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In-line and non-destructive monitoring of core temperature in sausages during industrial heat treatment by NIR interaction spectroscopy

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ABSTRACT

During industrial heat treatment of food products, the core temperature is a critical control parameter with respect to food quality and in particular food safety. This paper presents a novel prototype system based on near-infrared spectroscopy (NIRS) that enables continuous in-line and non-contact monitoring of core temperature in sausages during heat treatment in an industrial oven. NIRS interaction measurements in the 761–1081 nm region were used to probe the interior of the sausages. NIRS calibrations for the estimation of core temperature were developed for three different sausage types in the temperature range 60–90 °C. The best accuracy obtained for core temperature with NIRS was about ±1.0 °C. Results indicate that calibrations for core temperature can be transferred between different sausage types, which will ease implementation of such a method. The method was successfully tested in a modern sausage production plant.

1. Introduction

During industrial heat treatment of food products, the core temperature is a critical control parameter with respect to food quality and in particular food safety. This is especially critical for ready-made products since they can be consumed without further heat treatment. Today, most temperature measurements during processing are typically based on random spot-checks on a small number of products. The core temperature of heat-treated products is usually the most critical and needs to be measured using an insertion thermometer.

This procedure is insufficient since it leaves the producer with a large degree of uncertainty; only very few products of the total production volume are checked, and, due to manual insertion, it is not guaranteed that the measurement is taken at the core of the product. Due to these limitations, current practice is to over-cook the food to ensure that everything has reached the critical core temperature. This can reduce the quality of the end-product and also requires overuse of energy. In the food industry there is a need for non-contact, in-line core temperature measurements for improved control of the cooking process. The ideal system should be able to log the temperature in the entire production volume.

Non-contact temperature measurement can be done by infrared (IR) measurements, but these instruments probe only the surface of a product (Gowen et al., 2010). To measure the actual core temperature directly, requires that the inner part of the product is probed. Near-infrared spectroscopy (NIRS) is recognized for its rapid measurement speed, robustness and versatility with regard to sampling. It is possible to sample rather large surfaces and volumes, and the NIR radiation can penetrate some distance into bio-materials. Applications of deep penetrating NIR spectroscopy are already established in the food processing industry for e.g. quality grading of fruit (Nicolaï et al., 2007), crabs (Wold et al., 2010) and chicken fillets (Wold et al., 2017).

It is well known that the near infrared spectrum of water is affected by sample temperature (Buning-Pfaue, 2003). The absorption bands of water are shifted to longer wavelengths with decreasing temperature. The water has absorption peaks at around 840 nm, 970 nm, 1190 nm, and 1450 nm due to a combination of different overtones of OH stretching and bending bands. These temperature shifts can be used to monitor the temperature in materials. Monitoring of tissue temperature has been reported for medical purposes by for instance Hollis et al. (2001), who suggested that NIR could detect changes in human brain tissue temperature during surgery down to about 15 mm depth by using

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the wavelength range 700–1000 nm. This could be done by illuminating the brain at one spot and detecting the radiation at a distance away to ensure that the light travels to certain depths, a measurement mode termed *interaction*. A similar approach was used to monitor temperature in the forearm of humans (Chung et al., 2010). When it comes to foods, measurement of core temperature in baked liver paté has been attempted (O'Farrell et al., 2011). Quite good results were obtained with prediction errors in the range 1.5–4.3 °C. A challenge when measuring temperature in materials like liver pate or brain tissue is that the measured NIR signal is affected not only by the temperature at a certain depth, but also the temperature gradient from surface and down toward the region of interest. O'Farrell et al. (2011) demonstrated that large prediction errors could occur for test samples with temperature gradients different from the calibration set. Another study showed that it is possible to estimate core temperature in fish cakes by NIR interactance with a prediction error around ±2.3 °C (Wold, 2016). Temperature differences at 11–13 mm depths could in this case be registered by the NIR system, but the main optical information comes from the above layers. The study also illustrated that in order to obtain good estimates of core temperature, it is important to use an NIR instrument that is optimised to get good signals from deeper parts of the food product. A drawback with the instrument used in the described studies on foods (O'Farrell et al., 2011; Wold, 2016) is that it required physical contact (or a maximum distance of 10 mm) with the samples. By measuring in physical contact stray-light is reduced and the stronger surface-reflected light is blocked from dominating the weaker but more information-rich interacted light. However, being in contact is neither desirable nor practical for in-line industrial use.

Another important topic regarding practical use of this application is calibration transfer, not between instruments but between food products. With NIR spectroscopy, specific calibration models have to be made for different products. The calibrations in the case of temperature will rely mainly on spectral shifts. These shifts would be quite similar for slightly different products and might allow the same calibration to be used for a range of products with just small modifications. Simplified calibration transfer would be of importance to suppliers of such systems, since it would reduce costs connected with installations in new process lines and for new products.

