VALIDATION OF A DECISION SUPPORT SYSTEM FOR DETERMINING THE SEVERITY OF SCOLIOTIC SPINAL DEFORMITY USING RADIOGRAPHIC IMAGE ANALYSIS

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Objective. To prove the possibility of using a domestic computer program in clinical practice to determine Cobb angle by means of comparative analysis of the obtained automated data with the data of manual measurement by specialists.
Material and Methods. A total of 411 digital x-rays of the spine of children and adolescents were selected from the medical database of Prosthetic and Orthopedic Center «Scoliologic.ru». They were measured by a radiologist with significant experience in vertebrology (VR-standard), by a radiologist without experience in vertebrology (R-beginner) and a computer program (CP). The CP data were compared with the standard twice – initially (CP1) and after fine-tuning (CP2). The mean absolute error and mean absolute deviation of the standard data of Cobb angle measurements were analyzed when compared with the indicators obtained by R-beginner, CP1 and CP2 for different types of scoliosis according to the Rigo classification, and in determining the main curve of different magnitude from 20° to 41° and more. The Pearson coefficient (R) and the intraclass correlation coefficient (ICC) were calculated.
Results. After fine-tuning, the domestic computer program improved the accuracy of measurement in general for curves and types of scoliosis, exceeding the R-beginner indicators almost twice in mean absolute error. The previously identified program drawback in measuring the magnitude of the lumbar (lumbosacral) curve was eliminated. The CP2 data have the highest correlation with the standard (R = 0.94). The excellent level of reliability of the program (ICC = 0.95 when counting on the main curve and 0.97 when counting on all curves) comparable with foreign analogues was proved. It was also confirmed that the average absolute deviation of ±3.2° and ±4.0° for the main curve corresponds to foreign data.
Conclusion. It is possible to conclude that the domestic computer program may be validated, since it has been proven that when compared with a reference measurement, its current algorithm provides accuracy higher than that of a radiologist with no experience in vertebrology, and is comparable with foreign analogues.
Keywords: spine; idiopathic scoliosis; Cobb angle; computer program.
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The Cobb angle is a measurement used to determine the severity of scoliotic spinal deformity and to make evidence-based medical decisions on treatment strategy. That is why high reliability of the determination of this angle is of fundamental importance. However, it is known that the measurement of the Cobb angle in scoliotic spine in the clinical setting is subject to fluctuations among different specialists. Thus, Srinivasalu et al. [1] pointed out that when using the standard Cobb measurement technique, the intra-rater variability of results was 2.8°–4.9° and the inter-rater variability of results was 6.3°–7.2°. Several authors [2, 3] suppose that the clinical acceptability limits for the Cobb angle is ⩽5°.

To improve the accuracy of measurements, foreign researchers propose determining the Cobb angle and diagnosing the severity of scoliosis on chest radiographic images using an automated computer-aided technique [4, 5]. In Russia, there were also attempts to develop automated systems for determining the angles of spinal scoliotic deformity [6], however, they were not tested in clinical practice. In 2020, using a grant from the Foundation for Assistance to Innovations in Russia, a real progress was made towards developing an innovative product (Decision Support System for Determining the Severity of Scoliotic Spinal Deformity Using Radiographic Image Analysis) using deep neural networks in terms of recognizing 2D spinal images and automatic measurement of Cobb angles; this is confirmed by a Certificate of registration with the Federal Service for Intellectual Property [7]. Since 2021, this computer program (CP) was integrated into the medical system of the Prosthetic and Orthopedic Center "Scoliologic.ru" for fine-tuning and optimizing deterministic algorithms. Analysis of its performance on 411 radiographic images conducted in 2023–2024 demonstrated its high reliability; therefore, it can be recommended for automated determination of the Cobb angle, especially for traumatologists and orthopedists with no experience in vertebrology [8]. Due to the errors found in the CP performance, its fine-tuning was continued on an additional dataset following by a repeated automatic measurement of the same 411 radiographic images. Thus, this study is a continuation of the authors' work which began in 2020 [7, 8].

The objective was to prove the possibility of using a Russian computer program in clinical practice to determine Cobb angle by means of comparative analysis of the obtained automated data with the data of manual measurement by specialists.

