How Can the Check Standard Influence Measurement Process Capability

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ABSTRACT

Purpose: The main objective of the paper is an analysis of the behaviour of capability indices under different conditions. It is assumed that the metrological properties of a check standard are correct, however, the uncertainty of the check standard affects the evaluation of the measurement process capability. The paper analyses individual cases of the influence of the check standard bias and its influence on the measurement process capability.

Methodology/Approach: Statistical analysis of both the measurement process and the check standard is provided at the beginning. Development and analysis of possible cases, when the bias of a check standard affects the calculated capability index of a measurement process follows.

Findings: The paper confirmed the theoretical assumption that a bias of a check standard can affect the calculated capability index of a measurement process, thus shifting the judgment on the measurement process capability.

Research Limitation/Implication: The paper is based on the theoretical assumptions of the measurement process capability as well as on the analysis of the possible behaviour of a respective check standard.

Originality/Value of paper: The paper clarifies that several particular and specifically selected cases of bias of a check standard may affect the resulting capability index negatively/positively, which may lead to inaccurate decisions on measurement process capability. This is confirmed by simulations of a biased check standard, clearly visualizing the shifts in capability indices.

Category: Research paper

Keywords: measurement process; capability index; measurement uncertainty; check standard; probability distribution

1 INTRODUCTION

Capability indices are significantly used in the management of production processes. Many studies in this area are elaborated (Pearn and Kotz, 2006; Pearn and Liao, 2006; Baral and Anis, 2015; Grau, 2013; Haq et al., 2015; Malek et al., 2017; IST/SEMATECH, 2012; Bordignon and Scagliarini, 2002; Kotz, Pearn and Johnson, 1993; Montgomery, 2004). Further references are given in the cited texts. Relyea (2011) lists many issues related to the metrological characteristics of measurement devices and the competence of measurement processes. Issues related to digitalization in industrial and societal infrastructures are also addressed by (Santos et al., 2021), which is also closely related to process capability.

Capability indices compare the required (prescribed) precision of the measurement process (MP) with real process variability and deflection (bias). In praxis the so-called first generation of the indices: C_g and C_{gk} are used. The calculated values of these indices should be higher than 1.33 to claim that the measurement process is suitable for the process it has been created for.

The use of capability indices makes it possible to avoid controlling the suitability of the measurement process by means of uncertainties determined according to (JCGM 100:2008; JCGM 102:2011). GUM, which is challenging since the sources of uncertainty and their valuation needs to be determined. The use of capability indices is conditioned using so-called check standard (CS). The exact "true" nominal value of the CS is not known. We can only estimate its value with a certain uncertainty. This CS uncertainty under 10% of the overall process uncertainty is usually neglected, similarly like the measurement uncertainty in manufacturing processes. This assumption assumes that the error of CS during a repeated measurement is within the limits of the expanded uncertainty and is therefore random. Unfortunately, during the repeated measurements, the check standard can develop a bias under some specific conditions. The Influence of the CS uncertainty was also analysed by the authors in (Kureková, 2017; Palenčár et al., 2018). There was thesis, which also proposes usage of the capability indices of next generations in measurement process analysis (Palencar, 2017). In the upcoming sections of this publication the effect of such bias will be shown together with the evidence that a CS uncertainty with a value less than 10% of overall MP uncertainty can have a considerable effect on the final value of the capability indices and consequently on the final assessment of the capability of the measurement process.

2 THEORETICAL BASIS

Assume that probability distribution of the measurement process whose distribution we want to determine, is $X \sim N(\mu, \sigma^2)$, probability distribution of the check standard is $X_{\mathrm{CS}} \sim N(\mu_{CS} = \hat{\mu}_{CS} + \delta_{\mathrm{CS}}, \sigma_{\mathrm{CS}}^2)$ and measurement result Y, obtained by measurement of the check standard, is $Y \sim N(\mu_Y = \mu + \delta_{CS}, \ \sigma_Y^2 =$

$\sigma^2 + \sigma_{CS}^2)$, where μ is the mean value of the measurement process, σ is standard deviation of the measurement process, $\hat{\mu}_{CS}$ is the estimate of mean value from measurements of CS, δ_{CS} is a systematic part of the check standard deviation, σ_{CS} is characteristics of the random part of the check standard deviation.