The objective of this paper was to evaluate how a novel NIR technique can be used to monitor core temperature of sausages during industrial heating in a steam oven. An instrument was specifically designed for non-contact interaction measurements and continuous monitoring of food processes. Due to several practical issues it was impossible to perform the NIR calibration measurements in the steam oven. The calibration work was, therefore, done in a laboratory using raw sausages obtained from the industrial process line. Core temperature calibrations were made for three different sausage types varying in size, color and chemical composition. The ability to apply one calibration based on one sausage type on the two other types was explored. Finally, the calibrated NIR instrument were installed in the industrial steam oven and performance evaluated.

2. Materials and methods

2.1. Sausages

Three types of raw sausages were made in a commercial meat processing plant. Two types of grill sausages; with and without cheese pieces (*Grill* and *Cheese*), and one type of so-called meat sausage (*Meat*). The crude chemical compositions of the sausages were only slightly different (Table 1), but a notable difference was that the cheese grill contained 6% cheese. In addition, there were different spice mixes in the three sausage types. Meat and grill sausages had a diameter of 34 mm and 23 mm, respectively. The freshly made raw sausages were stored over one night before cooking and calibration measurements.

Table 1
Crude chemical composition of the sausage types.

	Fat (%)	Carbohydrate (%)	Protein (%)	Salt (%)
Grill	18	5.5	10	2
Cheese grill	20	5.3	10	1.8
Meat sausage	18	5.5	9.5	1.7

2.2. NIR system

The prototype NIR system was designed to measure in interactance mode. A halogen light source of 50 W was used to illuminate the sample in two rectangular regions of approximately 2 mm*20 mm. The distance between the two illuminated regions was 24 mm. Between the two illumination regions, there was a 4 × 4mm field-of-view that was imaged at the spectrometer. The light travels from the illuminated regions through the sausage, exiting again for detection in the 4 × 4mm field of view (see Fig. 1). The collected light is estimated to have travelled to a depth of up to 13 mm. The spectra consisted of twenty evenly spaced wavelengths in the region 761–1081 nm. Fifty spectra were collected per second, allowing several measurements per sausage as it passed by the instrument. Working distance between instrument and sample was 20 cm, so the instrument was not in physical contact with the sample.

2.3. Temperature calibration procedure

Each batch of sausages were cooked in a small convection oven, Electrolux MENU/9764531201 (Electrolux, Stockholm, Sweden). The oven had a door so that sausages could quickly and easily be taken out for measurement. Hundred sausages of regular *Grill* and *Meat* sausages and 68 C*heese* grill were used for the calibrations. The sausages were gradually heated from approximately 60 °C–86 °C. During heating, sausages were taken out one-by-one for measurements. Each sausage was measured 1) stationary by NIR, 2) in movement by NIR, and 3) using a digital handheld insertion thermometer HFT80 (Anritsu Meter CO., LTD, Kanagawa, Japan) equipped with an immersion probe TK301 (VWR-Avantor, Radnor, PA). Each sausage was held vertically and moved horizontally across the instrument's field-of-view for 2 s, during which 100 spectra were recorded. The speed of the moving sausages was approximately the same as the speed in the industrial oven (one sausage per sec). The entire measurement sequence per sausage (removal from oven and recording of NIR spectra and reference temperature) took about 10 s. A quick procedure was important to secure a good match between NIR measurements and core temperature, since the temperature in the sausage drops rather quickly when taken out of the oven. The core temperature was measured at the middle point of the sausage along the length of the sausage, and the thermometer was inserted

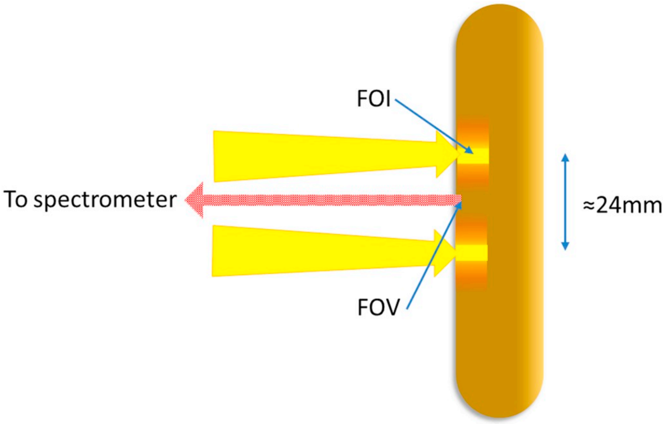

Fig. 1. Illumination pattern (FOI) and field of view (FOV) on sausage.

perpendicularly into the sausage core at this point. Depth to the core was marked with tape on the thermometer so that correct insertion depth was found quickly. Each sausage went through the measurement sequence only once, it was not returned to the oven for further heating and measurements. The gradual heating in the oven was done quite slowly for each series of sausages (over 90 min) and this avoided any temperature gradients in the sausages.