Material and Methods

The research protocol was approved by the Ethics Committee of the Prosthetic and Orthopedic Center "Scoliologic.ru" (Protocol No. 4 dated August 1, 2024). The article describes the study results without identifying patients, and this does not contradict the ethical standards of the Helsinki Declaration of the World Medical Association – Ethical Principles for Medical Research Involving Human Participants as amended in 2000 and the Clinical Guidelines of the Ministry of Health of the Russian Federation approved by the Order of the Ministry of Health of Russia No. 266 dated June 19, 2003. The study subjects and their legal representatives were informed about the objectives, techniques, expected benefits, as well as the risks and inconveniences associated with their participation.

For comparative analysis, 411 digital radiographic images of the spine of children and adolescents were selected from the medical database of Prosthetic and Orthopedic Center "Scoliologic.ru". They were undergoing treatment for grade II–IV idiopathic scoliosis with Rigo-Cheneau braces designed in Rodin4D NEO software using CAD/CAM technology. Radiographic images were performed in the anteroposterior plane, with the visualization of spine from the C7 to the S1, ribs, chest and abdominal cavity, engaging of the pelvic bones. All radiographic images for determining the Cobb angle of the present deformity curves were sequentially measured manually by two specialists, i.e. a certified radiologist (VR-standard) with experience in describing over 30,000 spinal radiographic images and a certified radiologist with no experience in vertebrology (R-beginner), as well as with an automated CP Decision Support System for Determining the Severity of Scoliotic Spinal Deformity Using Radiographic Image Analysis computer program. Notably, the CP parameters were compared twice with the VR-standard measurement: initially (CP1) and after fine-tuning (CP2). The analyzed deformity curves were defined down from the top as "curve 1", "curve 2", "curve 3", and "curve 4". As in foreign studies, a manual procedure performed by the VR-standard [1] was used as a reference.

The mean absolute percentage error (MAPE) and mean absolute deviation (MAD) of the Cobb angle measurement results for the reference values were compared with the values obtained by the R-beginner, CP1 and CP2 in general, as well as for different scoliosis types according to the classification by Rigo et al. [9], where type A – a three curve scoliosis, type B –a four curve scoliosis, type C – non three, non four curve scoliosis, and type E – a single curve (Fig. 1). This classification was selected because the authors were not involved in the surgical treatment of idiopathic scoliosis, and the Rigo classification was specifically developed for brace treatment of scoliosis and is included in Idiopathic Scoliosis national clinical guidelines (2024) adopted by the Association of Traumatologists and Orthopedists of Russia and approved by the Ministry of Health of Russia [10].

Moreover, MAPE was compared for all the curves measurements made by the R-beginner, CP1 and CP2 with a confidence interval of the difference in the Cobb angle measurements of 1°, 3°, and 5°.

To assess the reliability of measurements, the intraclass correlation coefficient (ICC) for the R-beginner, CP1 and CP2 measurements was calculated from the reference value of the main scoliosis curve that is the key in determining its grade. MAD and MAPE were calculated depending on the magnitude of the main curve in groups of 20°–30°, 31°–40°, 41°–50°, and over 50°. ICC was calculated for R-beginner, CP1 and CP2 for the total of main curves, with the value assessed according to Koo and Li [11]: less than 0.5 means low reliability; 0.5–0.75 means moderate reliability; 0.75–0.9 means high reliability; and >0.9 means very high reliability.

To confirm the concurrent validity, the Pearson correlation coefficient was assessed, as well as VR-standard-R-beginner, VR-standard-CP1, VR-standard-CP2, R-beginner-CP1, and R-beginner-CP2 were compared. The Pearson correlation coefficient was assessed using the Chaddock scale [12]: less than 0.3 – negligible correlation; 0.3–0.5 – weak correlation; 0.5-0.7 – moderate correlation; 0.7–0.9 – strong correlation; and more than 0.9 – very strong correlation.

Results

To evaluate the quality of measurements, MAPE and MAD were analyzed for the R-beginner, CP1 and CP2 and compared with the VR-standard (Table 1).