Sometimes its estimate is known as $\hat{\sigma}_{CS} = u_{A_{CS}}$, which is standard type A uncertainty of the CS. Assumption of normality is not stringent, practically speaking, all that is required is that the distribution of measurements be bell-shaped and symmetric.

Let us define parameter λ_A as a relative variation of the control standard value in the control measurements there on due to the required uncertainty of the measurement process:

$$\lambda_A = \frac{2\sigma_{CS}}{U}, \tag{1}$$

where U is the overall (required) uncertainty of the measurement process, $\sigma_{CS} = u_{A_{CS}}$, which is standard uncertainty type A of the CS, λ_A represents the relative variation of the CS value in the control measurements related to the required measurement process uncertainty.

When we assess the measurement process capability, we need the most unfavorable situation to consider. This is when the CS error is equal the value of the U_{CS} and at the same time will be aiming opposite direction like the true deflection of the MP.

3 CAPABILITY INDEX C_g AND UNCERTAINTY OF THE CHCECK STANDARD

Capability index C_g is defined as (Pearn and Kotz, 2006; Grau, 2013):

$$C_g = \frac{USL - LSL}{4\,\sigma} = \frac{U}{2\,\sigma}. \tag{2}$$

The empirical capability index C_g^Y is obtained by the substitution μ for μ_Y and σ for σ_Y. Then the relationship between the actual process capability index C_g and the empirical capability index C_g^Y will be:

$$C_g^Y = \frac{U}{2\,\sigma_Y} = \frac{U}{2\,\sqrt{\sigma^2 + \sigma_{CS}^2}} = \frac{U}{2\sigma}\frac{1}{\sqrt{1 + \sigma_{CS}^2/\sigma^2}} = C_g\frac{1}{\sqrt{1 + \lambda_A^2 C_g^2}} \tag{3}$$

and because:

$$\frac{\sigma_{CS}}{\sigma} = \frac{\sigma_{CS}}{U}\frac{U}{\sigma} = C_g\lambda_A\,, \tag{4}$$

then also:

$$\frac{C_g^Y}{C_g} = \frac{1}{\sqrt{1 + \lambda_A^2 C_g^2}}. \tag{5}$$

Figure 1 shows dependence of the ratio C_g^Y / C_g on λ_A.

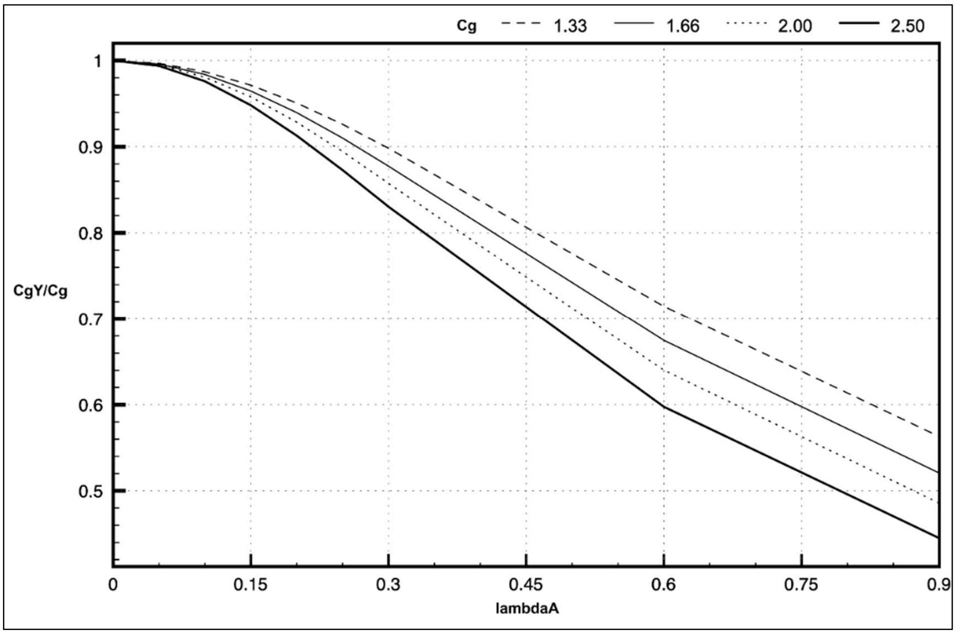

Figure 1 – Ratio of the Experimental Capability Index C_g^Y to the Actual Capability Index C_g