2.4. Data modelling

The 100 NIR spectra obtained from each stationary sausage was averaged to one mean spectrum that was used for calibration. For sausages in movement, it was important to extract and use only those spectra of the 100 recorded, which were measured at approximately the center of the sausage. Detection of these “good” spectra was done automatically by a selection algorithm using a criterion involving the intensity, shape and contrast of the spectra. The “good” spectra from the sausages had a different shape compared to measurements on the edge of the sausages or measurements out in the air. The accepted spectra from each moving sausage (typically 30–40 spectra) were averaged, and the mean spectrum was used for calibration. The measured intensity spectra were linearized and transformed to absorption spectra by taking the logarithm of the inverse of the interaction spectrum ($\log10(1/I)$), where I is the intensity of the detected light. To minimize variation in the spectra induced by light scattering and varying distance between instrument and sample, the absorption spectra were normalized by standard normal variate (SNV) (Barnes et al., 1989): For each absorption spectrum the mean value was subtracted, and the spectrum was then divided by the standard deviation of the spectrum.

Calibration models were made by partial least squares regression (PLSR) (Martens and Næs, 1989). Two calibration models were made for each type of sausage, one for spectra collected from stationary sausages and one for spectra from sausages in movement. The optimal number of factors in the models was determined after cross validation by evaluation of the squared correlation (R^2) between measured and estimated temperature, and the root mean square error of cross validation prediction (RMSECV) defined as

$$RMSECV = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(y_n - \widehat{y}_n)^2}$$

where N is total number of samples, $\hat{y}_n$ is the predicted value, y_n is the measured reference value and n denotes the samples from 1 to N. The final regression vectors for the calibrations were implemented in the instrument for in-line testing.

To evaluate if a calibration for *one* sausage type could easily be transferred to *another* sausage type with a minimum of work, two strategies were tested.

1. Apply calibration as is on new sausage type and estimate prediction errors based on the measured core temperatures.
2. Measure 5 sausages of the new sausage type with both NIR and thermometer. The 5 temperatures vary from low to high. Use these values to bias and slope correct existing calibration. Use corrected calibration to estimate temperatures in new sausages and estimate prediction errors based on the measured core temperatures.

Multivariate calibrations were made by use of the software The Unscrambler version 9.8 (CAMO Software AS, Oslo, Norway) while instrument control, data collection, and spectral pre-treatment were performed in Matlab version R2007b (The Mathworks Inc., Natic, MA).

2.5. Industrial testing

Testing of the instrument was done in a modern sausage production plant where linked sausages were cooked on a continuous line using a steam oven (ALKAR-RapidPak.Inc, Lodi, WI). Fig. 2*a* illustrates the stream of sausages and where on the sausages the measurement occurs. The sausages travel through three cooking zones before they enter a chilling zone. At the end of the last cooking zone, the temperature in the sausages is at the highest, and therefore the proper place to monitor the core temperature. A 6 cm diam. hole was made in the oven wall at this point in the process, so that the NIR instrument could be positioned at the correct height and at the optimal distance from the sausages passing by (Fig. 2*b*). Distance from the hole in the wall to the sausages was about 14 cm. A black tube with air purging was mounted in front of the NIR instrument to prevent condensation on the instrument window and to minimize the potential scattering and absorption of the NIR radiation due to steam in the optical path between instrument and sausages. The sausages moved with a speed of about 1.2 sausages per sec. The NIR instrument continuously collected NIR spectra with an acquisition time of 5 s, i.e. each measurement contained approximately 250 spectra. Of these 250 spectra, only those that were regarded as “good spectra”, according to criteria described above, were averaged. Based on this average spectrum, a temperature estimate was calculated for the 5 s period. Hence, a temperature estimate was produced for about every fifth sec.

Tracksense Pro (Ellab A/S, Hilleroed, Denmark) was used to log the actual core temperature of a selection of 14 sausages during heating. The 14 reference sausages were sent through the oven separated by approximately 15–20 min to evaluate the performance of the NIR system over a 4 h period. The wireless loggers contained one thermometer positioned in the core of the sausage, measuring core temperature, and one that measured ambient temperature in the oven. The probe with the sausage was hooked on the chain with the other sausages and logged the temperature every sec through the whole heating process. By recording the arrival time at the end of heating zone 3 we could synchronize the measured core temperature in the reference sausage with NIR estimates of core temperature of the sausages at the same time, allowing a close comparison. During the 4 h period, the temperature in the oven was adjusted to vary between 74 °C and 82 °C to obtain a reasonable span in core temperature.

