Predicting Finger PPG by using Sensor PPG waveform and data via regression analysis with two different methods, matching time and matching glucose (GH-Method: math-physical medicine)

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Research Article

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Introduction

This paper describes the research results of predicted finger-piercing postprandial plasma glucose (PPG) value using a Sensor PPG waveform and its data collected from the continuous glucose monitoring (CGM) device. The author utilized a regression analysis based on two distinctive methods, Method A on matched timing and Method B on matched PPG. In other words, he tries to identify one particular sensor PPG value on the sensor's 3-hour waveform, which is "nearly-equal" to the measured finger PPG value.

Methods

Since 1/1/2012, the author has measured his glucose values using finger-piercing method: once for FPG and three times for PPG each day. On 5/5/2018, he applied a CGM device on his upper arm and checked his glucose measurements ~80 times each day. After the first bite of his meal, he measures his interstitial glucose level every 15 minutes for a total of 3-hours or 180 minutes.

He has maintained these dual glucose testing for 706 days (5/5/2018 - 4/11/2020) for the purpose of in-depth glucose research and a special comparison of these two different PPG measurement results. During the period of 2014-2017, he has already developed some conversion formulas, calculation equations, and outcome refinements for some important diabetes variables, such as PPG relationship with diet, exercise, weather temperature, glucose prediction, HbA1C prediction, and much more. The author has also discovered that both finger and sensor measurements have some inherent issues related to device reliability and data accuracy. In addition, there are no strong correlation (R = 29% to 46%) between his finger PPG curve and his sensor PPG curve (see **Figure 1)**. Therefore, it is vital for him to continue with these two parallel glucose measurements for a longer period in order to conduct a big data analytics to have a better understanding of device reliability, data accuracy, and data integrity. He tries extremely hard not to introduce more uncertainty or inaccuracy on top of his existed pool of data, equations, and conclusions.

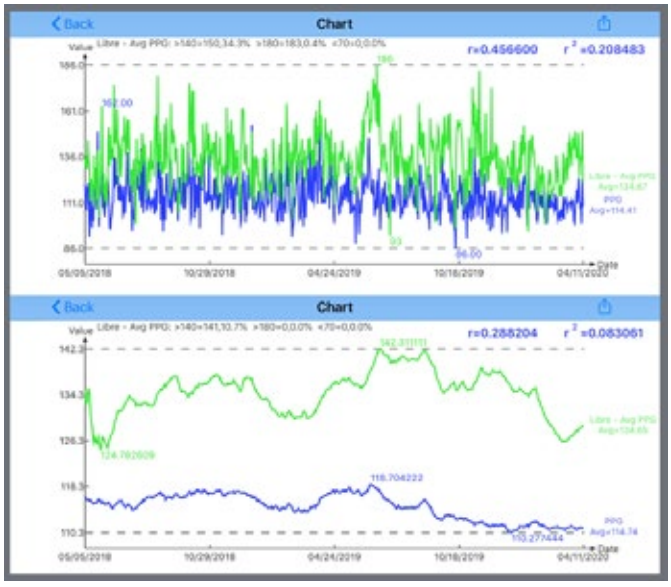

Figure 1: Correlation Coefficient R between Finger PPG and Sensor PPG (daily data with R of 46% and 90-days moving average with R of 29%)

On 5/4/2020, he will have collected glucose data on two parallel tracks for two complete years (730 days). If he can find out that one specific PPG value at a specific time instant on the sensor waveform is "near-equal" go Finger measured PPG value, he can then stop his time-consuming finger piercing task and solely rely on this mathematically derived Finger PPG prediction value from his sensor collected glucose data. Meanwhile, all of his existing ready-developed equations and formulas for prediction of HbA1C and other important variables will still be useful.

All meals must be distinguished among breakfast, lunch, and dinner.

In addition, he has conducted two sets of numerical calculations regarding these "near-equal" PPG data, both Finger and Sensor. For the first set, the **quarterly analysis,** he divided this entire 706 days into 8-quarters (three-months each, with the exception of the last one only having 66 days) for comparison of each quarter's findings. For the second set, the **cumulative analysis,** he added the present quarter results on top of the summary results of all of his previous quarters for deriving out the final cumulative conclusions.

Within these quarterly and cumulative analyses, he has further utilized the following two different models:

Model A (timing based):

Using regression analysis to search for the matching time instants and then calculate their associated PPG values.