Data analysis demonstrated that the accuracy of measurements was improved in the CP2 in general for all scoliosis curves and types compared with the CP1. Thus, in general, CP1 MAPE was 23.9%, and MAD was 4.2°. The CP2 demonstrated an almost 2-fold decrease in the mean absolute error – 12.8%, and MAD was determined as 3.2°. The decrease in the CP2 MAPE by curve levels was illustrative. The initial analysis of the CP1 performance demonstrated that there was no adequate consideration to the curve 4 when examining radiographic images of the spine with type B scoliosis, and the magnitude of the lumbar (lumbosacral) curvature was not determined; all this should be considered a diagnostic deficiency [8]. To eliminate it, fine-tuning of the software (CP2) was carried out. CP2 increased the measurement accuracy by 10.1%, 2.6% and 3.9% for curves 1, 2, and 3, respectively, and by 27.9% for curve 4. The accuracy of CP2 in comparison to the reference value for curve 4 increased for type B1 scoliosis by 63.0%, and for type B2 scoliosis by 68.5%. It should be mention that MAD value for curve 4 also decreased from 10.1° to 2.7° for type B1, and from 11.8° to 2.8° for type B2.

A note should be made that the CP2 demonstrated no significant improvement in performance compared to the CP1 for the rarest type E. There was a decrease in MAPE by 2.4% for type E1, and by only 1.0% for type E2. At that, the mean absolute deviation of the CP2 increased to ±6.0° for type E1 (CP1 ±3.8°) and to ±6.8° for type E2 (CP1 ±3.9°). We should mention the increase in the CP2 MAD compared to the CP1 for all curves of types E1 and E2. Analysis of this case demonstrated that another fine-tuning of the CP2 is required for type E scoliosis.

Comparison of the R-beginner MAPE and MAD values and the CP2 as a software under validation confirms its performance. In general, the CP2 MAPE is reduced almost 2-fold compared to the R-beginner values (12.8% vs 21.8%). This value decreased from 5.5% to 13.1% for different types of scoliosis. Meanwhile, the CP1 MAPE is 23.9%, which is 2.1% higher than the R-beginner value. The CP2 mean absolute deviation is less than the R-beginner one by 2°, and the C1 – by 1°. Let us pay attention to the values for type B scoliosis. Here, the CP2 has better performance, with reducing MAPE compared to the R-beginner by 10.2% (type B1) and 7.9% (type B2). The CP1 demonstrates worse results: MAPE increases by 10.1% (type B1) and by 16.1% (type B2). The difference is especially significant for curve 4 in type B scoliosis. Comparison of MAPE data for the R-beginner with the CP1 and CP2 conclusively proves that the CP2 determines the magnitude of curve 4 significantly better than the CP1. Thus, the CP2 increases the accuracy by 15.5% for type B1 scoliosis, and by 6.1% for type B2. Unlike the CP2, the CP1 decreases the accuracy by 48.2% for type B1 scoliosis, and by 62.4% for type B2 scoliosis. This proves once again that the CP2 drawback in term of the accuracy of determining curve 4 was completely eliminated.

The MAD and MAPE values for different magnitudes of main scoliotic curve are provided in Table 2.

The data in the table show that the CP2 for all main curves provides a mean absolute deviation of ±4.0°, with the smallest deviation of ±2.7° for curve magnitude of 20°-30°, the software makes errors in 10.6% of cases. The CP2 makes the least errors for curve magnitude of 31°–40° (8.7%). The mean absolute error of the CP2 for all main curves was determined to be 9.8%, which is similar to the CP1 and 2-fold lower than that for the R-beginner (17.5%). As for curves of 41° and greater, the CP2 is slightly inferior in accuracy compared to the CP1 – by 1.8% (for curves of 41°–50°) and by 2.3% (for curves greater than 50°), however, it exceeds the R-beginner accuracy by 5% or more.

The parallel validity of the results obtained by the R-beginner and two CP versions (CP1 and CP2) in comparison to the reference values (VR-standard) was assessed based on the calculation of the Pearson correlation coefficient (R). The following values were compared pairwise: VR-standard-R-beginner, VR-standard-CP1, VR-standard-CP2, R-beginner-CP1, and R-beginner-CP2. Comparison of the values with the reference revealed a very strong correlation: VR-standard-R-beginner ($R = 0.91$); VR-standard-CP1 ($R = 0.92$); VR-standard-CP2 ($R = 0.94$), when the CP2 after fine-tuning demonstrated the strongest correlation with the VR-standard. The correlation between the R-beginner and the CP1 was determined as strong ($R = 0.84$), and the correlation between the R-beginner and the CP2 as very strong ($R = 0.93$).