3. Results and discussion

3.1. Temperature ranges

Core temperature for the calibration sausages varied rather evenly in the range 58–85 °C for *Grill* and *Meat*, and in the range 57–92 °C for *Cheese*. These temperature spans were wider than what is relevant during industrial production of sausages (typically 70–82 °C), but suitable for making NIR calibrations that could work well in the relevant span.

3.2. Spectral measurements

Fig. 3*a* shows SNV normalized spectra from three grill sausages with different core temperatures. The water absorption peak at around 980 nm originates from the second overtone of the OH stretching bond and dominates the spectra. There is also a small water peak at about 840 nm (combination of the third overtone OH stretching and OH bending bands). The two absorption bands vary in intensity and are shifted with variations in temperature (Hollis et al., 2001). Shifts are most easily seen in the 980 nm peak, which was shifted towards shorter wavelengths with increasing temperature. Systematic changes in the less intense absorption band at 840 nm are difficult to discern, however, the effect is reported (Hollis et al., 2001). The same pronounced temperature shift in the peak at 980 nm was observed also on liver pate and fish cakes (O'Farrell et al., 2011; Wold, 2016). There was an apparent isosbestic point around 981 nm, but the exact wavelength is difficult to determine due to low spectroscopic resolution. An isosbestic point for temperature

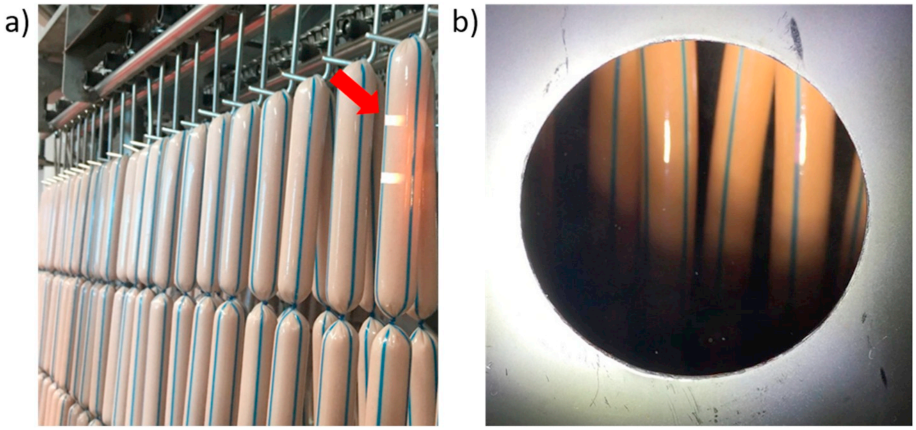

Fig. 2. *a)* Chain of sausages before entering the oven. The two bright spots shows the illumination from the NIR instrument. ***b)*** Actual measurement situation, view to sausages in the oven.

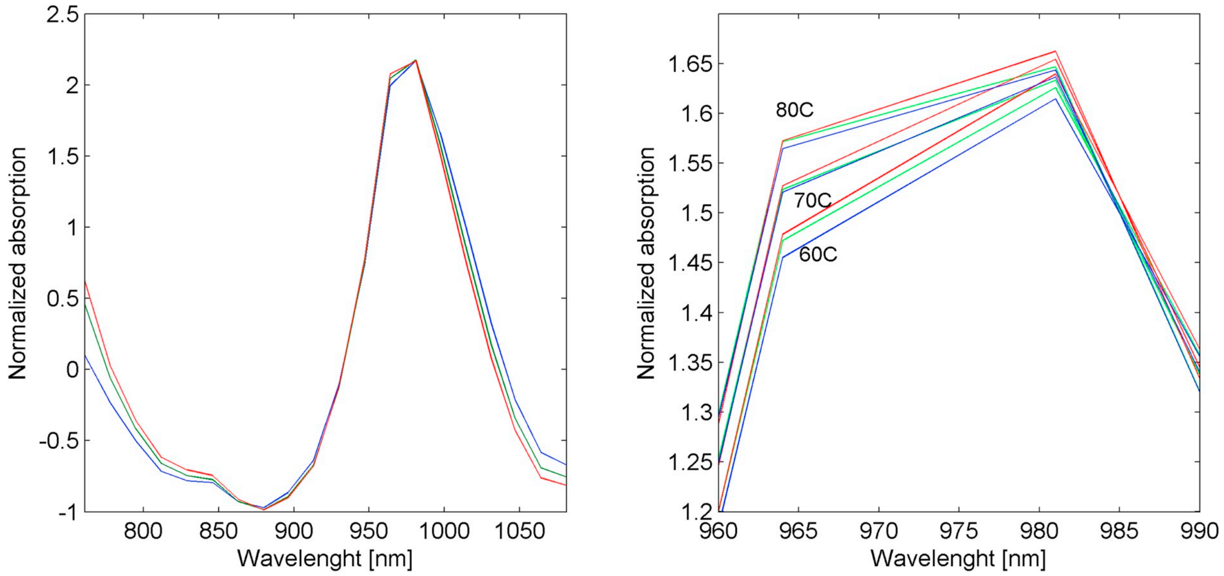

Fig. 3. *a)* Normalized NIR spectra from grill sausages with core temperatures at 60.7 °C (blue), 72.2 (green), and 82.0 (red). ***b)*** Water absorption peak for grill (blue), cheese grill (red), and meat sausage (green) at about 60 °C, 72 °C and 80 °C.

