 0.95, 0.06% and -0.00% for protein, 0.91, 0.06% and 0.00% for lactose, 0.94, 0.88 mg/dL and -0.00 mg/dL for MUN, and 0.91, 0.09 log SCC/mL and -0.00 log SCC/mL for SCC, respectively. Sufficient levels of precision and accuracy for predicting the three major milk constituents were indicated by the high values of r^2 and small values of SEP compare with the range of each constituent and by the negligible values of the bias (almost zero).

However, Kawasaki *et al.* (2008) reported the accuracy of an NIR spectroscopic sensing system that they used. The coefficient of determination (r^2), standard error of prediction (SEP) and bias of the validation set for fat were 0.93, 0.47% and 0.00% respectively. The values of r^2, SEP and bias were 0.80, 0.09% and -0.00% for protein, 0.85, 0.06% and 2.60% for lactose, 0.85, 1.64 mg/dL and -0.00 mg/dL for MUN, and 0.70, 0.02 log SSC/mL and -0.00 log SCC/mL for SCC, respectively.

Our results (Table 3) showed higher levels of accuracy than did the results obtained by Kawasaki *et al.* (2008). The higher levels of accuracy are thought to be due to the improvement of the NIR spectroscopic sensing system that was set at increased repetition times (ten repetition times). Repetition times are the multiple milk measurements taken in the same experimental run. The increase in repetition times reduced the noise data and improved the precision of calibration models. Three halogen lamps were used as near-infrared light sources and the milk samples were irradiated from three directions with a longer exposure time of 200ms. It was observed that the three halogen lamps accurately captured the near-infrared light by fat content unlike the one halogen lamp used by Kawasaki *et al.* (2008). Thus, the samples had a larger light receiving area, and a high signal intensity was generated, consequently increasing the signal-to-noise ratio. Exposure time is the length of time the NIR sensor is exposed to infrared light. The longer exposure time ensured that the important bright part of the captured spectra is not lost and thus reduced various random noise and fixed pattern noise, consequently improving the performance of calibration models. The results obtained indicated that the NIR spectroscopic sensing system designed in this study can be utilized for online real-time monitoring of milk constituents while milking.

4. Conclusions

Milk constituents (fat, protein, lactose), MUN and SCC can be monitored online in real time by using the NIR spectroscopic sensing system developed in this study. The system can provide farmers with information on milk quality and physiological condition of each cow with sufficient precision and accuracy while milking. The system will also contribute to give livestock farmers' feedback control for upgrading dairy farm management and consequently enable them to produce high-quality milk. Thus, the system will enable realization of precision dairy farming.

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

Milk quality items	n	Range	r^2	SEP	Bias	RPD	Regression line
Fat (%)	218	1.05 - 9.00	0.99	0.17	0.00	9.53	y = 0.99 x + 0.04
Protein (%)	218	3.09 - 4.27	0.95	0.06	-0.00	4.31	y = 0.95 x + 0.18
Lactose (%)	218	3.67 - 4.62	0.91	0.06	0.00	3.36	y = 0.92 x + 0.34
MUN (mg/dL)	218	5.7 - 16.90	0.94	0.88	-0.00	3.92	y = 0.94 x + 0.72
SCC (log SCC/mL)	218	4.28 - 5.67	0.91	0.09	-0.00	3.41	y = 0.92 x + 0.40

n: number of validation samples. r^2: coefficient of determination. SEP: standard error of prediction

RPD: Residual predictive deviation. Regression line: Regression line from predicted value (x) to reference value (y)