Model B (glucose based):

Using regression analysis to search for the near-equal glucoses and then calculate their associated time instants.

Other than using the regression analysis concept and method, the majority of his tasks are actually quite simple and straightforward mathematics and statistics work plus some software modifications for big data analytics. His primary concerns are still his data accuracy and data integrity because he cannot allow to create an inaccurate Finger PPG prediction value from a collected Sensor PPG waveform.

Final step, his computer algorithm of "auto-detection and auto-correction" and its associated software programs must start from the initial value of the first two-years data which end on 5/4/2020. Starting from 5/5/2020, he will automatically update his calculation on his iPhone's data server on a monthly basis. These computer operations will run automatically and continuously in order to keep the high accuracy of this "predicted Finger PPG" which are inverted from his collected Sensor PPG results. This is a never-ending task of data accumulation, processing, verification, and correction.

Results

First, he has calculated the average PPG (mg/dL) for three meals on a daily basis and continuously during this entire period of 706 days. These results are shown in Figure 2

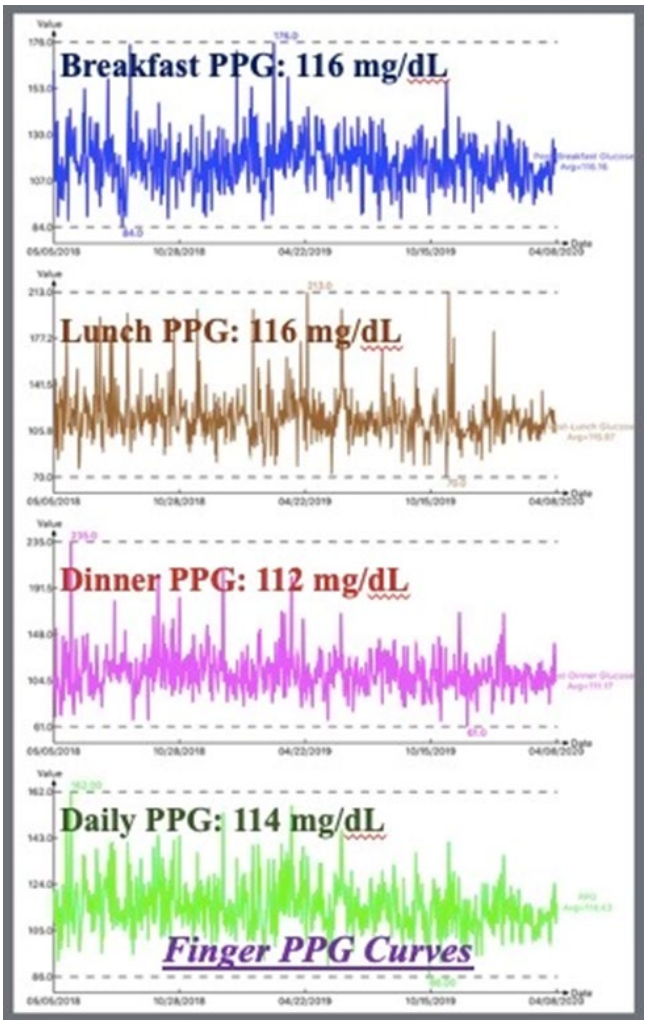

Figure 2: Measured Finger PPG (5/5/18 - 4/8/20)

Finger PPG

breakfast 116 mg/dL
lunch 116 mg/dL
dinner 112Gg mg/dL
daily 114 mg/dL

Second, based on Model A, he calculates the matching time instant (minutes) in which these two methods have "near-equal" PPG values for three meals each day throughout the entire period of 706 days. These results are reflected in Figure 3:

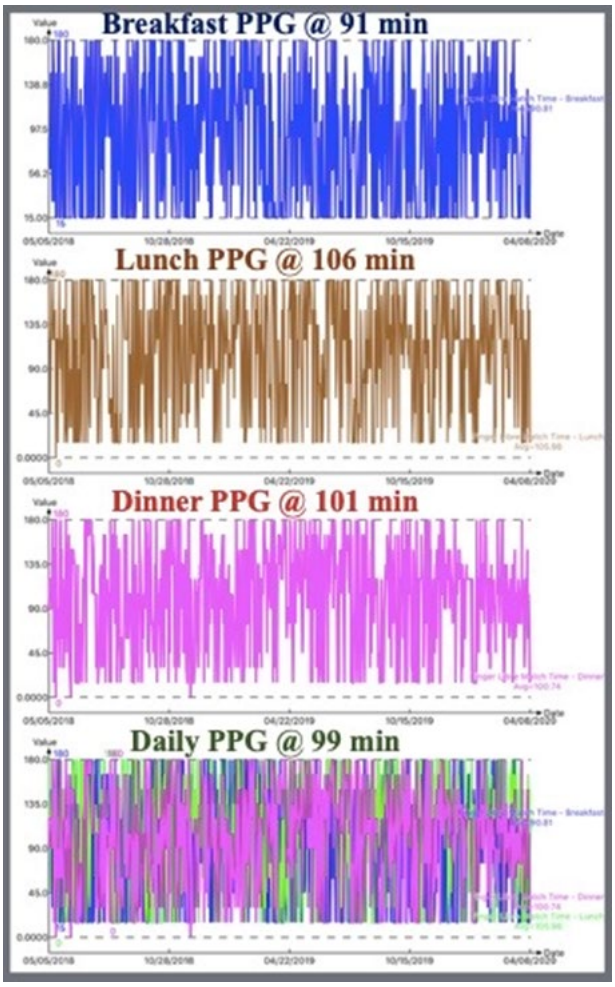

Figure 3: Example of Matching time instants of Sensor PPG with Finger PPG

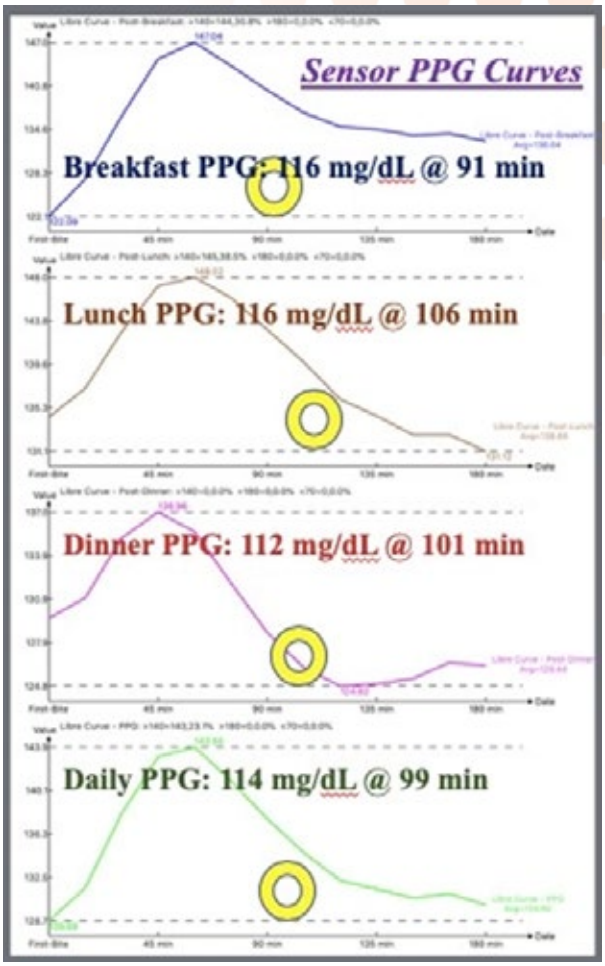

Figure 4: Matched PPG values and time instants (yellow rings)

Match timing

breakfast 91 minutes
lunch 106 minutes
dinner 101 minutes
daily 99 minutes

From his previous research work, the sensor collected PPG peaks occur approximately 60 minutes (between 45 min to 75 min) after the first bite of food. Based on his recent neuroscienctific research on food and neuroscience, he has also identified that liquid meals reach to their peaks around 30-45 minutes, while solid meals reach to their peaks around 60-75 minutes. The conventional medical advice of taking finger-piercing glucose samples about 2-hours after the first bite of food, would result in missing the peak glucose.

