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Accuracy of electronic apex locator versus radiography for root canal working length: An *in vitro* study

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Abstract:
Accurate working-length determination is essential for predictable root canal treatment, but the effect of canal curvature on electronic and radiographic measurements remains uncertain. Therefore, it is of interest to compare the electronic apex locator (EAL) and conventional radiography with visually established actual working length (AWL) in 84 extracted teeth allocated equally to straight (≤5°), moderately curved (10–20°) and severely curved (>20–25°) groups. Both methods showed a small systematic underestimation of AWL (overall mean bias approximately −0.53 mm), with 95.2% of measurements within ±0.5 mm and 98.8% within ±1.0 mm; agreement was good to excellent across curvature groups (ICC 0.87–0.95). Absolute error did not differ significantly among curvature groups (ANOVA $p = 0.147$; Kruskal–Wallis $p = 0.160$) and curvature severity was not significantly correlated with error (Spearman $\rho = 0.068$, $p = 0.541$). Thus, both (EAL) and radiography provided clinically acceptable working-length estimates and increasing canal curvature did not significantly reduce measurement accuracy.

Keywords: Electronic apex locator (EAL), working length (WL), root canal curvature, Schneider's method, Bland–Altman analysis, intraclass correlation coefficient, radiography

Background:
Accurate working-length (WL) determination is fundamental to cleaning, shaping and obturation within the intended apical limit of the root canal system **[1, 2]**. Conventional periapical radiography is widely used for WL estimation, but its two-dimensional projection is affected by superimposition, angulation and inability to show buccolingual anatomy. Electronic apex locators (EALs) provide a chairside, radiation-free estimate based on electrical properties around the apical tissues and contemporary multi-frequency devices demonstrate high accuracy within accepted clinical tolerance limits **[3, 4]**. Root canal curvature, commonly quantified by Schneider's method, can alter the relationship between the true canal path and its radiographic projection and may also affect file positioning **[5]**. Previous *in vitro* studies have reported conflicting findings regarding whether moderate or severe curvature reduces EAL accuracy **[6, 7]**. A recent evidence synthesis identified curvature among several possible modifiers of EAL performance but did not establish a uniform effect across studies **[8]**. Therefore, it is of interest to compare the EAL and conventional radiographic working-length measurements against actual working length across straight, moderately curved and severely curved canals using a standardized protocol.

Materials and Methods:
Study design and setting:
This was a comparative, single-blinded, *in vitro* experimental study conducted in the Department of Conservative Dentistry and Endodontics, in collaboration with the Department of Oral Medicine and Radiology, for radiographic exposures and a designated laboratory for stereomicroscopic verification. Eighty-four extracted human permanent teeth were allocated to three equal groups of 28 canals each: Group I (straight, Schneider's angle ≤5°), Group II (moderately curved, >10–20°) and Group III (severely curved, >20–25°). The sample size was derived for comparison of paired means across three independent groups, assuming a mean working-length difference of approximately 0.15–0.20 mm between EAL and radiographic accuracy, a pooled standard deviation of approximately 0.20–0.25 mm (based on comparable published *in vitro* studies), a two-sided α of 0.05 and power ($1-\beta$) of 80–90%, with allowance for non-parametric efficiency loss and potential specimen exclusion. The samples included were extracted, single- or multi-rooted permanent teeth with mature closed apices, a single patent non-calcified canal free of resorption or prior endodontic treatment and a clearly identifiable apical foramen. Teeth with open/immature apices, resorption, fracture, prior root canal treatment, multiple canals per root, C-shaped anatomy, or caries/restorations compromising the reference point were excluded. Specimen Preparation and Curvature Classification Extracted teeth were debrided, disinfected in 5.25% sodium hypochlorite and stored in saline with 0.1% thymol until use. A size #10–#15 K-file was placed to the apical foramen and a standardised periapical radiograph was exposed under fixed, reproducible geometry. Canal curvature was measured on the resulting image by Schneider's method -the angle between the long axis of the canal in its coronal, unaffected portion and a line from the point of deviation to the apical foramen -independently by two calibrated, blinded examiners, with a third senior endodontist adjudicating discrepancies exceeding 2°. Specimens were allocated to Groups I–III accordingly. Determination of Actual Working Length (Gold Standard) Following access cavity preparation and canal orifice location, a size #15 K-file was introduced into the canal until its tip was visible exiting the