Based on (5) it is valid that for $\lambda_A C_g < 1$.

$$C_g^Y = \frac{C_g}{\sqrt{1 + \lambda_A^2 C_g^2}} \Rightarrow C_g = C_g^Y \frac{1}{\sqrt{1 - \lambda_A^2 {C_g^Y}^2}}. \tag{6}$$

The calculated capability index C_g^Y is always smaller than the actual capability index C_g. That is, if the calculated index C_g^Y is satisfactory, the actual index C_g is satisfactory as well. Also, knowledge of the uncertainty of the control standard caused by the variation of the control standard values, obtained when the control standard is used, allows evaluation of a capability index. In assessing the capability of a measurement process, the relationship (6) enables correcting the capability index C_g by a correction factor of $\frac{1}{\sqrt{1-\lambda_A^2 {C_g^Y}^2}}$, if λ_A is known. However, the knowledge of λ_A may not be simple, so let's settle for the fact that the calculated capability index C_g^Y is always smaller than the actual capability index C_g.

For measured values Y_i, the capability index C_g^Y will be calculated from empirical data:

$$\hat{C}_g^Y = \frac{U}{2s_Y}, \tag{7}$$

where $s_Y = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2}$ and $\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$ are maximum plausible estimates of σ_Y^2 and μ_Y.

4 CAPABILITY INDEX C_{gk} AND UNCERTAINTY OF THE CHCECK STANDARD

Capability index C_{gk} is defined as (Pearn and Kotz, 2006; Grau, 2013):

$$\begin{aligned} C_{gk} &= min\left(\frac{USL-\mu}{2\sigma}, \frac{\mu - LSL}{2\sigma}\right) \\ &= min\left(\frac{(\hat{\mu}_{CS}+U)-\mu}{2\sigma}, \frac{\mu-(\hat{\mu}_{CS}-U)}{2\sigma}\right). \end{aligned} \tag{8}$$

If we denote $\delta = \mu - \hat{\mu_{CS}}$, where μ is the mean value of the MP and the $\hat{\mu}_{CS}$ is the estimate of mean value from measurements of CS (values from CS certificate), in the case of symmetrical uncertainty of the check standard, then:

$$C_{gk} = \frac{U - |\delta|}{2\sigma} = C_g(1 - v), \tag{9}$$

where $v = \frac{|\delta|}{U}$ is the relative bias of the measurement process with respect to the desired expanded uncertainty of the measurement process.

Empirical capability index C_{gk}^Y is obtained by replacing μ by μ_Y and σ by $\sigma_{Y.}$ For measured values Y_i, the capability index $\hat{C}_{gk}^Y$ will be calculated from empirical data:

$$\hat{C}_{gk}^Y = \frac{U - |\bar{Y} - \hat{\mu}_{CS}|}{2s_Y}, \tag{10}$$

where $s_Y = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2}$ and $\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$ are maximum plausible estimates of σ_Y^2 and μ_Y.

If we denote the parameter $\gamma = \frac{|\delta_{CS}|}{U}$ as the relative systematic error (bias) of the check standard with respect to the required extended uncertainty of the measurement process, following cases may be considered:

1. The bias of the check standard γ and the bias of the measurement process v act against each other:

$$C_{gk}^{Y} = min\left(\frac{(\hat{\mu}_{CS} + U) - (\mu - |\delta_{CS}|)}{2\sqrt{\sigma^2 + \sigma_{CS}^2}}, \frac{(\mu - |\delta_{CS}|) - (\hat{\mu}_{CS} - U)}{2\sqrt{\sigma^2 + \sigma_{CS}^2}}\right). \tag{11}$$

   a) For $\gamma \leq$ v is valid:

$$C_{gk}^{Y} = \frac{U - (|\delta| - |\delta_{CS}|)}{2\sqrt{\sigma^2 + \sigma_{CS}^2}} = C_g \frac{1 - v + \gamma}{\sqrt{1 + \lambda_A^2 C_g^2}} = C_{gk} \frac{1 - v + \gamma}{(1 - v)\sqrt{1 + \lambda_A^2 C_g^2}}$$
$$= C_{gk}\left(1 + \frac{\gamma}{1 - v}\right)\frac{1}{\sqrt{1 + \lambda_A^2 C_g^2}}. \tag{12}$$