Additionally, the accuracy of measurements for all scoliosis curves was analyzed with an error of 1°, 3°, and 5° (Fig. 2).

Thus, for all scoliosis curves, the coincidence of the CP2 with 3° error increases to 70%, and with 5° error (clinical acceptability [2, 3]) increases to 84%. At that, the coincidence of the CP1 with 5° error was determined to be 75%, and of the R-beginner – 66%.

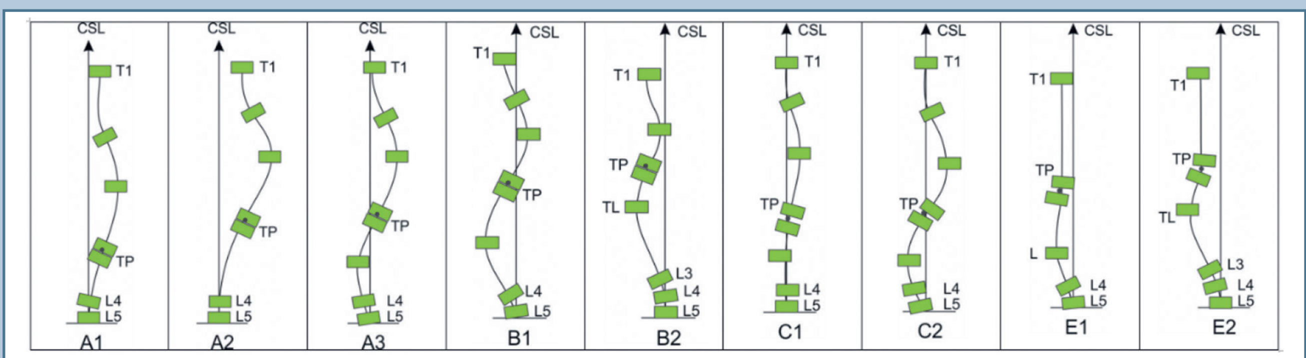

Fig. 1
Scheme of the classification by Rigo et al. [9]

Table 1

Mean absolute error and mean absolute deviation of the Cobb angle measurement from the VR-standard measurement for the R-beginner, CP1 and CP2

Comparison type	Curve 1			Curve 2			Curve 3			Curve 4			Total		
	R-b	CP1	CP2	R-b	CP1	CP2	R-b	CP1	CP2	R-b	CP1	CP2	R-b	CP1	CP2
Mean absolute error, %															
Total	31.8	28.7	18.6	20.8	13.1	10.5	18.9	15.8	11.9	15.8	38.1	10.2	21.8	23.9	12.8
Type A1 scoliosis	26.6	21.3	9.7	19.7	9.6	8.0	27.2	22.6	17.4	3.3	3.7	2.6	19.2	14.3	9.4
Type A2 scoliosis	28.0	23.5	17.6	18.4	11.0	9.3	21.9	17.2	17.2	1.9	1.5	0.6	17.6	13.3	9.7
Type A3 scoliosis	23.6	20.0	12.3	15.1	9.5	8.5	13.0	10.5	9.1	2.7	4.9	2.3	13.6	11.2	8.1
Type B1 scoliosis	25.7	25.6	14.7	16.3	10.	8.1	14.2	11.4	8.1	40.5	88.7	24.8	24.1	34.2	13.9
Type B2 scoliosis	28.5	35.9	19.1	19.3	14.8	8.7	15.7	14.7	10.0	24.5	86.9	18.4	22.0	38.1	14.1
Type C1 scoliosis	30.3	43.2	17.9	24.9	25.3	15.9	26.7	16.7	19.3	16.8	8.3	7.1	24.7	23.4	15.0
Type C2 scoliosis	38.6	22.9	14.7	22.6	12.9	9.2	21.5	24.1	11.8	8.7	5.8	3.2	22.9	16.4	9.8
Type E1 scoliosis	59.7	37.9	44.7	37.8	28.2	24.8	15.3	12.4	8.8	1.8	12.3	2.9	28.6	22.7	20.3
Type E2 scoliosis	61.1	47.0	43.4	38.3	18.4	22.4	22.5	16.1	19.4	1.6	10.5	2.6	30.9	23.0	22.0
Mean absolute deviation, degrees															
Total	5.3	4.0	3.1	6.4	3.7	3.5	5.3	4.0	3.7	3.5	5.0	2.4	5.2	4.2	3.2
Type A1 scoliosis	5.8	4.0	2.1	5.7	2.9	2.4	4.6	4.3	3.4	1.0	0.7	0.4	4.3	3.0	2.1
Type A2 scoliosis	5.3	3.5	3.4	7.0	3.8	4.2	4.9	3.8	2.6	0.5	0.1	0.1	4.4	2.8	2.6
Type A3 scoliosis	6.3	5.2	3.1	7.5	4.7	4.4	4.4	3.7	3.3	3.1	2.1	1.8	5.3	3.9	3.2
Type B1 scoliosis	4.2	3.3	2.5	5.0	2.8	2.7	3.9	3.4	2.3	3.8	10.1	2.7	4.2	4.9	2.5
Type B2 scoliosis	4.6	4.9	2.9	6.1	4.3	2.9	4.3	4.3	2.7	3.6	11.8	2.8	4.6	6.3	2.8
Type C1 scoliosis	4.4	4.3	3.0	3.9	3.9	3.5	5.7	3.7	4.6	3.4	0.5	1.7	4.3	3.1	3.2
Type C2 scoliosis	6.1	3.5	2.7	7.2	3.9	3.1	5.5	3.9	3.3	7.6	1.2	5.3	6.6	3.1	3.6
Type E1 scoliosis	6.5	3.1	4.9	7.6	3.7	4.5	10.7	3.9	8.7	9.0	4.4	5.8	8.5	3.8	6.0
Type E2 scoliosis	7.3	4.0	5.4	9.5	4.3	5.9	11.4	5.4	10.4	6.9	1.9	5.4	8.8	3.9	6.8

