

Skin-to-Subarachnoid Space Depth in Adults Undergoing Spinal Anaesthesia: A Central-Indian Anthropometric Prediction Model and Its Agreement with Ultrasonography and Established Formulae

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Abstract

Background: Accurate prediction of the skin-to-subarachnoid space depth improves the safety and efficiency of spinal anaesthesia, yet no depth-prediction model has been derived for the Central-Indian population and most reports exclude overweight and obese patients. We derived and internally validated a population-specific anthropometric model and compared it, and pre-procedural ultrasonography, with established formulae.

Methods: In this single-centre, prospective study, 210 adults (ASA I–II) undergoing spinal anaesthesia had the actual depth (D_a) measured at free cerebrospinal-fluid flow. The ultrasound depth and the Stocker, Craig and Bonadio estimates were recorded blind to the reference. A multivariable model was derived and internally validated (10-fold cross-validation, bootstrapping). Agreement was assessed by Bland–Altman analysis and the intraclass correlation coefficient (ICC); accuracy was the proportion within ± 0.5 cm.

Results: Mean D_a was 4.50 ± 0.56 cm. Backward elimination retained sex and weight: depth (cm) = $2.397 + 0.137(\text{male}) + 0.0316 \times \text{weight (kg)}$ (R^2 0.62). Ultrasound showed the best agreement (bias +0.06 cm; ICC 0.90) and the model was unbiased (bias 0.00 cm; ICC 0.77), both far exceeding the formulae, which overestimated depth (ICC 0.31–0.58). Within ± 0.5 cm, ultrasound and the model reached 93.3% and 84.3% versus 40.5–62.4% for the formulae, and both stayed accurate across BMI strata while the formulae deteriorated. First-attempt success fell with rising BMI ($P < 0.001$).

Conclusion: A simple sex-and-weight model predicts subarachnoid depth without bias and outperforms legacy formulae, especially in higher-BMI patients; pre-procedural ultrasound remains the most accurate option.

Keywords: Anthropometry; Bland–Altman Analysis; Prediction Model; Spinal Anaesthesia; Subarachnoid Space; Ultrasonography.

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Introduction

Spinal anaesthesia is among the most widely used regional techniques for lower-abdominal, pelvic, lower-limb and obstetric surgery, valued for its rapid, dense and reliable block, minimal systemic drug exposure and low cost. Its success rests on accurate localisation of the subarachnoid space, which depends in turn on the operator's ability to judge the depth from skin to the subarachnoid space.[1] When this skin-to-subarachnoid space depth is misjudged, the consequences are repeated needle passes and redirections, longer procedures, patient discomfort and an increased risk of traumatic tap, post-dural-puncture headache and, rarely, neurological injury.[1] [8]

Conventional needle placement relies on surface landmarks such as Tuffier's line. This serves well in patients with easily palpable spines but becomes

unreliable in obesity, oedema, poorly palpable landmarks or altered anatomy — precisely the patients in whom an accurate pre-procedural estimate of depth would be most valuable.[2] Two broad strategies exist to anticipate the depth before insertion: an objective imaging method, pre-procedural ultrasonography of the lumbar spine, and simple anthropometric formulae based on routinely measured body parameters.[2] [3]

Several anthropometric formulae have been proposed, including those of Stocker, Craig, Bonadio and Abe.[4] [5] [6] [7] It is important to recognise that most were originally derived in children; Stocker's weight-based rule, for instance, was developed for paediatric lumbar puncture, so its application to adults is an extrapolation that warrants explicit validation rather than

assumption.[4] [24] Pre-procedural ultrasound, by contrast, allows direct, individualised measurement of the depth to the posterior and anterior dural complexes and consistently shows the closest agreement with the actual needle depth.[3] [11] Several studies, including recent Indian cohorts, have compared formulae and ultrasound against the actual insertion depth and have consistently found that ultrasound agrees more closely with the true depth than weight- or height-based formulae, while the formulae remain useful where ultrasound is unavailable.[1] [23] Yet most of this work has been conducted in patients of normal body habitus and in populations outside Central India, and most reports stop at correlation coefficients without quantifying clinically actionable agreement or linking prediction accuracy to procedural outcomes.[9] [10] Because body proportions and soft-tissue distribution differ across regional and ethnic groups, a formula calibrated elsewhere may perform poorly locally; and correlation, which measures association rather than agreement, can remain high even when one method systematically over- or under-estimates the other.[12] [16]