has been reported at 996 nm for pure water (Chung et al., 2010), but spectra from sausage will be affected also by fat, protein and the fraction of water bound to macro molecules such as proteins (Chung et al., 2008; Wold et al., 2017), which can explain this deviation. A similar isosbestic point around 980 nm was observed for heated fish cakes (Wold, 2016).

There were also systematic changes with temperature at short wavelengths toward the visible region. This variation was related to color changes, since the sausages became slightly darker with higher temperatures.

The same spectral properties were observed for the two other types of sausages, but there were small systematic differences between the sausage types, in particular at short wavelengths, related to color differences. Fig. 3b shows, however, that the spectral variation at the water peak due to temperature was very similar for all sausage types. This indicates the potential for using spectral data as function of temperature from one type of sausage to estimate core temperature in another type.

3.3. Calibration results

Table 2 summarizes the calibration results for NIR data collected on sausages in steady state and in motion. Models were obtained based on 3 PLS factors in all cases. The high correlations indicate a close relationship between the NIR spectra and core temperature in these samples (Fig. 4). The prediction errors were quite similar for all sausage types and smaller than reported for earlier related studies. O'Farrell et al. (2011) obtained prediction errors in the range 1.3–4.3 °C for core temperature in liver pate, while Wold (2016) obtained prediction errors in the range 2.1–2.3 °C for core temperatures in fish cakes. Compared to those two products, sausages are more homogeneous products in terms of size and shape. We can also assume that the sausages were more

Table 2

Cross validated regression models for core temperature in sausages, measured stationary or in movement.

Sausage type	Stationary			Movement		
	#factors	R^2	RMSECV	#factors	R^2	RMSECV
Grill	3	0.96	1.19	3	0.96	1.27
Cheese grill	3	0.97	1.28	3	0.97	1.41
Meat	3	0.98	1.00	3	0.96	1.28

RMSECV – Root Mean Square Error of Cross validation.
R^2-Squared correlation coefficient.
#factors – number of factors in the PLS regression model.

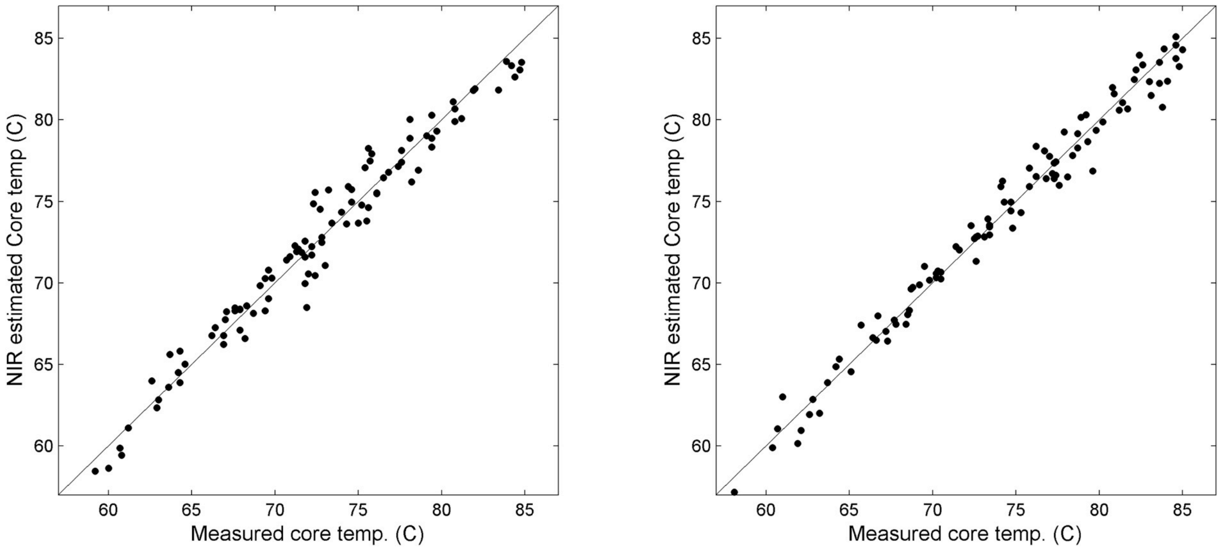

Fig. 4. Predicted versus measured core temperature in a) grill sausage and b) meat sausage. Values are based on cross validation.

evenly heated with smaller internal gradients in temperature, while for the liver pate and fish cakes it was reported notable variations in the temperature gradients during heat treatment. Such gradients will affect the spectra and complicate the calibrations.