Figure 4 illustrates the synthesized PPG curves (i.e. waveforms) for three meals and daily average PPG curve with a yellow ring on the diagram indicating the matching time instant (via Model A) of his finger PPG data. Listed below are average sensor PPG values (Figure 4):

Sensor PPG

breakfast 136 mg/dL
lunch 139 mg/dL
dinner 129 mg/dL
daily 135 mg/dL

By comparing his PPG results of finger vs. sensor, it is evident that the average sensor PPG values are 18.4% higher than the average finger PPG values. In Figure 5, the exceeding % amount of PPG values are listed below:

Sensor PPG > Finger PPG

breakfast 17%
lunch 20%
dinner 15%
daily 18%

The sensor/finger glucose difference % is defined as follows:

Difference % =
(Sensor PPG - Finger PPG) /
(Sensor PPG)

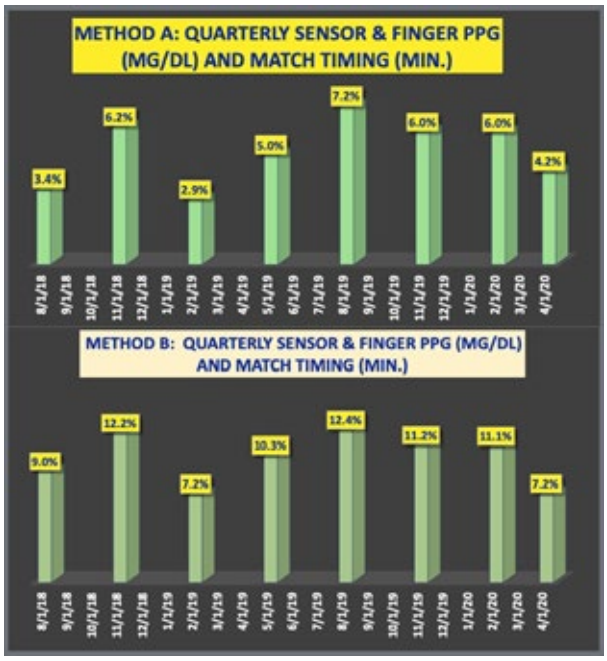

Figure 5: Comparison between Sensor and Finger PPG, daily average measurements (Sensor is 18% higher than Finger)

Figures 6, 7, and 8 show comparison between Model A and Model B regarding PPG, matching time, and sensor/finger difference % for quarterly case.

Method A: Quartly	5/5/18-8/4/2018	8/5/18-11/4/2018	11/5/18-2/4/2019	2/5/19-5/4/2019	5/5/19-8/4/2019	8/5/19-11/4/2019	11/5/19-2/4/2020	2/5/20-4/11/2020
Breakfast Finger	118	115	115	121	118	114	116	111
Breakfast Sensor	122	125	120	126	127	122	124	115
Breakfast Timing	92	91	102	90	79	89	95	88
Breakfast %	3%	8%	4%	4%	7%	6%	6%	4%
Lunch Finger	120	119	115	119	115	114	113	112
Lunch Sensor	126	127	118	128	125	122	120	119
Lunch Timing	102	99	110	108	108	106	106	111
Lunch %	4%	6%	3%	7%	8%	7%	6%	6%
Dinner Finger	111	117	113	113	111	109	108	106
Dinner Sensor	114	124	115	118	119	115	114	109
Dinner Timing	95	97	94	112	111	96	103	98
Dinner %	3%	5%	2%	4%	7%	5%	5%	3%
Diff % (Quartly)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily Finger	**116**	**117**	**114**	**118**	**115**	**112**	**112**	**110**
Daily Sensor	**120**	**125**	**118**	**124**	**123**	**119**	**119**	**115**
Daily Timing	96	96	102	103	100	97	101	99
Diff % (Quartly)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily %	3.4%	6.2%	2.9%	5.0%	7.2%	6.0%	6.0%	4.2%
Method B: Quartly	**5/5/18-8/4/2018**	**8/5/18-11/4/2018**	**11/5/18-2/4/2019**	**2/5/19-5/4/2019**	**5/5/19-8/4/2019**	**8/5/19-11/4/2019**	**11/5/19-2/4/2020**	**2/5/20-4/11/2020**
Breakfast Finger	118	115	115	121	118	114	116	111
Breakfast Sensor	133	133	126	135	136	133	130	120
Breakfast Timing	128	135	133	139	133	133	130	130
Breakfast %	11%	13%	9%	11%	13%	14%	11%	8%
Lunch Finger	120	119	115	119	115	114	113	112
Lunch Sensor	131	137	125	137	133	130	129	123
Lunch Timing	131	140	137	144	140	131	126	129
Lunch %	8%	13%	8%	13%	14%	13%	13%	9%
Dinner Finger	111	117	113	113	111	109	108	106
Dinner Sensor	119	131	118	121	124	116	119	111
Dinner Timing	125	97	125	136	139	128	122	117
Dinner %	7%	10%	4%	6%	11%	6%	9%	5%
Diff % (Quartly)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily Finger	**116**	**117**	**114**	**118**	**115**	**112**	**112**	**110**
Daily Sensor	**128**	**133**	**123**	**131**	**131**	**126**	**126**	**118**
Daily Timing	128	124	132	140	137	130	126	125
Diff % (Quartly)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily %	9.0%	12.2%	7.2%	10.3%	12.4%	11.2%	11.1%	7.2%