We therefore set out to derive and internally validate a population-specific, equipment-free anthropometric model for predicting the skin-to-subarachnoid space depth in Central-Indian adults; to benchmark this model and pre-procedural ultrasonography against the established Stocker, Craig and Bonadio formulae using agreement-based statistics, with Bland–Altman analysis and the intraclass correlation coefficient as the primary endpoints; to compare predictive accuracy across the body-mass-index range, including a prespecified overweight or obese stratum; and to relate each method's accuracy to real procedural outcomes.

Materials and Methods

Study Design, Setting and Ethics: This single-centre, prospective, observational diagnostic-accuracy and prediction-model development study was conducted in the Department of Anaesthesiology of a tertiary-care teaching hospital in Bhopal, Central India. Reporting follows the TRIPOD statement for prediction-model studies and the STROBE statement for observational research.[13] [14] The protocol was approved by the Institutional Ethics Committee, and the study was conducted in accordance with the Declaration of Helsinki and the Indian Council of Medical Research National Ethical Guidelines. Written informed consent was obtained from every participant.

Participants: We enrolled 210 adults aged 18 to 65 years, of ASA physical status I or II, scheduled for elective surgery under single-shot spinal anaesthesia in the sitting position. Patients with

hypersensitivity to local anaesthetics, infection at the puncture site, coagulopathy or anticoagulant therapy, haemodynamic instability, clinically evident vertebral deformity or previous lumbar spine surgery, and pregnant women were excluded. Recruitment was planned across the full body-mass-index range, with deliberate enrichment of the overweight and obese strata so that the difficult population was adequately represented.

Sample size: The sample size was driven by the precision of the principal correlation between the actual depth and its ultrasound- and model-based estimates, using the Fisher z-transformation.[26] Assuming a conservative correlation of 0.82, with a two-sided alpha of 0.05 and a 95% confidence-interval half-width of 0.05, the required size was approximately 210. This same sample provided roughly 42 participants per predictor for a five-predictor model, comfortably exceeding the minimum recommended for stable derivation and internal validation,[18] [27] and estimated the Bland–Altman limits of agreement to within about 0.1 cm.[16]

Predictor, Comparator and Outcome Measurements: Spinal anaesthesia was performed by anaesthetists of comparable experience using a standardised midline approach at the L3 to L4 interspace under strict asepsis with a fixed needle type and gauge. At free cerebrospinal-fluid flow the needle was marked at the skin, withdrawn, and the marked length measured with Vernier callipers; this actual depth (D_a) served as the reference standard. Before the block, a trained operator scanned the lumbar spine with a low-frequency curvilinear probe, identified the L3 to L4 interspace in paramedian sagittal-oblique and transverse views, and recorded the mean of the skin-to-posterior-complex and skin-to-anterior-complex depths as the ultrasound depth (D_u).[2] For every participant an analyst blinded to D_a and D_u computed the Stocker estimate ($\text{mm} = 0.5 \times \text{weight} + 18$), the Craig estimate ($\text{cm} = 0.03 \times \text{height}$) and the Bonadio estimate ($\text{cm} = 0.77 + 2.56 \times \text{body-surface area}$), with body-surface area by the Mosteller method.[4] [5] [6] [15] Age, sex, weight, height, body-mass index, the number of attempts and redirections, first-attempt success, time to free cerebrospinal-fluid flow and complications were recorded in a structured proforma.