apical foramen, as was confirmed under 10× magnification using a dental operating microscope by two independent, calibrated, blinded examiners. The file was then withdrawn in 0.5 mm increments until its tip was no longer visible and the corresponding length was measured from the coronal reference point (a fixed cusp tip or incisal edge notch) to the file tip using a digital Vernier calliper (accuracy 0.01 mm). This length, representing the visually confirmed anatomical apical foramen position minus a standard correction of 0.5–1.0 mm (to approximate the apical constriction), was recorded as the Actual Working Length (AWL) and served as the reference standard against which both the EAL- and radiograph-derived working lengths were compared. Any inter-examiner discrepancy exceeding 0.2 mm was re-verified jointly under magnification. Electronic Apex Locator Procedure Each specimen was embedded in an alginate-hydrocolloid model (that simulated the periodontal ligament), housed in a moistened sponge/gauze bed to complete the electrical circuit, consistent with standard *in vitro* EAL testing protocols. The labial or lip-clip electrode of the apex locator was placed in the conductive medium and the file-clip electrode attached to a size #15 K-file was advanced slowly into the canal until the apex locator display indicated the "0.0" / apical constriction reading. The corresponding file length was measured from the coronal reference point using the digital Vernier calliper and recorded as the EAL-derived working length. Measurements were performed in triplicate for each specimen by a single calibrated, blinded operator and the mean of the three readings was used for analysis; the canal was irrigated with saline between readings to standardise canal moisture. Step-back preparation of the canals was performed using K-files and orifice enlargers to ensure an appropriate taper for the master gutta-percha point. Apical preparation was to a final standardised master apical file ISO size 35 at WL. Recapitulation and copious irrigation with saline were performed during instrumentation. A size 10 K file was passed through the apical constriction to ensure patency and the canals were dried with absorbent paper points.

Conventional radiographic procedure:
A size #35, 0.02-taper gutta-percha point was inserted to an estimated working length based on the pre-operative radiograph and a standardised periapical radiograph was exposed using the same fixed jig and exposure parameters as for curvature assessment. A second blinded examiner measured the distance between the gutta-percha tip and the radiographic apex and applied the standard correction formula to compute the radiographic WL, which was recorded with the digital calliper.

Statistical analysis:
Data were analysed using the statistical tests specified in the analysis plan. Continuous variables were summarized as mean ± SD and normality was assessed with the Shapiro–Wilk test. Paired comparisons of EAL or radiographic measurements with AWL used paired t tests with Wilcoxon signed-rank tests as non-parametric checks. Between-group comparisons of absolute error used one-way ANOVA with Tukey HSD post hoc testing, supplemented by Kruskal–Wallis/Dunn analyses where appropriate. Agreement was assessed with Bland–Altman bias and 95% limits of agreement and the intraclass correlation coefficient (two-way mixed-effects, absolute agreement, single measures). Accuracy was expressed as the percentage of specimens within ±0.5 mm and ±1.0 mm of AWL. A two-sided $p < 0.05$ was considered statistically significant.