Figure 6: Calculation Table Comparison between Model A and Model B (Quarterly)

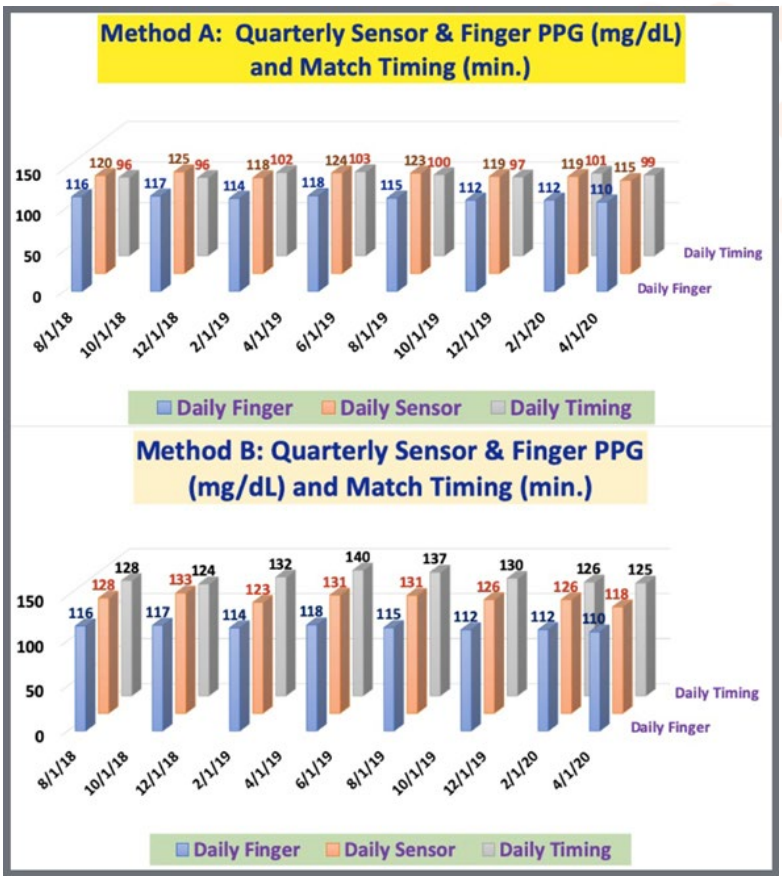

Figure 7: Two PPG & Matching Time Comparison between Model A and Model B (Quarterly)