R-b — radiologist without experience in vertebrology; CP1 — initial computer program; CP2 — computer program after fine-tuning.

In conclusion, we provide an example of the CP2 performance compared to the VR-standard and the R-beginner measurements (Fig. 3).

The R-beginner measurements differed significantly from the VR-standard ones: 4° to 12°. The CP correctly identified and assessed all available deformity curves; the difference between the VR-standard and automatic measurement of the Cobb angle was 1°–2° and was determined as negligible.

Table 2

Mean absolute deviation (MAD) and mean absolute error (MAPE) values for different magnitudes of the main scoliosis curve

Main curve magnitude (Cobb angle), degrees (percentage of total)	R-beginner		CP1		CP2	
	MAD, degrees	MAPE, %	MAD, degrees	MAPE, %	MAD, degrees	MAPE, %
20–30 (34.1%)	±5.2	20.5	±2.9	11.6	±2.7	10.6
31–40 (21.8%)	±5.9	16.6	±3.7	10.3	±3.1	8.7
41–50 (19.1%)	±7.6	16.7	±3.6	7.8	±4.4	9.6
>50 (25.0%)	±9.6	16.1	±5.5	8.8	±7.0	11.1
All main curves (100%)	±6.8	17.5	±3.8	9.8	±4.0	9.8

R-beginner — radiologist without experience in vertebrology; CP1 — initial computer program; CP2 — computer program after fine-tuning.

Discussion

The mean absolute deviation of the Cobb angle measurement results obtained by foreign researchers was ±3.19° [13]; ±3.3° [14]; ±3.52° [15]; ±5° in 88.7% of cases [16]; <5° in 95.9% of cases [17].

Thus, the Russian CP demonstrating a mean absolute deviation of ±3.2° for all curves and ±4.0° for the main curve is actually not inferior to foreign analogues.

The ICC value obtained with the Russian CP was compared with foreign data provided by different authors, as well as with the data obtained with the Russian CP before fine-tuning (Table 3).

If the CP1 value for the intraclass correlation coefficient for the main curve was in the range of high reliability (ICC = 0.9), then the CP2 demonstrated very high reliability comparable with the latest foreign studies [17, 19, 20]. It should be mentioned that the calculation of the CP2 ICC for all curves also confirms the very high reliability of the CP: ICC = 0.97.