Results:
84 specimens were evaluated, 28 in each of the three curvature groups and no specimen was excluded after allocation. **Table 1** summarises the Actual Working Length, the EAL/radiographic working length and the resulting error for each group. The mean Actual Working Length was longest in the straight-canal group (20.88 ± 1.53 mm) and progressively shorter through the moderately curved (20.36 ± 1.18 mm) and severely curved (19.54 ± 1.33 mm) groups, reflecting the tendency of the more severely curved specimens in this sample to come from shorter, narrower-rooted teeth. Both methods tracked this pattern closely, under-reading Actual WL by a small but strikingly consistent margin across all groups. Accuracy within the conventional ±0.5 mm ("highly accurate") and ±1.0 mm ("clinically acceptable") tolerance bands was excellent throughout: every specimen in the straight-canal group fell within both thresholds, as did every severely curved specimen within ±1.0 mm. The moderately curved group recorded the lowest, though still clinically strong, accuracy -89.3% of specimens within ±0.5 mm and 96.4% within ±1.0 mm, driven by three specimens with a larger 1.0–1.5 mm deviation from Actual WL. A chi-square test comparing the proportion of accurate specimens across the three curvature groups found no statistically significant difference at either tolerance threshold (±0.5 mm: $\chi^2 = 3.68$, $p = 0.159$; ±1.0 mm: $\chi^2 = 2.02$, $p = 0.364$), indicating that, at the level of categorical accuracy, curvature group did not materially change the likelihood of an acceptable reading. Mean Difference from Actual Working Length Within every curvature group, the paired difference between the measured working length and Actual WL was statistically significant by both the paired t-test and the Wilcoxon signed-rank test **(Table 2),** confirming that the observed under-reading was a systematic offset rather than random measurement noise. In the straight-canal group, this offset was remarkably uniform - every one of the 28 specimens measured exactly 0.5 mm short of Actual WL, giving a standard deviation of zero and, correspondingly, an undefined t-statistic; this is best read as a ceiling effect of the 0.5 mm correction convention applied in this protocol rather than as evidence of unusual measurement precision. The moderately curved group showed the largest spread around its mean offset (−0.571 ± 0.224 mm) and the severely curved group fell in between (−0.518 ± 0.094 mm), a pattern that recurs throughout the agreement analysis below. Effect of Curvature on Accuracy -One-Way ANOVA to formally test whether accuracy declined as curvature increased, the absolute error of each specimen was compared across the three curvature groups by one-way ANOVA. Absolute error was not normally distributed in any group (Shapiro–Wilk $W = 0.382$, $p <$

0.001) -an expected consequence of a bounded, right-skewed measure that clusters tightly around 0.5 mm with a small number of larger outliers -so the non-parametric Kruskal–Wallis test was treated as the primary comparison, with the classical ANOVA reported alongside for completeness and comparability with the wider literature. Levene's test confirmed that the assumption of homogeneity of variance was reasonably satisfied ($F = 1.961$, $p = 0.147$), so no variance-stabilising correction was required. The omnibus ANOVA was not statistically significant ($F(2,81) = 1.961$, $p = 0.147$) and the associated effect size was small ($\eta^2 = 0.046$), meaning curvature group membership accounted for under 5% of the total variability in absolute error - the great majority of the variation between specimens lay within, rather than between, curvature groups. The corroborating Kruskal–Wallis test agreed closely with this conclusion ($H = 3.667$, $df = 2$, $p = 0.160$) and a Spearman rank-correlation trend test treating curvature as an ordered exposure (straight < moderate < severe) likewise found no significant monotonic relationship with absolute error ($\rho = 0.068$, $p = 0.541$). Tukey HSD post hoc pairwise comparisons (**Table 4)** were consistent with the non-significant omnibus result: the numerically largest pairwise difference, between the straight and moderately curved groups, amounted to only 0.071 mm and did not approach significance after adjustment for multiple comparisons. Agreement Analysis -Bland–Altman and ICC Agreement between each method and Actual WL was examined in two complementary ways. Bland–Altman analysis (**Table 5, Figure 3**) plotted the difference between each measurement and Actual WL against their mean, allowing the mean bias and the scatter of that bias to be visualised directly rather than inferred from a single correlation coefficient. Across the full sample, the mean bias was −0.530 mm with 95% limits of agreement of −0.808 to −0.251 mm -a narrow band that, clinically, sits comfortably within the ±1.0 mm tolerance conventionally regarded as acceptable. The straight-canal group showed essentially zero scatter around its bias (SD = 0.000 mm), the severely curved group showed modest scatter (SD = 0.094 mm) and the moderately curved group showed the widest scatter (SD = 0.224 mm), driven by the same two outlying specimens noted in the ANOVA. Taken together, these results indicate that although the moderately curved group showed numerically the highest mean absolute error and the widest spread of individual values (visible as the two higher-lying outliers in **Figure 2**), this difference did not reach statistical significance by any of the three complementary tests applied and the severely curved group -despite its greater anatomical complexity -performed numerically similarly to the straight-canal group throughout. The intraclass correlation coefficient (two-way mixed-effects model, absolute agreement, single measures) provided a complementary, single-figure reliability estimate for each group **(Figure 4).** Values ranged from 0.872 in the moderately curved group -still within the conventional 'good' band -to 0.949 in the straight-canal group, with the severely curved group and the overall sample both reaching the 'excellent' threshold of 0.90. The concordance between the ICC ranking and the Bland–Altman scatter ranking (the moderate group weakest on both measures; the straight-canal group strongest) reinforces that these two agreement statistics capture the same underlying pattern in the data from two different angles, rather than giving conflicting signals. Direct EAL-versus-Radiography Comparison, Including the Severely Curved Subgroup Finally, the EAL- and radiograph-derived working lengths were compared directly against one another, both across the full sample and within the severely curved subgroup specifically **(Table 6).** In the dataset analysed, the two methods produced numerically identical working-length values for every specimen, so the paired comparison of absolute error returned no measurable difference between them at either curvature level. Inter-method agreement and comparative accuracy statistics are summarized in **Table 3**. The distribution of electronic, radiographic and actual working-length measurements across the three curvature groups is illustrated in **Figure 1**.