The prediction errors were slightly lower for stationary sausages compared to those in movement. This is reasonable since an average spectrum from 2 s (stationary sausages) has a higher signal-to-noise level than an average spectrum from about 1 s or less (measurement time during movement). The movement also brings in some uncertainties in the measurements. The final spectrum extracted for each moving sausage could be affected by for instance edge effects – the “good” spectra selected could include slightly distorted spectra where for instance just half the width of the sausage was illuminated. However, the differences between the two calibrations were small, and prove that the instrument collected spectroscopic data with high signal-to-noise from both stationary and moving sausages.

For a continuous sausage production line, an average temperature estimate could be calculated based on e.g. 10 or 20 sausages, and then, assuming the error is not systematic, the prediction error will be lower than for just one single sausage as reported here. This effect has been shown for NIR estimation of fat content in pork meat batches of different sizes (Wold et al., 2011).

Fig. 5 shows typical regression coefficients for the estimation of core temperature based on the NIR spectra. The main emphasis is on the wavelength region around the major water absorption peak, where shifts in this peak are the main quantitative source when core temperature is estimated. The shape of this vector corresponds with earlier reports (O’Farrell et al., 2011). The spectral region from 761 to 895 nm contributes less to the model, and this region can be omitted from the calibration without any increase in prediction error. This spectral region is also affected by color and color variations, which means that the model becomes less sensitive to color variations without this part of the spectrum. This is important when a calibration from one sausage type is to be used on another sausage type, since there are systematic differences in color between different sausage types. Fig. 5 also shows a typical regression vector for a model when only the water absorption region was included. In this case the SNV normalization was performed on this region alone before calibration.

3.4. Calibration transfer

Since the spectra from different sausage types were quite similar, it was investigated if a calibration for one sausage type could be used on another type, even though they had slightly different chemical composition and shape. In these analyses we used only calibrations for stationary sausages. We also used models where the 761–895 nm region was omitted. Table 3 shows that when the calibration models listed in Table 2 were used directly on other types of sausages, the correlations were still high, but some prediction errors increased notably compared with results in Table 2. The main reason for this increase was that slope and/or bias were introduced due to systematic differences in the spectra between sausage types. In particular, the temperature in the *Cheese* sausages was not well predicted by calibration models based on *Grill* and *Meat*. This was probably due to the 6% content of cheese, which would alter the spectra slightly.

In a typical calibration transfer situation, one would include new measurements of core temperature on the new sausage type, and adjust the existing calibration by a slope and offset correction. By using only five measured temperatures on the “new” sample set to correct the existing calibration we obtained the same high correlations and also much lower prediction errors (Table 3). The prediction errors were not as low as for the calibrations made on the actual sausage type, but probably good enough to be used in a practical industrial setting.

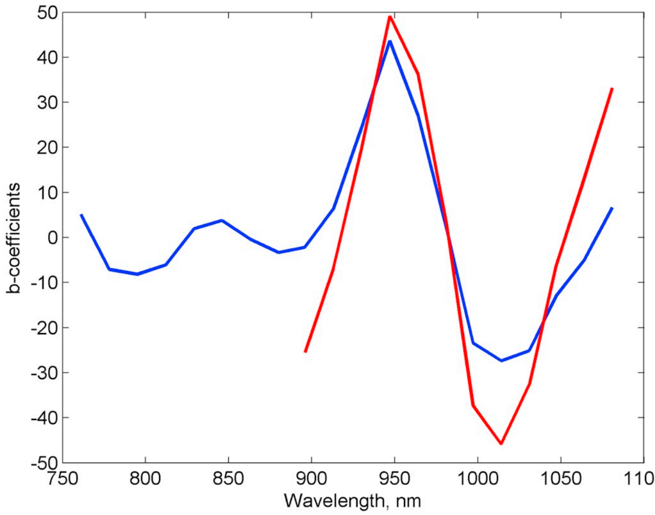

Fig. 5. Regression vectors for core temperature in grill sausages for entire spectral region (blue) and for mainly the water absorption peak (red).

Table 3
Prediction results for core temperature in sausages (stationary at measurement) when applying original and bias adjusted calibration models based on other types of sausages.

Data set	Calibration	Original calibration		Bias adjusted calibration	
		R^2	RMSEP	R^2	RMSEP
Cheese	Grill	0.97	2.52	0.97	1.52
Cheese	Meat	0.97	2.21	0.97	1.39
Grill	Cheese	0.94	1.58	0.94	1.69
Grill	Meat	0.96	1.28	0.96	1.20
Meat	Cheese	0.95	1.45	0.95	1.46
Meat	Grill	0.98	1.16	0.98	1.03

RMSEP – Root Mean Square Error of Prediction.
R^{2-}Squared correlation coefficient.
Data set – Data from sausage type used to estimate core temperature.
Calibration – The sausage type the calibration is based on.