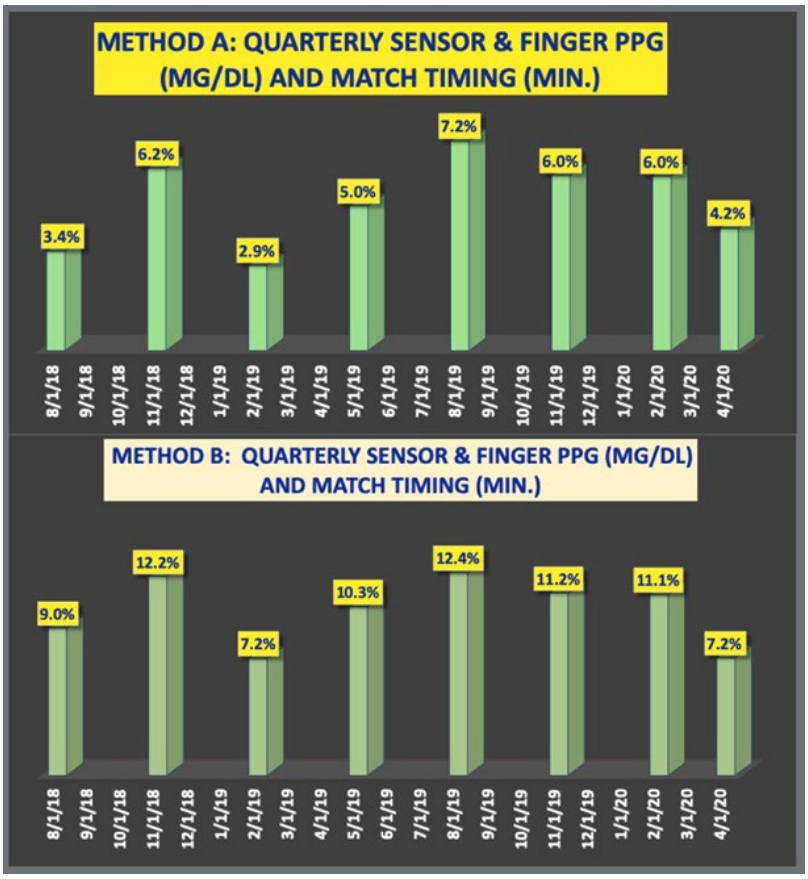

Figure 8: Sensor/Finger Ratio % Comparison between Model A and Model B (Quarterly)

Figures 9, 10, and 11 show comparison between Model A and Model B regarding PPG, matching time, and sensor/finger difference % for **cumulative case.**

Method A: From 5/5/2018 to:	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Breakfast Finger	118	117	116	117	117	117	117	116
Breakfast Sensor	122	124	122	123	124	124	124	123
Breakfast Timing	92	92	95	94	91	91	91	91
Breakfast %	3%	6%	5%	5%	5%	5%	6%	5%
Lunch Finger	120	120	118	118	118	117	116	116
Lunch Sensor	126	126	123	125	125	124	124	123
Lunch Timing	102	101	104	105	105	106	106	106
Lunch %	4%	5%	4%	5%	6%	6%	6%	6%
Dinner Finger	110	114	114	114	113	112	112	111
Dinner Sensor	114	119	118	118	118	117	117	116
Dinner Timing	95	96	96	100	102	101	101	101
Dinner %	3%	4%	3%	3%	4%	4%	4%	4%
Diff % (From 5/5/2018 to:)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily Finger	**116.3**	**116.7**	**115.9**	**116.3**	**116.0**	**115.3**	**114.9**	**114.4**
Daily Sensor	**120.4**	**122.7**	**121.0**	**121.7**	**122.1**	**121.6**	**121.3**	**120.7**
Daily Timing	**96**	**96**	**98**	**99**	**99**	**99**	**99**	**99**
Diff % (From 5/5/2018 to:)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily %	**3.4%**	**4.9%**	**4.2%**	**4.4%**	**5.0%**	**5.2%**	**5.3%**	**5.2%**
Method B: From 5/5/2018 to	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Breakfast Finger	118	117	116	117	117	117	117	116
Breakfast Sensor	133	133	131	132	133	133	132	131
Breakfast Timing	128	132	132	134	134	134	133	133
Breakfast %	11%	12%	11%	11%	12%	12%	12%	11%
Lunch Finger	120	120	118	118	118	117	116	116
Lunch Sensor	131	134	131	133	133	132	132	131
Lunch Timing	131	135	136	138	138	137	136	135
Lunch %	8%	11%	10%	11%	11%	11%	12%	11%
Dinner Finger	111	114	114	114	113	112	112	111
Dinner Sensor	119	125	123	122	123	121	121	120
Dinner Timing	125	132	130	131	133	132	131	129
Dinner %	7%	9%	7%	7%	8%	8%	8%	8%
Diff % (From 5/5/2018 to:)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily Finger	**116**	**117**	**116**	**116**	**116**	**115**	**115**	**114**
Daily Sensor	**128**	**131**	**128**	**129**	**129**	**129**	**128**	**127**
Daily Timing	**128**	**133**	**133**	**134**	**135**	**134**	**133**	**132**
Diff % (From 5/5/2018 to:)	**8/4/18**	**11/4/18**	**2/4/19**	**5/4/19**	**8/4/19**	**11/4/19**	**2/4/20**	**4/11/20**
Daily %	**9.0%**	**10.7%**	**9.5%**	**9.8%**	**10.3%**	**10.4%**	**10.5%**	**10.2%**

Figure 9: Calculation Table Comparison between Model A and Model B (Cumulative)