Statistical Analysis: Data were analysed in R version 4.2.2. Continuous variables were summarised as mean $\pm$ SD or median (IQR) and categorical variables as frequency (%); normality was assessed by the Shapiro–Wilk test with skewness. The primary analysis was agreement of each estimate with D_a , quantified by Bland–Altman analysis (mean bias and 95% limits of agreement)[16] and by the intraclass correlation

coefficient (ICC; two-way, absolute-agreement, single measures).[17]

A multivariable linear regression model for D_a was derived from age, sex, weight, height, body-mass index and body-surface area using a priori selection with backward elimination, guided by the variance inflation factor; it was internally validated by 10-fold cross-validation and 1000-replication bootstrapping to obtain optimism-corrected performance. Predictive accuracy was the proportion of estimates within 0.5 cm and 1.0 cm of D_a , overall and by body-mass-index stratum. A two-sided P below 0.05 was considered significant.

Results

Participant characteristics: Two hundred and ten patients were studied [Table 1]. The mean age was 42.39 ± 11.80 years and 125 (59.5%) were male; mean weight was 63.79 ± 12.69 kg, height 159.85 ± 9.21 cm and body-mass index 24.90 ± 4.13 kg/m². Most were ASA I (180; 85.7%). By body-mass-index category, 112 (53.3%) were of normal weight, 71 (33.8%) overweight and 27 (12.9%) obese, so that 46.7% lay in the difficult, higher-mass strata.

Normality and descriptive comparison: On Shapiro–Wilk testing, D_a , D_u and the Bonadio estimate were normally distributed, whereas the Stocker and Craig estimates, weight, height and body-mass index were not; critically, all four difference variables (D_a minus each method) were normal, supporting parametric limits of agreement [Table 2]. The mean actual depth was 4.495 ± 0.557 cm (range 3.12 to 6.25), close to D_u (4.437 ± 0.630 cm). The formulae diverged more, the Stocker, Craig and Bonadio estimates averaging 4.989, 4.796 and 5.062 cm respectively [Table 3].

Derivation and internal validation of the model: Backward elimination retained only sex and weight as independent predictors of D_a [Table 4]. The resulting equation, D_a (cm) = $2.397 + 0.137$ (male sex) + $0.0316 \times$ weight (kg), explained a substantial share of the variance (R^2 0.620; adjusted R^2 0.616; root-mean-square error 0.343 cm). Age, height, body-mass index and body-surface area were dropped as non-significant or collinear. Internal validation was reassuring: the 10-fold cross-

validated agreement was essentially identical to the apparent fit (bias +0.00 cm, limits of agreement ± 0.68 cm, ICC 0.76), indicating minimal optimism.

Agreement with the actual depth: Agreement with D_a differed markedly across methods [Table 5; Figure 1; Figure 2]. Ultrasound showed the smallest bias (+0.058 cm) and the narrowest limits of agreement (-0.45 to $+0.57$ cm), with excellent reliability (ICC 0.90; 95% CI 0.87 to 0.92). The derived model was essentially unbiased (bias 0.00) with limits of agreement of ± 0.67 cm and good reliability (0.77; 0.70 to 0.82). The formulae performed less well and systematically overestimated the depth: the Stocker, Craig and Bonadio estimates carried biases of -0.495 , -0.301 and -0.568 cm and wider limits of agreement, with intraclass correlations of only 0.58, 0.31 and 0.49 and confidence intervals that crossed or approached zero.

Predictive accuracy and BMI subgroups: These differences translated directly into clinical accuracy [Table 6; Figure 3]. Ultrasound placed 93.3% of estimates within 0.5 cm of D_a and the derived model 84.3%, both reaching 100% within 1.0 cm, with mean absolute errors of 0.211 and 0.273 cm. The formulae were substantially less accurate (Craig 62.4%, Stocker 49.5%, Bonadio 40.5% within 0.5 cm). Importantly, the accuracy of ultrasound and of the derived model was preserved across body-mass-index strata, whereas the formulae deteriorated or behaved erratically in overweight and obese patients; Stocker's accuracy, for example, fell from 61.6% in normal-weight patients to 35.7% in the overweight or obese.