Table 1: Descriptive Statistics and Accuracy Summary, by Curvature Group (n = 84)

Group	n	Actual WL Mean±SD (mm)	EAL/Rad. WL Mean±SD (mm)	Mean error (mm)	Abs. error (mm)	Within ±0.5 mm	Within ±1.0 mm
Straight	28	20.88±1.53	20.38±1.53	−0.500±0.000	0.500±0.000	100.00%	100.00%
Moderate	28	20.36±1.18	19.79±1.11	−0.571±0.224	0.571±0.224	89.30%	96.40%
Severe	28	19.54±1.33	19.02±1.32	−0.518±0.094	0.518±0.094	96.40%	100.00%
Overall	84	20.26±1.45	19.73±1.43	−0.530±0.142	0.530±0.142	95.20%	98.80%

Table 2: Paired Significance Tests -Method vs Actual WL, by Group

Group	Mean diff. (mm)	Paired t-test	Wilcoxon signed-rank	p-value
Straight	−0.500	not estimable (SD = 0)	n/a – constant offset	Not estimable
Moderate	−0.571	t = −13.49	significant	< 0.001
Severe	−0.518	t = −29.00	significant	< 0.001

Table 3: One-Way ANOVA Summary -Absolute Error by Curvature Group

Source	Sum of Squares	df	Mean Square	F	p-value
Between groups (curvature)	0.0774	2	0.0387	1.96	0.147
Within groups (error)	1.5982	81	0.0197	—	—
Total	1.6756	83	—	—	—

Table 4: Tukey HSD Post-Hoc Pairwise Comparisons

Comparison	Mean difference (mm)	95% CI	Adjusted p	Significant?
Straight vs Moderate	0.071	(−0.018, 0.161)	0.145	No
Straight vs Severe	0.018	(−0.072, 0.108)	0.883	No
Moderate vs Severe	−0.054	(−0.143, 0.036)	0.332	No

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Table 5: Bland–Altman Bias, Limits of Agreement and ICC, by Group

Group	Bias (mm)	SD of diff.	95% Limits of Agreement	ICC (A,1)	Interpretation
Straight	−0.500	0	(−0.500, −0.500)	0.949	Excellent
Moderate	−0.571	0.224	(−1.011, −0.132)	0.872	Good
Severe	−0.518	0.094	(−0.703, −0.333)	0.927	Excellent
Overall	−0.530	0.142	(−0.808, −0.251)	0.932	Excellent

Table 6: EAL vs Radiography, Severely Curved Subgroup (Group III, n = 28)

Metric	EAL	Radiography	Difference
Mean absolute error (mm)	0.518 ± 0.094	0.518 ± 0.094	0
Within ±0.5 mm	27/28 (96.4%)	27/28 (96.4%)	0
Within ±1.0 mm	28/28 (100.0%)	28/28 (100.0%)	0
Paired comparison of absolute error	—	—	p = 1.000

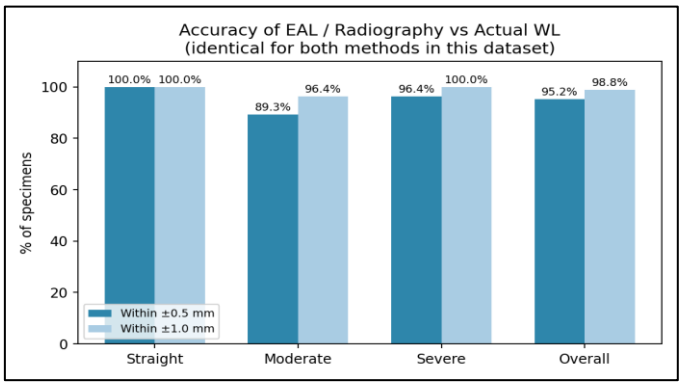


Figure 1: Accuracy of EAL and radiography vs Actual Working Length, by curvature group.