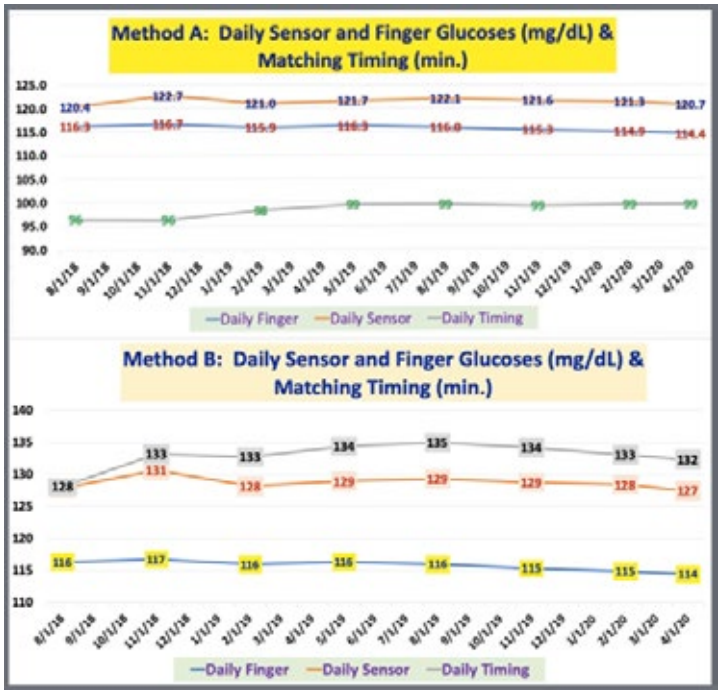

Figure 10: Two PPG & Matching Time Comparison between Model A & Model B (Cumulative)

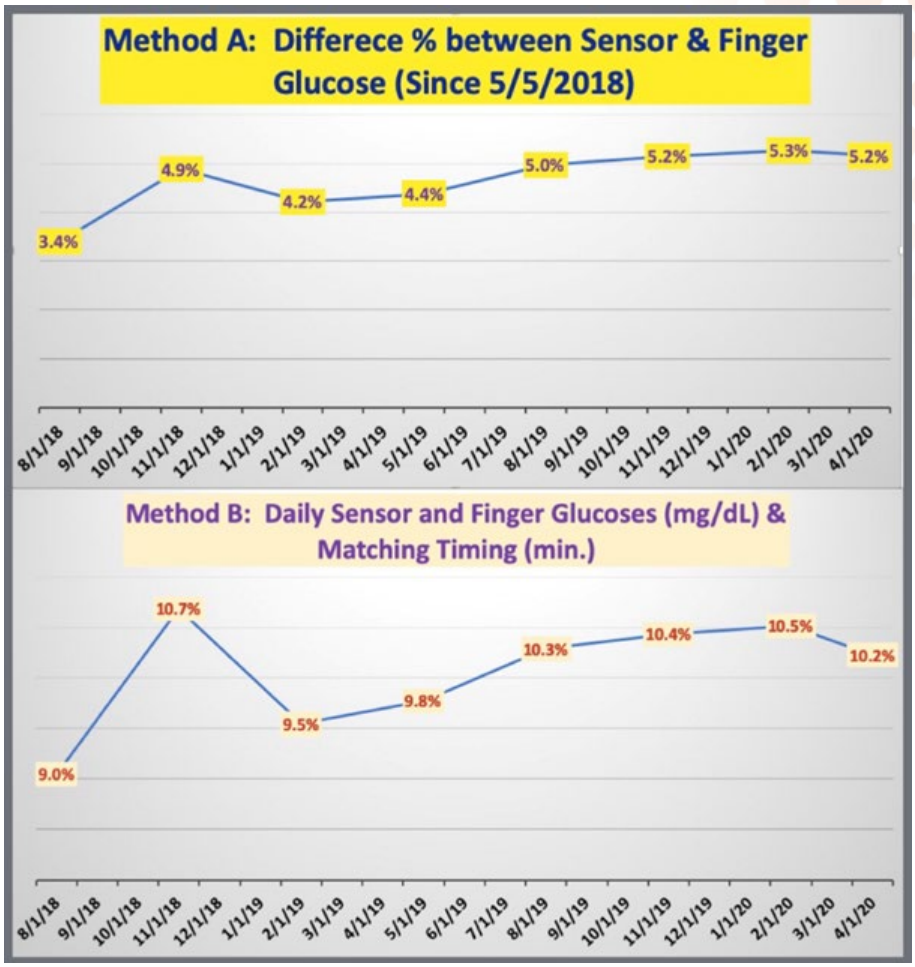

Figure 11: Sensor/Finger Ratio % Comparison Table between Model A & Model B (Cumulative)

For a better understanding of his **first conclusion,** let us focus on the latest quarter (ending on 4/11/2020) of the cumulative case. For Model A, the matched sensor PPG value is 121 mg/dL which is higher than finger PPG 114.4 mg/dL at the matching time of 99 minutes. For Model B, the matched sensor PPG value is 127 mg/dL which is also higher than finger PPG 114.4 mg/dL at the matching time of 132 minutes.