A sausage factory would typically make many different types of sausages. The opportunity to use one master calibration for a certain sausage type and simply adjust this to work on other sausage types with just a few reference measurements, would save a lot of calibration work. This would also be the case for situations where it is impractical to do the calibration work in the factory. The approach needs to be thoroughly validated.

3.5. Industrial testing

The industrial testing was challenging because the measurement point was not visible (it was inside the oven with no kind of window for inspection). It was therefore difficult to identify or investigate possible sources of unexpected variations. Fig. 6 illustrates the main unexpected phenomenon during in-line measurements. The temperature estimates were in the correct range, however, we observed significant cyclic fluctuations with a period of approximately 25 s (Fig. 6*a*). The estimated temperature varied periodically with as much as 4 °C, an unlikely variation in the actual sausages. The source of this unwanted variation was eventually determined to be a valve operation in the oven that distributed steam around the chamber to keep temperature and humidity stable. Approximately every 25 s, a cloud of hot steam was blown into the optical pathway between the instrument and the sausages. The effect of this steam on the spectral shape was small (Fig. 6b), but it was enough to give notable higher estimated temperatures. When the valve was de-activated, the temperature estimates became stable with no periodic fluctuations. For safe operation of the oven, it was not possible to de-activate the valve over longer periods during regular sausage production. Efforts to reduce these fluctuations by increasing the pressure on air purging to reduce the steam in the optical path gave just small improvements. The tube was also lengthened between the instrument and the sausages to shorten the part of the optical path affected by steam, but this did not reduce the fluctuations. The steam could affect the absorption spectra by both absorption and light scattering. The steam is hot and the water is not bound to proteins, and both factors could introduce a shift in the water peak towards shorter wavelengths (Buning-Pfaue, 2003; Chung et al., 2008), corresponding to Fig. 6b. Light scattering from the dense steam will also affect the spectra. More light will be backscattered and mix with the light that has interacted with the sausage and is on the way back to the instrument. This might give spectra with lower contrast, and the shape will deviate slightly from those in the calibration set, which were recorded with no steam present. Another explanation could be that the steam might also affect the surface temperature of the sausage, by condensing on contact.

The best way to eliminate the fluctuation problem would be to synchronize the NIR measurements with the valve operation. This was not feasible for this experiment, so we used a moving average that averaged readings over 60 s to reduce the fluctuations. Fig. 7 shows averaged NIR estimated core temperature in sausages over a period of 4 h plotted together with core temperature and ambient temperature measured with wireless thermometer loggers. The estimates corresponded quite well with the reference measurements of core temperature, with a correlation of 0.94 and a RMSEP of 1.25 °C. If the first registered reference measurement (at about NIR measurement no. 120) was omitted (possible outlier), then an RMSEP of 1.05 °C was obtained. These prediction errors were at the same level as for the calibration models (Table 2). The core temperature was usually lower than the ambient temperature in the oven. When temperature in the oven increased rapidly (at about measurement points 400 and 1350) the ambient temperature was 3–4° higher that the core temperature. The estimated core temperatures were in these cases higher than the measured core temperatures, probably because the outer and warmer parts of the sausages affected the spectra, and consequently also the estimated core temperature. Such rapid temperature changes are, however, not common during normal production, they were induced to test the limits of the NIR system. There were some sudden drops and steps in estimated temperature (around measurement points 210, 280, 310 and 350) that did not seem reasonable based on how the oven was operated. We regard these as artefacts, and since we could not visually