Procedural outcomes: Procedural outcomes reflected the same anatomy [Table 7]. First-attempt success was 90.5% overall but fell significantly with increasing body mass, from 94.6% in normal-weight to 91.5% in overweight and 70.4% in obese patients (chi-square P below 0.001). The mean number of attempts was 1.11 ± 0.37 and redirections 0.32 ± 0.59 ; the median time to free cerebrospinal-fluid flow was 36 seconds (mean 41.7 ± 20.5). Complications were infrequent: traumatic tap in 7 patients (3.3%), post-dural-puncture headache in 5 (2.4%), hypotension in 38 (18.1%) and a single failed spinal (0.5%).

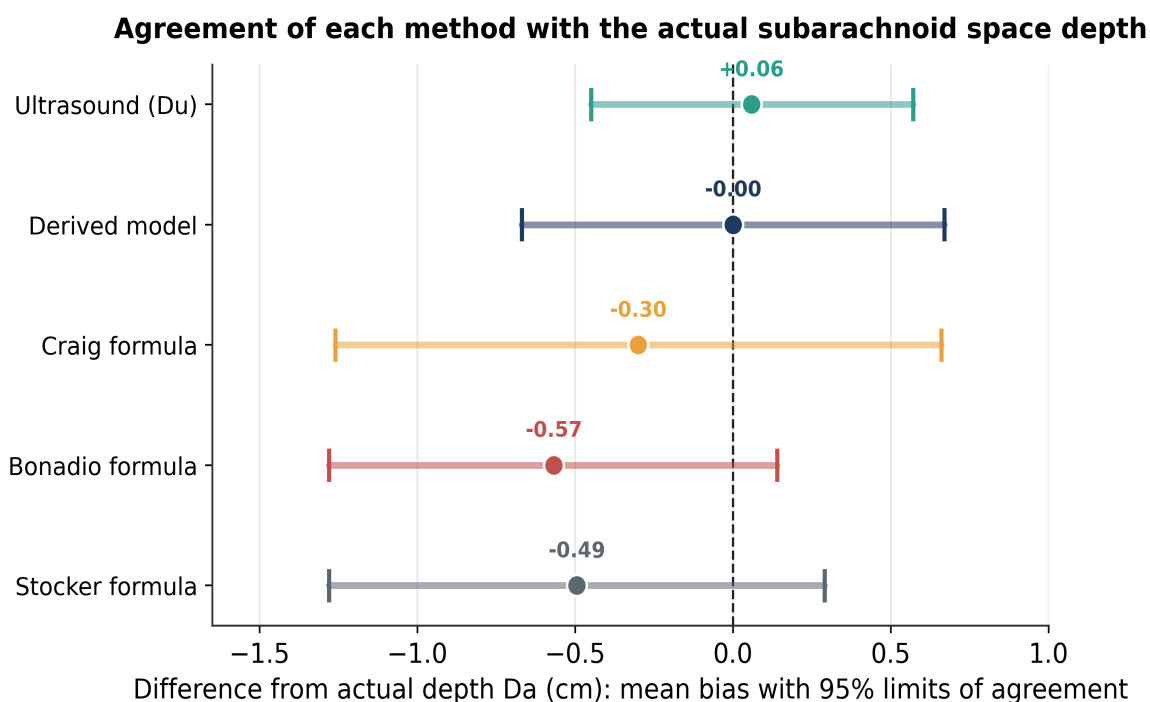


Figure 1: Agreement of each method with the actual subarachnoid space depth.

Mean bias (point) with 95% limits of agreement (whiskers) for each estimate relative to the actual depth D_a (Table 5). The dashed line marks zero (perfect agreement); a negative bias indicates that the method overestimates the depth.