His **second conclusion** is the sensor/finger difference %. For Model A, the sensor/finger difference % is stabilized around 5.2%; and for Model B, the sensor/finger difference % is stabilized around 10.2%.

These two conclusive findings are especially important (see **Figures 12 & 13**). For Model A, the author can use his future sensor PPG waveform's glucose at 99 minutes (between 90 minutes and 105 minutes after first bite of food) and then multiply it by **0.948** to get a predicted Finger PPG at 144.4 mg/dL (100% accuracy). For Model B, the author can use his future sensor PPG waveform's glucose at 132 minutes (between 120 minutes and 135 minutes after first bite of food) and then multiply it by **0.898** to get a predicted Finger PPG at 144.5 mg/dL (99.9% accuracy).

Both Model A and Model B have yielded the same predicted Finger PPG value at 114 mg/dL with a **>99.9% accuracy**.

Method A: Quartly	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Sensor / Finger Difference %	3.4%	6.2%	2.9%	5.0%	7.2%	6.0%	6.0%	4.2%
Method A: Quartly	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Measured Finger PPG	116	117	114	118	115	112	112	110
Predited PPG (Finger by Sensor)	114	119	112	117	117	113	113	109
Acuuracy % Predited Finger PPG	98%	101%	98%	100%	102%	101%	101%	99%

Method A: From 5/5/2018 to:	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Sensor / Finger Difference %	3.4%	4.9%	4.2%	4.4%	5.0%	5.2%	5.3%	5.2%
Method A: Cummulative	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Measured Finger PPG	116	117	116	116	116	115	115	114
Predited PPG (Finger by Sensor)	114	116	115	115	116	115	115	114
Acuuracy % Predited Finger PPG	98%	100%	99%	99%	100%	100%	100%	100%

Method B: Quartly	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Sensor / Finger Difference %	9.0%	12.2%	7.2%	10.3%	12.4%	11.2%	11.1%	7.2%
Method B: Quartly	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Measured Finger PPG	116	117	114	118	115	112	112	110
Predited PPG (Finger by Sensor)	115	120	111	118	117	113	113	106
Acuuracy % Predited Finger PPG	99%	102%	97%	100%	103%	101%	101%	97%

Method B: From 5/5/2018 to	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Sensor / Finger Difference %	9.0%	10.7%	9.5%	9.8%	10.3%	10.4%	10.5%	10.2%
Method B: Cummulative	8/4/18	11/4/18	2/4/19	5/4/19	8/4/19	11/4/19	2/4/20	4/11/20
Measured Finger PPG	116	117	116	116	116	115	115	114
Predited PPG (Finger by Sensor)	115	117	115	116	116	116	115	114
Acuuracy % Predited Finger PPG	99%	101%	99%	99%	100%	100%	100%	100%

Figure 12: Accuracy % between measured PPG and Predicted PPG (from Sensor PPG and difference % adjustments) for both Quarterly and Cumulative

	Method A	Method B
Averaged Finger PPG	114.4	114.4
Averaged Sensor PPG	120.7	127.5
Matched Timing (min)	99	132
Cumulative Difference %	5.2%	10.2%
Calculated Finger from Sensor	114.4	114.5

Figure 13: Almost identical values of (114.4 mg/dL & 114.5 mg/dL) Predicted Finger PPG via Sensor PPG waveform and applying two different adjustment factors for Model A (5.2%) and Model B (10.2%)

Conclusion

After obtaining these two conclusive results, particularly the findings of the two matched timing instants at 99 and 135 minutes, the matched Finger PPG of 114.4 mg/dL will then be further modified by multiplying two different adjustment factors of 0.948 and 0.898 to achieve a predicted Finger PPG with an accuracy of >99.9%.

The author can then proceed with his software enhancement work of replacing finger PPG measurement data entry by using the computer calculated input results from the measured sensor PPG waveform data directly. This approach will not only save the author lots of data-entry time, but also maintain the continuous usage and data accuracy's confidence level of applying his existed equations and formulas to further predict other important biomedical variables, such as the predicted HbA1C value [1-5].

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