The study revealed that the Russian CP after fine-tuning improved the measurement accuracy in general for scoliosis curves and types, exceeding the MAPE value of a radiologist with no experience in vertebrology by 2-fold. The previously found drawback in measuring the size of the lumbar (lumbosacral) curve was eliminated. The CP2 values have the strongest correlation with both the VR-standard (R = 0.94) and the R-beginner values (R = 0.93). The very high reliability of the CP was proven (ICC = 0.95 for the main curve and 0.97 for all curves) that was comparable with foreign analogues; and it was also confirmed that the mean absolute deviation of ±3.2°, and ±4.0° for the main curve, is actually not inferior to foreign analogues and is within the range of clinical acceptability [2, 3].

An additional fine-tuning of the CP will be carried out for the identified drawbacks of the CP2 in terms of rare E type scoliosis.

Conclusion

Based on the analysis of the performance and reliability level of Decision Support System for Determining the Severity of Scoliotic Spinal Deformity Using Radiographic Image Analysis computer program, we can conclude that it can be validated in the clinical settings. This CP may be recommended for automated determination of the Cobb angle, since it is proven that the current

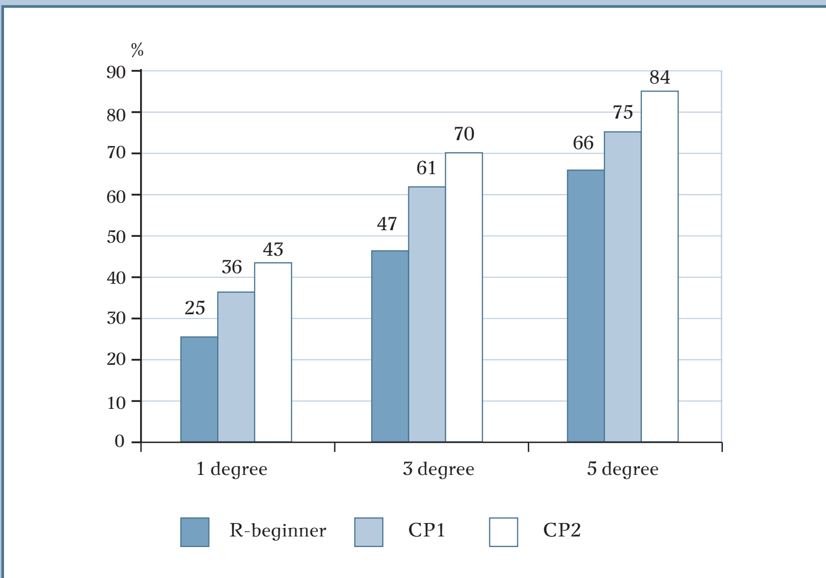

Fig. 2

Coincidence frequency of the results for of the R-beginner, CP1 and CP2 measurements of all scoliosis curves with an acceptable value of discrepancies of 1°, 3° and 5°: R-beginner – radiologist without experience in vertebrology; CP1 – initial computer program; CP2 – computer program after fine-tuning

CP algorithm provides a sufficiently high clinical accuracy compared to the reference measurement by a radiologist with experience in vertebrology and somewhat exceeds the accuracy of a radiologist with no such experience. The validated CP for widespread clinical use is available on the site of the Prosthetic and Orthopedic Center “Scoliologic.ru”.

The study had no sponsors. The authors declare that they have no conflict of interest.
The study was approved by the local ethics committees of the institutions.
All authors contributed significantly to the research and preparation of the article, read and approved the final version before publication.

Fig. 3
Presentation of the computer program performance after fine-tuning (CP2): **a, d** – reference manual measurements (VR-standard); **b, e** – measurements by a radiologist without experience in vertebrology; **c, f** – CP2 automated measurements

Table 3
Comparison of the correlation coefficient in the Russian version of the CP2 with foreign versions of the CP and CP1 for determining the Cobb angle of the main curve

Study	ICC value	Reliability level
Pan et al. [14]	0.854	High
Prestigiacomo et al. [18]	0.864	High
Caesarendra et al. [19]	>0.95	Very high
Sun et al. [20]	0.994	Very high
Wang et al. [17]	0.981	Very high
Initial CP, G.A. Lein et al. [8]	0.90	High
CP after fine-tuning	0.95	Very high

CP — computer program; CP1 — initial computer program; CP2 — computer program after fine-tuning.

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