   b) For $\gamma \geq$ v is valid:

$$C_{gk}^{Y} = \frac{U - (|\delta_{CS}| - |\delta|)}{2\sqrt{\sigma^2 + \sigma_{CS}^2}} = C_g \frac{1 + v - \gamma}{\sqrt{1 + \lambda_A^2 C_g^2}} = C_{gk} \frac{1 + v - \gamma}{(1 - v)\sqrt{1 + \lambda_A^2 C_g^2}}$$
$$= C_{gk}\left(1 + \frac{2v - \gamma}{1 - v}\right)\frac{1}{\sqrt{1 + \lambda_A^2 C_g^2}}. \tag{13}$$

2. The bias of the check standard γ and the bias of the measurement process v act in the same direction:

$$C_{gk}^{Y} = \frac{U - (|\delta_{CS}| + |\delta|)}{2\sqrt{\sigma^2 + \sigma_{CS}^2}} = C_{gk} \frac{1 - v - \gamma}{(1 - v)\sqrt{1 + \lambda_A^2 C_g^2}}$$
$$= C_{gk}\left(1 - \frac{\gamma}{1 - v}\right)\frac{1}{\sqrt{1 + \lambda_A^2 C_g^2}}. \tag{14}$$

Let us define parameter h:

1. First case, when the bias of the CS γ and the bias of the MP v act against each other.

   a) For $\gamma \leq v$ is valid $h = \frac{\gamma}{1-v}$.

   b) For $\gamma \geq v$ is valid $h = \frac{2v-\gamma}{1-v}$.

2. Second case, when the bias of the CS γ and the bias of the MP v act in the same direction $h = -\frac{\gamma}{1-v}$.

Then it is valid:

$$C_{gk}^{Y} = C_{gk} \frac{1}{\sqrt{1+\lambda_A^2 C_g^2}} (1+h) , \tag{15}$$

respectively,

$$C_{gk} = C_{gk}^{Y} \frac{1}{\sqrt{1-\lambda_A^2 {C_g^Y}^2}} \frac{1}{1+h}, \tag{16}$$

and the ratio:

$$\frac{C_{gk}^{Y}}{C_{gk}} = \frac{1}{\sqrt{1+\lambda_A^2 C_g^2}} (1+h) . \tag{17}$$

If deviation of the check standard acts against the deviation of the measurement process, also $\gamma \leq 2v$, then empiric index C_{gk}^{Y} will be bigger than the actual one.