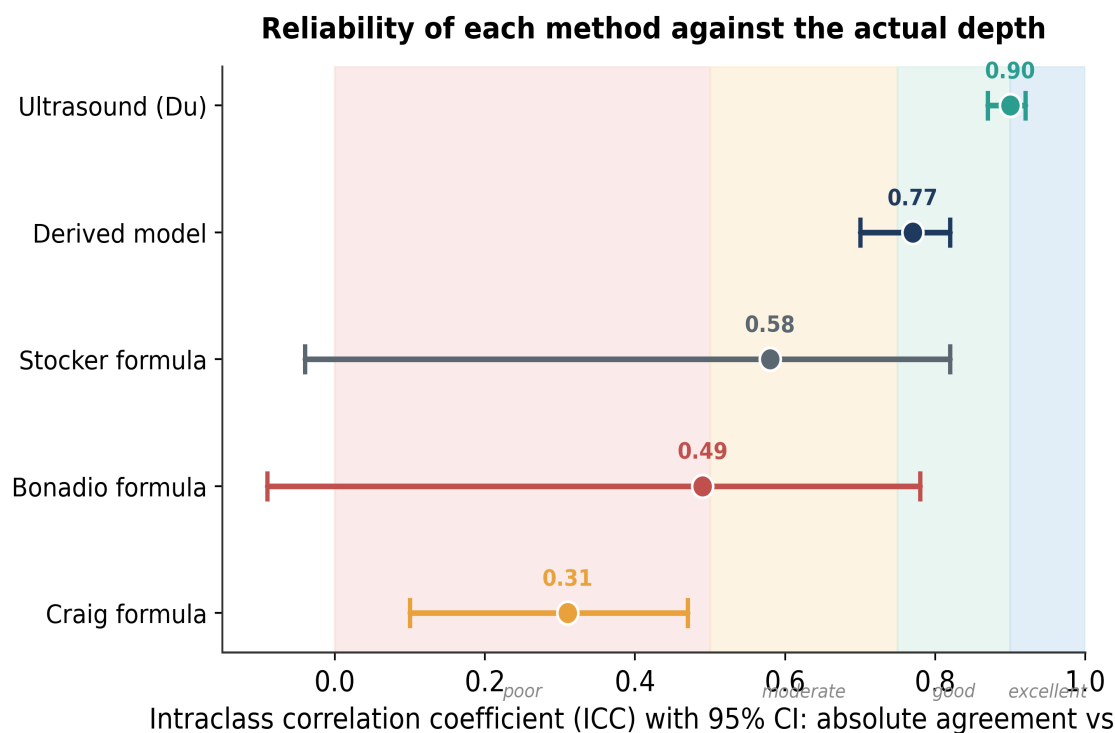


Figure 2: Reliability of each method against the actual depth.

Intraclass correlation coefficient (ICC, two-way absolute-agreement, single measures) with 95% confidence interval for each method (Table 5). Shaded bands denote conventional reliability strata (poor < 0.5; moderate 0.5–0.75; good 0.75–0.90; excellent > 0.90).