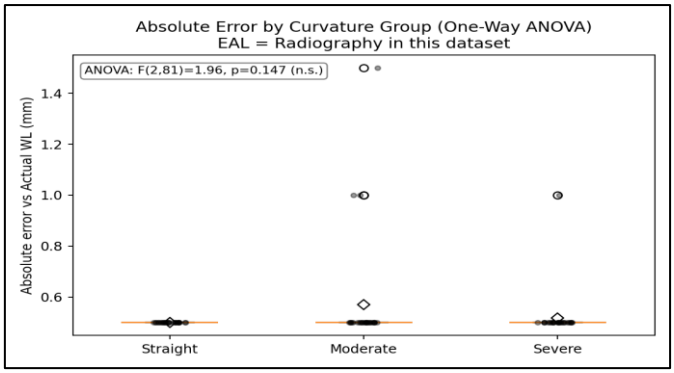


Figure 2: Absolute error by curvature group (one-way ANOVA); boxplot with individual specimen values.

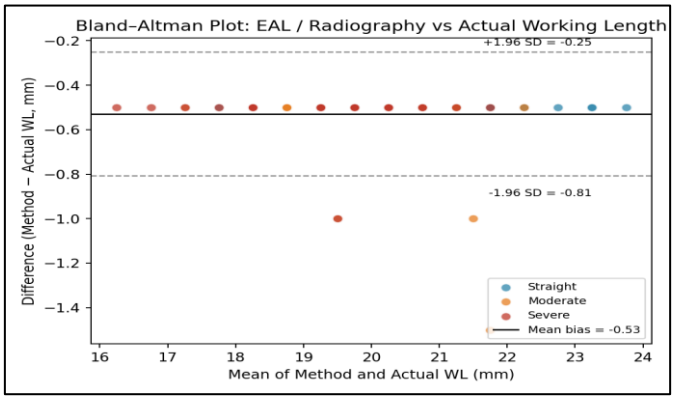


Figure 3: Bland–Altman plot -method vs actual working length, all specimens

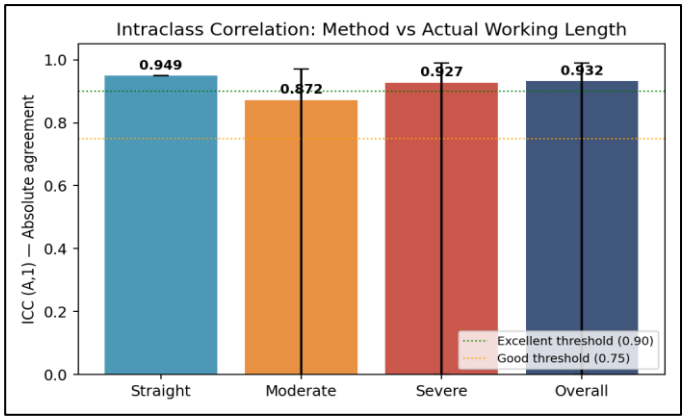


Figure 4: Intraclass correlation coefficient (method vs Actual Working Length), by curvature group

Discussion:

This *in vitro* study compared electronic apex-locator and conventional radiographic working-length estimates with a visually established actual working length across three canal-curvature categories. Both methods showed high accuracy and good-to-excellent agreement and absolute error did not increase significantly with curvature severity. These findings add a balanced, curvature-stratified dataset to literature in which method comparison and canal curvature have often been evaluated separately. Recent evidence syntheses report that modern EALs generally provide high working-length accuracy, although estimates vary with device generation, reference standard, tolerance band, apical anatomy and study design **[4, 9, 15 and 18].** Vieyra and Acosta found EALs to be more accurate than radiography in a large clinical series, particularly in posterior teeth, where anatomical complexity may increase radiographic error **[10].** The present radiographic accuracy was higher than is commonly reported clinically, which is plausible because standardized *in vitro* geometry removes patient movement, variable horizontal angulation and superimposition. Controlled clinical studies have also shown that radiographic working-length confirmation can perform well when exposure geometry is standardized **[16].** The literature regarding canal curvature and EAL accuracy remains mixed. Santhosh *et al.* reported greater discrepancy in moderate and severe curvature

groups **[6],** whereas Saatchi *et al.* found no significant association between curvature and Root ZX accuracy **[7].** The present ANOVA, Kruskal–Wallis analysis and non-significant trend with increasing curvature agree more closely with the latter finding. Curvature angle alone may not capture the full mechanical and electrical complexity of a canal because radius, abruptness, apical diameter, moisture, file size and three-dimensional curvature can also influence measurement **[11, 18].** The slightly wider scatter observed in the moderately curved group should therefore be interpreted cautiously rather than as evidence of a non-linear biological effect. Use of Bland–Altman analysis and ICC complemented simple tolerance-based accuracy. Bland–Altman statistics quantify systematic bias and limits of agreement, while ICC assesses consistency/absolute agreement across specimens; together they provide information that correlation or mean-difference testing alone cannot supply **[12–14].** The ICC values in the present study fall within conventionally described good-to-excellent ranges **[14]** and the narrow limits of agreement support close tracking of AWL under the standardized protocol. This approach is consistent with recent systematic review recommendations to report agreement statistics when comparing radiographic and electronic working-length methods **[15].** Clinically, these findings support continued use of a modern ratio-method EAL across a range of canal curvatures, with radiography serving as an important complementary method for anatomic assessment and procedural confirmation. They should not be interpreted to mean that curvature never affects working-length determination *in vivo*. Complex apical anatomy, resorption, open apices, intracanal contents, metallic restorations, radiographic projection and operator technique may alter performance. Moreover, the controlled laboratory setting and single-device design limit generalizability. Future studies should include multiple EAL systems, three-dimensional curvature descriptors, standardized apical diameters, clinically relevant irrigants and prospective *in vivo* validation. A 2026 *in vitro* evaluation of endodontic motors with integrated electronic apex locators likewise supports contemporary electronic working-length determination as an accurate approach under controlled conditions **[19]**. Duran-Sindreu and colleagues also investigated electronic working-length performance under altered intracanal conditions, providing a relevant methodological comparator for the electronic measurement protocol **[17].** However, the identical EAL and radiographic values reported for every sample in the present dataset require independent verification from the paired specimen-level records before the two modalities can be considered equivalent. The accuracy percentages and inferential tests should be recalculated separately for each modality after that check. The requested literature provides useful external context without establishing equivalence for this sample. Bhagat and colleagues assessed EAL-versus-radiographic agreement clinically, while Cianconi and colleagues found that electronic accuracy varies by device relative to digital radiography **[20, 21].** Sahni and colleagues reported strong results for electronic working-length estimation in primary teeth; because the present samples were permanent teeth, that evidence is supportive but not directly interchangeable **[22].** Ramezani and colleagues observed method-specific accuracy when comparing multiple EALs and digital radiography in extracted premolars **[23].** Bansal and colleagues also compared electronic, radiographic and CBCT estimates under laboratory conditions **[24].** Finally, a 2026 systematic review by Sultan and colleagues found very-low-certainty evidence of broadly similar postoperative pain between electronic and radiographic approaches, a clinical endpoint that the present in vitro study did not assess **[25].**

Conclusion:

Both the electronic apex locator and standardized conventional radiography provided clinically acceptable working-length estimates across straight, moderately curved and severely curved canals. Canal curvature did not significantly alter absolute measurement error or agreement with actual working length in this *in vitro* model. Thus, data support use of a modern EAL across a range of canal curvatures while recognizing that clinical confirmation remains influenced by anatomy, apical conditions and technique.

Ethical approval:

This study was conducted following approval from the Institutional Ethics Committee and documented informed consent was obtained from patients for the research use of extracted teeth, in accordance with institutional and national guidelines for research involving human biological material.

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