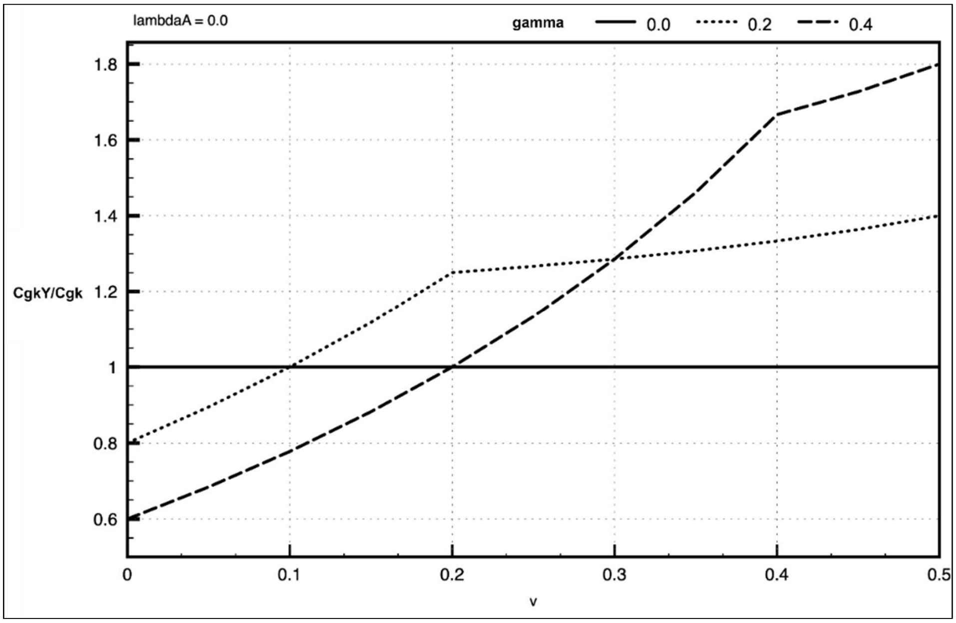

Figure 2 – Ratio of Experimental Capability Indices to the Actual Ones for $\lambda_A = 0$

Figure 2 shows the ratio of empirical and actual capability index C_{gk}^{Y}/C_{gk} for $\lambda_A = 0$ in case bias of the check standard γ and bias of the measurement process ν act against each other. The graph allows the interpretation of the empirical capability index values obtained.

We can see that:

i. for $\nu < 0.5\,\gamma$, the empirical capability index is smaller than the actual one and decreases with decreasing bias of the MP,

ii. for $\nu = 0.5\,\gamma$, the empirical capability index is identical to the actual one,

iii. for $\nu > 0.5\,\gamma$ is empirical capability index bigger than the actual one and with increasing ν against γ the empirical capability index rises in comparison with the actual one,

iv. the point $\nu = \gamma$ represents a value, from which the empirical capability index increases slower with increasing bias of the measurement process.

The relationship (15) indicates that the empirical capability index may be either smaller or larger than the actual capability index. If the check standard bias acts against the bias of a measurement process and $\gamma \leq 2\nu$, the empirical capability index C_{gk}^{Y} will be greater than the actual one. The correction factor for determining the actual capability index C_{gk} is $\frac{1}{\sqrt{1-\lambda_A^2 C_g^{Y\,2}}}\,\frac{1}{1+h}$. This correction assumes knowledge of the components of the uncertainty of the check standard, i.e., the proportion of uncertainty caused by the variation in check standard values when used and the bias of check standard when used. This we called a combined approach which is a combination of the statistical approach and the conservative approach. Here we consider the most unfavorable case, i.e., $|\delta_{CS}| = U_{CS} - 2\sigma_{CS}$.

If we assume that uncertainty of the check standard arises mainly from random fluctuations of check standard values, when it is used (control of measurement process capability), then γ is considered as negligible and the whole expanded uncertainty of the check standard U_{CS} is substituted for $2\sigma_{CS}$ to calculate λ_A. This we called statistical approach.

If we assume that uncertainty of the check standard arises mainly from the systematic deviation of check standard values, when it is used (control of measurement process capability), then λ_A is considered as negligible and the whole expanded uncertainty of the check standard U_{CS} is substituted for δ_{CS} to calculate γ (relative deviation of the check standard). This we called conservative approach.

Table 1 – Empirical Capability Index C_{gk}^{Y} Values for Different γ and for the Actual Capability Index $C_{gk} = 1.33$ (Conservative Approach)

γ	v							
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
0	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33
0.02	1.30	1.36	1.36	1.37	1.37	1.38	1.40	1.42
0.04	1.28	1.39	1.40	1.41	1.42	1.44	1.46	1.51
0.06	1.25	1.42	1.43	1.44	1.46	1.49	1.53	1.61
0.08	1.22	1.45	1.46	1.48	1.51	1.54	1.60	1.68
0.10	1.20	1.48	1.50	1.52	1.55	1.60	1.66	1.77
0.12	1.17	1.45	1.53	1.56	1.60	1.65	1.73	1.86
0.15	1.13	1.40	1.59	1.62	1.66	1.74	1.83	2.00
0.20	1.06	1.33	1.66	1.71	1.77	1.86	2.00	2.22

Table 2 – Empirical Capability Index C_{gk}^{Y} Values for Different Ratios h and for the Actual Capability Index $C_{gk} = 1.33$ (Conservative Approach)

h	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
C_{gk}^{Y}	1.33	1.46	1.60	1.73	1.86	2.00	2.13	2.26

Table 1 and Table 2 provide the minimum values of empirical capability indices C_{gk}^{Y}, required to declare a measurement process is capable, i.e., the actual capability index $C_{gk} > 1.33$. For $v < \gamma \leq 2v$, the empirical capability index is still greater than the actual index but decreases with increasing bias of the check standard. For $\gamma > 2v$ the empirical capability index already provides smaller value than the actual one. The correction factors for the individual cases are given in Table 3.