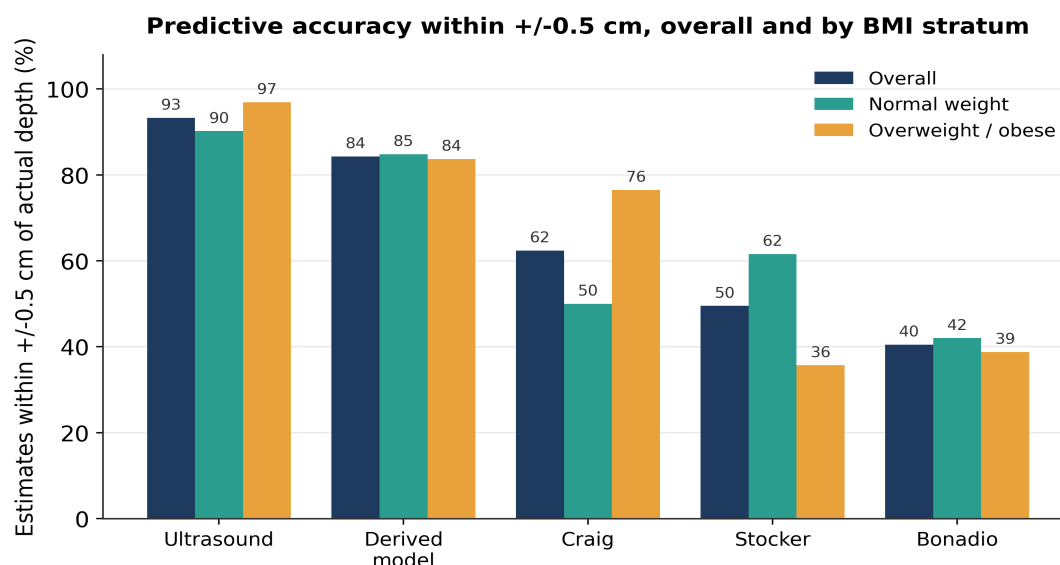


Figure 3: Predictive accuracy within ± 0.5 cm, overall and by BMI stratum.

Proportion of estimates falling within ± 0.5 cm of the actual depth, shown overall and within the normal-weight and overweight/obese strata (Table 6). Ultrasound and the derived model retain accuracy across strata, whereas the formulae deteriorate at higher body mass.

Table 1: Participant characteristics (N = 210)

Characteristic	Value
Age (years)	42.39 $\pm$ 11.80 (range 18–65)
Sex — Male / Female	125 (59.5%) / 85 (40.5%)
ASA I / II	180 (85.7%) / 30 (14.3%)
Height (cm)	159.85 $\pm$ 9.21
Weight (kg)	63.79 $\pm$ 12.69 (range 39.0–98.5)
BMI (kg/m ²)	24.90 $\pm$ 4.13 (range 17.45–35.51)
BSA (m ² , Mosteller)	1.677 $\pm$ 0.198
BMI — Normal	112 (53.3%)
BMI — Overweight	71 (33.8%)
BMI — Obese	27 (12.9%)

Values are mean $\pm$ SD or n (%). BSA by the Mosteller method. ASA = American Society of Anesthesiologists physical status; BMI = body-mass index; BSA = body-surface area.

Table 2: Shapiro–Wilk tests of normality

Variable	W	p-value	Skew	Distribution
D _a (actual depth)	0.987	0.051	+0.37	Normal
D _u (ultrasound)	0.996	0.899	−0.04	Normal
Stocker estimate	0.984	0.017	+0.32	Non-normal
Craig estimate	0.962	<0.001	−0.01	Non-normal
Bonadio estimate	0.991	0.218	+0.11	Normal
Weight	0.984	0.017	+0.32	Non-normal
Height	0.962	<0.001	−0.01	Non-normal
BMI	0.985	0.022	+0.24	Non-normal
Difference D _a − D _u	0.993	0.377	+0.20	Normal
Difference D _a − Stocker	0.995	0.689	−0.05	Normal
Difference D _a − Craig	0.995	0.700	+0.16	Normal
Difference D _a − Bonadio	0.995	0.690	+0.02	Normal

Shapiro–Wilk test; $p > 0.05$ indicates normality. All four difference variables are normal, supporting parametric Bland–Altman limits of agreement. D_a = actual depth; D_u = ultrasound depth; BMI = body-mass index.

Table 3: Depth to the subarachnoid space by each method (cm)

Method	Mean $\pm$ SD (cm)	Range (cm)
Actual depth (D_a) — reference	4.495 $\pm$ 0.557	3.12–6.25
Ultrasound (D_u)	4.437 $\pm$ 0.630	2.675–6.215
Derived model	4.495 $\pm$ 0.439	3.63–5.647
Stocker formula	4.989 $\pm$ 0.634	3.75–6.725
Craig formula	4.796 $\pm$ 0.276	4.35–5.34
Bonadio formula	5.062 $\pm$ 0.506	3.999–6.356

D_a measured at free cerebrospinal-fluid flow with Vernier callipers; values in cm.