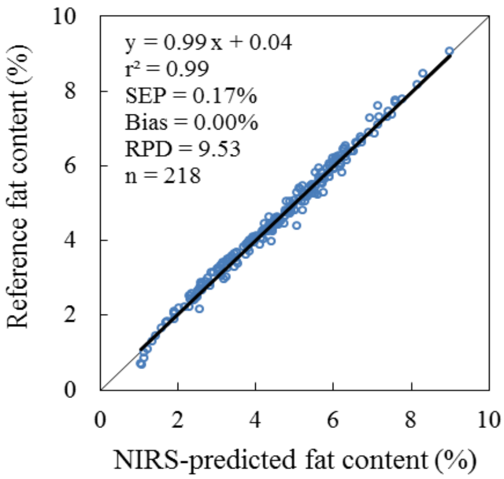

Fig. 4 Correlation between reference fat content and NIRS-predicted fat content

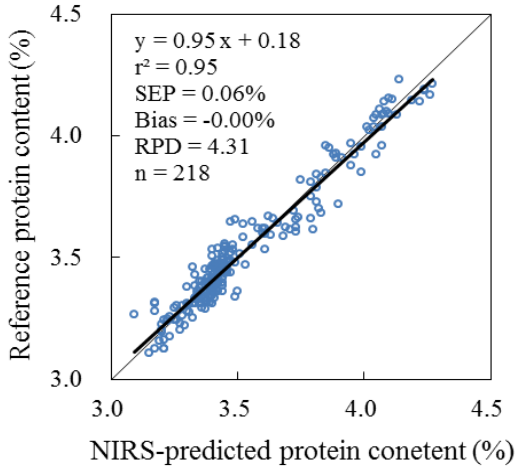

Fig. 5 Correlation between reference protein content and NIRS-predicted protein content

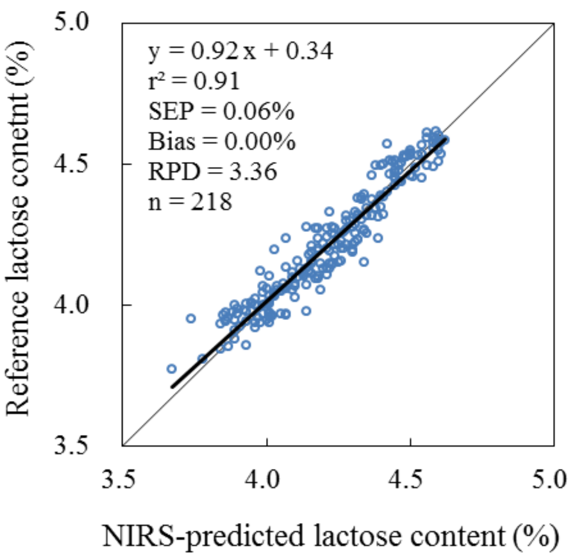

Fig. 6 Correlation between reference lactose content and NIRS-predicted lactose content

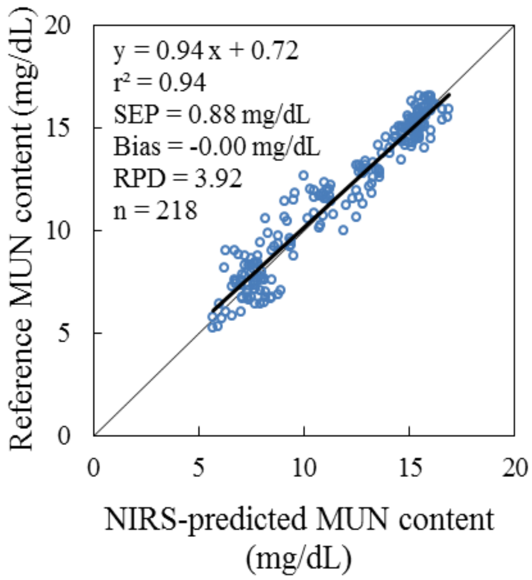

Fig. 7 Correlation between reference MUN content and NIRS-predicted MUN content

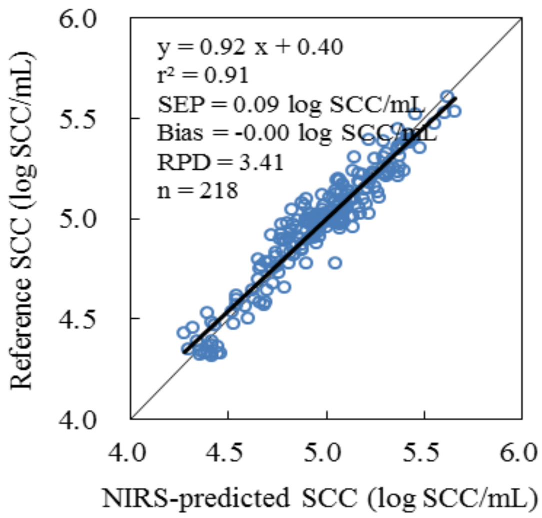

Fig. 8 Correlation between reference SCC content and NIRS-predicted SCC content

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