Table 3 – Correction Factors for Different Approaches of Capability Indices Assessment for $\lambda_A C_g < 1$

	Correction factors		
Capability index	Combined approach	Statistical approach	Conservative approach
C_g	$\frac{1}{\sqrt{1-\lambda_A^2 {C_g^Y}^2}}$	$\frac{1}{\sqrt{1-\lambda_A^2 {C_g^Y}^2}}$	1
C_{gk}	$\frac{1}{1+h}\frac{1}{\sqrt{1-\lambda_A^2 {C_g^Y}^2}}$	$\frac{1}{\sqrt{1-\lambda_A^2 {C_g^Y}^2}}$	$\frac{1}{1+h}$

5 EXAMPLE

Let us suppose measurement of outer dimensions and diameters by a digital micrometer (measuring range 25-50 mm), having a maximum permissible error of 0.001 mm.

Requirements put on measurement process are expressed by an expanded uncertainty $U = 0.01$ mm. The expanded uncertainty of the check standard is $U_{cs} = 0.0008$ mm, which stands for 8% of overall MP uncertainty. Measurement on check standard yields to the bias of $\delta = -0.0054$ mm with standard deviation $\sigma = 0.00152$ mm.

Case 1: Let us assume, that we have the information that standard uncertainty, connected with fluctuation of data of the check standard, is $u_{A_{CS}} = \sigma_{CS} = 0.000076$ mm, so we can use combined approach. Then ratio $\lambda_A = 0.015$ and parameter $h = 0.14$.

Case 2: Let us assume, that we have no information about CS uncertainty, so we use conservative approach, which represents worst case scenario. Then we assume that systematic part of the CS deviation $\delta_{CS} = U_{cs} = 0.0008$ and parameter $h = 0.17$.

Table 4 – Empirical Capability Indices Values Corrected by Combined and Conservative Approach

Empirical capability indices	$C_g^Y = 3.29$	$C_{gk}^Y = 1.51$
Corrected capability indices		
Combined approach	$C_g = 3.29$	$C_{gk} = 1.33$
Conservative approach	$C_g = 3.29$	$C_{gk} = 1.29$

Table 4 introduces values of empirical capability indices, corrected by combined approach and by conservative approach. Empirical capability indices declare that the measurement process is satisfactory. The actual combined capability index also indicates the measurement process capable, although the actual index is less than empirical. If we are not sure that the data fluctuations measured on the check standard are equal to the declared standard deviation of the check standard, we would have to use a conservative capability index and as shown in Table 4, we are not sure that the measurement process is satisfactory.

6 CONCLUSION

In practice, it is generally assumed that the uncertainty of the control standard in assessing the capability indices of measurement processes can be neglected. However, there may be situations where this is not the case. In this paper, we examined how uncertainty of the control standard affects capability indices. This may be particularly important at lower capability indices values, where data due to the uncertainty of the control standard indicate that the process is capable and in fact it may not be true. We can see that the automatic non-consideration of CS uncertainty U_{CS}, even at a value of less than 10% of the overall process uncertainty U, especially for small type A uncertainty, can lead to incorrect conclusions (see Figure 2 and Table 2 and Table 3). This applies to the capability index values C_{gk} approaching 1.33 and precisely at that time the neglect of the CS uncertainty can lead to improper evaluation of the measurement process capability. We see that the decisive role is played by parameter h, which represents the deflection relation CS and deflection MP. We have provided a correction factor that enables correcting the empirical value of the capability index and thus avoid a possible incorrect evaluation of the measurement process capability.

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Conceptualization, J.P. and R.P.; Methodology, M.H.; software, M.D.; Validation, M.D., A.K. and R.P.; Formal analysis, J.P.; Investigation, J.P.; Resources, J.P.; Data curation, A.K.; Original draft preparation, J.P.; Review and editing, M.H.; Visualization, J.P.; Supervision, Ľ.Š.; Project administration, J.P.; Funding acquisition, M.D.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.