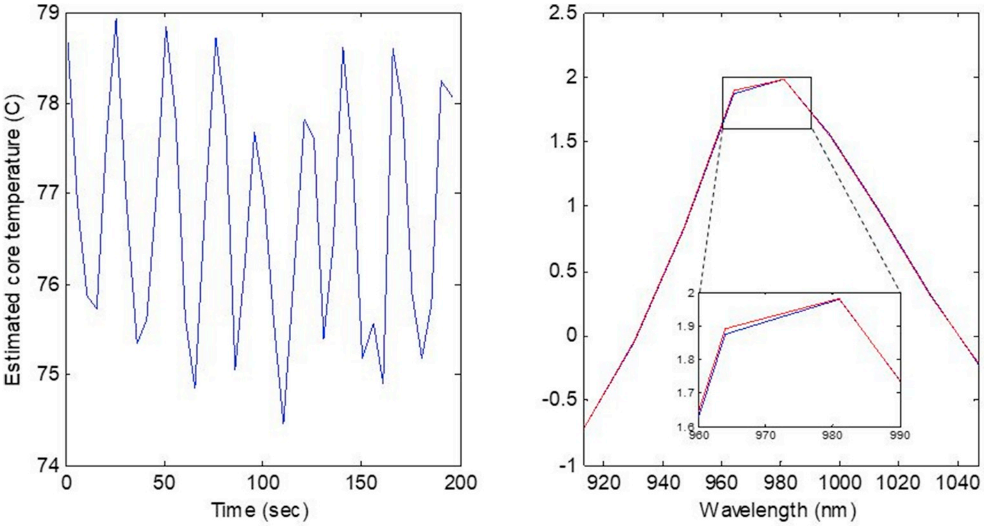

Fig. 6. *a*: Core temperature in sausages in oven estimated over every 10th sec. ***b***: Mean SNV corrected spectra for high (red) and low (blue) temperature estimates in Fig. 5a. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

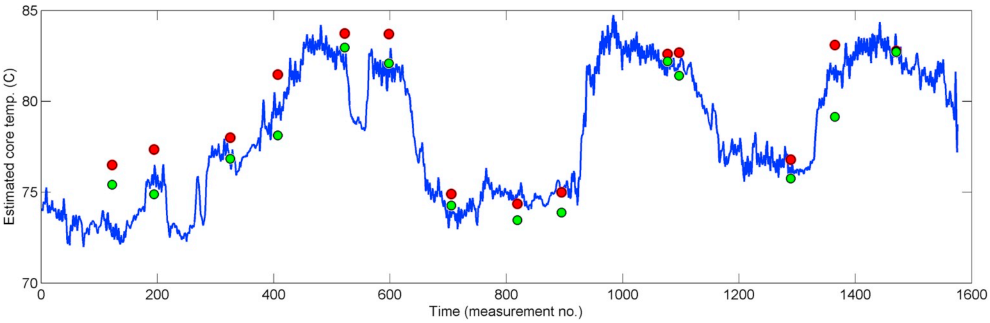

Fig. 7. Core temperature in sausages estimated with NIR during 4 h (blue line). Core temperature in reference sausages (green circles) and ambient air (red circles) measured with wireless thermometer loggers.

inspect the point of measurement, we do not know the exact reason for these possible deviations.

The prototype NIR instrument has not been described in technical detail in this paper. The most important feature compared with previously described NIR instruments tested for core temperature measurements in foods (O'Farrell et al., 2011; Wold, 2016) is the ability to obtain high quality interactance measurements from a long distance (20 cm) to the sample. This enables in-line measurements in real processes, which has not been possible before. For the in-line evaluation of NIR interaction for this application, it was necessary to build a prototype and adapt it to the oven environment following the design process outlined in Tschudi et al. (2018). By adopting an iterative approach and identifying and reducing the effects of sources of inaccuracy each time it was tested in-line, it was possible to determine the true potential of NIR interactance. Non-contact in-line interactance measurements are demanding as they require measurement of low intensity signals – signals from light that has interacted inside the sausage are much weaker compared to the signal from reflected light from the surface. This requires very tight control of the illuminated area and the detection area (Fig. 1) so that there is no crosstalk between the beams. The novelty of the NIR prototype used in this study is that it allows well-defined interactance measurements, at a working distance of 20 cm between instrument and sample. It also includes modulation of the illumination to make it more robust against ambient light.

4. Conclusion

The core temperature in a heat-treated product can vary due to several factors: Temperature in the oven, heat treatment time, temperature of the product before heat treatment, product variations in size and composition. The core temperature can therefore be difficult to control.

In-line monitoring of core temperature in the total production volume would give the producer a valuable tool to ensure safe products, to control the process to target temperature, and to efficiently learn how different process settings leads to variations in core temperature.

In spite of challenges with steam and a complex measurement situation reported in the this case, the results clearly indicate that NIR interaction measurements are suitable for non-contact core temperature measurements in foods during heat treatment. The challenge with steam is much less pronounced and even absent in many types of food heat treatment processes, such as for hamburgers, fish cakes and other products on conveyor belts.

The main challenges with NIR would be to develop robust calibrations that can handle 1) possible variation in temperature gradients in the product, 2) variation in product chemical composition, and 3) product color variations that might affect the NIR spectra. These are all variation factors that can be included in a calibration model, but it is then required to understand the process well. When sound and efficient protocols for calibration and for calibration transfer between products are developed, we think NIR spectroscopy can become a valuable in-line tool for food heat treatment control.

Author contribution statement

Jens Petter Wold: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing- Original draft, Writing Preparation, Supervision, Project administration, Funding acquisition. Marion O'Farrell: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Review & Editing. Jon Tschudi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Review & Editing. Carl Emil Eskildsen: Formal analysis, Writing - Review & Editing. Petter Vejle Andersen: Formal analysis, Investigation, Writing - Review & Editing, Writing Preparation. Silje Ottestad: Project administration, Writing - Review & Editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfoodeng.2020.109921.

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