Table 4: Multivariable linear regression model for the actual depth D_a (n = 210)

Predictor	Coefficient (β)	95% CI	p-value
Intercept	+2.3973	+2.146 to +2.649	<0.001
Sex (male = 1)	+0.1371	+0.027 to +0.247	0.015
Weight (kg)	+0.0316	+0.027 to +0.036	<0.001

$R^2 = 0.6201$; adjusted $R^2 = 0.6164$; RMSE = 0.3425 cm. Age, height, BMI and BSA were removed (non-significant or collinear). Derived equation: D_a (cm) = $2.397 + 0.137 \times (\text{sex: male} = 1, \text{female} = 0) + 0.0316 \times \text{weight (kg)}$. CI = confidence interval; RMSE = root-mean-square error.

Table 5: Agreement of each method with the actual depth D_a (Bland–Altman and ICC)

Method	Mean bias (cm)	95% LoA (cm)	$\frac{1}{2}$ LoA width	ICC (95% CI)
Ultrasound (D_u)	+0.058	−0.45 to +0.57	0.51	0.90 (0.87–0.92)
Derived model	−0.000	−0.67 to +0.67	0.67	0.77 (0.70–0.82)
Stocker formula	−0.495	−1.28 to +0.29	0.79	0.58 (−0.04–0.82)
Craig formula	−0.301	−1.26 to +0.66	0.96	0.31 (0.10–0.47)
Bonadio formula	−0.568	−1.28 to +0.14	0.71	0.49 (−0.09–0.78)

Bias = mean(D_a – method). ICC = two-way, absolute-agreement, single measures. The model's 10-fold cross-validated agreement was essentially identical (bias +0.00, LoA $\pm$ 0.68 cm, ICC 0.76), confirming minimal optimism. LoA = limits of agreement; ICC = intraclass correlation coefficient.

Table 6: Proportion of estimates within ± 0.5 cm and ± 1.0 cm of D_a

Method	≤ 0.5 cm (overall)	≤ 1.0 cm (overall)	≤ 0.5 cm Normal	≤ 0.5 cm OW/Obese	MAE (cm)
Ultrasound (D_u)	93.3%	100.0%	90.2%	96.9%	0.211
Derived model	84.3%	100.0%	84.8%	83.7%	0.273
Craig formula	62.4%	91.4%	50.0%	76.5%	0.465
Stocker formula	49.5%	89.5%	61.6%	35.7%	0.537
Bonadio formula	40.5%	88.1%	42.0%	38.8%	0.589

MAE = mean absolute error. Model values use 10-fold cross-validated predictions. OW/Obese = overweight + obese combined.

Table 7: Procedural outcomes and complications (N = 210)

Outcome	Value
First-attempt success	190 (90.5%)
– Normal / Overweight / Obese	94.6% / 91.5% / 70.4% (χ^2 P < 0.001)
Number of attempts	1.114 $\pm$ 0.374 (range 1–3)
Number of redirections	0.324 $\pm$ 0.587
Time to free CSF (s)	41.676 $\pm$ 20.453 (median 36)
Traumatic tap	7 (3.3%)
Post-dural-puncture headache (≤ 72 h)	5 (2.4%)
Hypotension	38 (18.1%)
Failed spinal	1 (0.5%)

Values are mean $\pm$ SD or n (%). CSF = cerebrospinal fluid.

Discussion

In a Central-Indian cohort spanning the full body-mass-index range, a two-variable model using only sex and weight predicted the skin-to-subarachnoid

space depth with no systematic bias, limits of agreement of about ± 0.67 cm, and good reliability that survived internal validation almost unchanged. Pre-procedural ultrasound performed best of all, with near-zero bias, the narrowest limits of

agreement and excellent reliability, while the established formulae agreed poorly with the actual depth and consistently overestimated it. To our knowledge this is the first locally derived and internally validated depth-prediction model reported from this region, and one of the few to evaluate these methods explicitly across body-mass-index strata and against real procedural outcomes.

That the model retained only sex and weight is physiologically coherent: subarachnoid depth is governed chiefly by the overlying soft-tissue mass, which scales with weight and is greater in men, whereas height contributes little once weight is known. The mean actual depth of about 4.5 cm matches the 4.4 to 5.0 cm reported in other Indian and Egyptian cohorts, supporting the external plausibility of our reference measurements.[8] [9] [10] Our finding that ultrasound agrees most closely with the actual depth is consistent with the wider literature, including recent studies reporting correlations of 0.92 to 0.94 and the closest limits of agreement for ultrasonography, and reinforces the view that ultrasound is the most accurate single tool for anticipating needle depth.[11] [12]

The more important message concerns the formulae. Stocker's, Craig's and Bonadio's rules were derived in children,[4] [5] [6] and our data show that this paediatric ancestry matters: each overestimated adult depth and none achieved better than moderate reliability, with the proportion of estimates within 0.5 cm falling below half for two of the three. Crucially, the formulae deteriorated in exactly the patients who need them most. In overweight and obese individuals, where landmark palpation fails and accurate depth prediction would be most valuable, Stocker's accuracy nearly halved, whereas ultrasound and the derived model held their performance.

This mirrors imaging studies showing that increasing body mass progressively distorts the relationship between simple anthropometry and the true depth,[19] [25] and explains why a model calibrated on a local, BMI-diverse population outperforms imported single-variable rules.[22] [23] These statistical differences carried real procedural weight. First-attempt success fell sharply with rising body mass, reaching only 70% in obese patients, echoing established difficulty-scoring work in spinal anaesthesia and underlining that the obese spine remains a genuine challenge even to experienced hands.[20] By providing an unbiased, BMI-robust depth estimate before insertion, the derived model offers a free, bedside adjunct wherever ultrasound is unavailable, while our data simultaneously quantify the additional accuracy that ultrasound provides when it is. We would therefore position the model not as a competitor to ultrasound but as a pragmatic floor:

better than legacy formulae everywhere, and especially in the difficult patient, with ultrasound reserved as the more accurate option where equipment and training allow. Two methodological points deserve emphasis. First, by analysing agreement rather than correlation we avoid a common pitfall: a method can correlate strongly with the truth yet remain systematically biased, as the formulae here illustrate.[16] Bland–Altman limits of agreement and the absolute-agreement intraclass correlation capture the clinically relevant question, namely how far an individual estimate is likely to lie from the real depth.[2] Second, internal validation by cross-validation and bootstrapping showed negligible optimism, suggesting the model should travel reasonably within similar populations, though this remains to be confirmed.[13]

Limitations

This study has limitations. It was single-centre, and although the model was internally validated it has not yet been externally validated in an independent population; geographic and ethnic differences in body habitus mean external recalibration may be needed before wider use. The work was observational rather than a randomised comparison of ultrasound-guided versus landmark-guided spinal anaesthesia, so the procedural benefits of each method are associative rather than causal. Depth was measured at a single interspace in the sitting position with a fixed technique, and pregnant patients, who have a distinct soft-tissue profile, were deliberately excluded; our findings should therefore not be extrapolated to obstetric practice.[21] Finally, ultrasound performance is operator-dependent, and our reassuring results were obtained by a trained sonographer.

Conclusion

In Central-Indian adults across the full body-mass-index range, a simple equation based only on sex and weight predicted the skin-to-subarachnoid space depth without systematic bias and with good, internally validated reliability, clearly outperforming the established Stocker, Craig and Bonadio formulae, which overestimated depth and faltered in overweight and obese patients. Pre-procedural ultrasonography was the most accurate method overall. Together these findings support a tiered approach: pre-procedural ultrasound where available, and this locally derived, equipment-free model as a dependable bedside alternative where it is not, with particular value in the difficult, higher-body-mass patient. External, multicentre validation and a randomised comparison with landmark technique are the natural next steps.

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