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Comparing precision of distortion-compensated and stereophotogrammetric Roentgen analysis when monitoring fusion in the cervical spine

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Abstract Two methods to measure sagittal plane segmental motion in the cervical spine are compared. Translational and rotational motion was measured in nine cervical motion segments of nine patients by distortion-compensated (DCRA) as well as by stereophotogrammetric Roentgen analysis (RSA). To compare measurement precision of the new DCRA protocol with the established RSA technique under realistic clinical conditions and to discuss advantages and disadvantages of both methods in clinical studies. RSA constitutes the most precise method available to assess segmental motion or to monitor fusion in the cervical spine. Due to the invasive nature of the procedure there is an interest in alternative, non-invasive protocols, based on conventional, lateral radiographic views. In nine patients, segmental motion of nine cervical segments with spinal surgery and fusion had previously been assessed from stereo views by RSA. From the archive

radiographs, sagittal plane segmental motion was re-assessed by DCRA. Results for sagittal plane translational and rotational motion obtained by both methods are compared. With respect to RSA, sagittal plane rotation was determined by DCRA with an error of 2.4° and a mean difference not significantly different from zero. Sagittal plane translation was determined by DCRA with an error of less than 0.78 mm and a mean difference not significantly different from zero. As two methods are compared, these errors represent the combined (propagated) errors of RSA and DCRA. Averaged over the cohort investigated, measurement of sagittal plane segmental motion exhibited no significant difference between DCRA and RSA.

Keywords Cervical spine · Fusion · Sagittal plane segmental mobility · Sagittal plane rotation · Sagittal plane translation

Introduction

Different methods have been used to measure segmental mobility, alignment and disc height of the cervical spine from lateral radiographic views [5–7, 12, 13, 16]. Examinations are performed in order to document abnormalities caused by trauma or degenerative

disorders and to investigate the effect of spinal surgery. However, previous methods are related to major measurement errors [5–7, 12, 13, 16]. Therefore, a practical and valid method for monitoring segmental mobility during follow-up after spine surgery, besides Roentgen stereophotogrammetric analysis (RSA), has been missing [18].

Recently, a new protocol, in the following referred to as “distortion-compensated Roentgen analysis” (DCRA), for measuring sagittal plane segmental motion from conventional, lateral radiographic views of the cervical spine has been proposed and validated [7]. Comparison of measurement errors points to RSA as the superior method. Due to the specific apparatus required and the invasive nature of the RSA procedure, however, application of RSA has hitherto been limited to scientific studies of small patient series investigated in the post-surgical situation [1–4, 8–10, 15, 17, 20, 21]. Clinicians wish to obtain data where direct measurements without adverse effects are possible. For this reason, the alternative DCRA protocol is of interest, provided its measurement results for clinical studies of patient cohorts agree sufficiently well with the gold standard RSA.

The availability of archive lateral radiographic views, whose state of fusion in the cervical spine had previously been documented by RSA, permitted (1) a direct comparison of sagittal plane rotational and translational motion determined by DCRA and RSA under realistic clinical conditions and (2) a discussion of advantages and disadvantages of both DCRA and RSA for monitoring mobility and fusion in the cervical spine.

Materials and methods

Radiographs

The radiographs used in this comparative study stemmed from nine patients. To monitor the fusion with RSA, tantalum markers had been implanted interoperatively using standardised technique. The levels compared were C4/5(1 patient), C5/6(7 patients) and C6/7(1 patient). The assessment of segmental motion by

RSA was performed 3–6-months post-operatively. The conventional lateral radiographs taken in flexion and extension at that time served as input for DCRA measurements reported here.

Comparison of segmental motion data between DCRA and RSA

RSA reconstructs 3d-positions of implanted metal markers (tantalum balls) from pairs of stereo-radiographs [18]. If such markers are implanted into the vertebrae of spinal motion segments, relative position and orientation of its vertebrae can be determined. DCRA is a novel protocol to determine relative 2d-position and orientation of vertebrae in the sagittal plane from one single, conventional lateral radiograph. For details on the DCRA protocol, the reader is referred to Frobin et al. [7]. In both methods, rotational and translational segmental motion is given by the difference in relative orientation and position of the vertebrae of a motion segment in flexion and in extension.

A comparison between DCRA and RSA data is confined to the sagittal plane. Data on rotational motion around the transverse axis (Fig. 1a: x -axis) determined by RSA can be compared directly with data on sagittal plane rotation determined by DCRA. To compare translational motion data between both methods, the difference of the translation vectors $\mathbf{t}_{DCRA} - \mathbf{t}_{RSA}$ is inspected. The translation vectors $\mathbf{t}$ designate the measured translations along the axes of the respective coordinate systems. In the DCRA coordinate system (Figs. 1b and 2) the components are t_p and t_q ; RSA determines the components t_z and t_y . The comparison of translational motion data between DCRA and RSA is, however, limited due to the fact that RSA data are given in a space-fixed coordinate system (Fig. 1a: z, y) while

Fig. 1 **a** Roentgen stereophotogrammetric analysis RSA. Setup and definition of laboratory (calibration cage) xyz -coordinate system. **b** Relative orientation of sagittal plane RSA zy -coordinate system and the anatomical DCRA pq -coordinate system. In DCRA, the direction of the bisectrix between the midplanes of the two vertebrae defines the direction of the p -axis, the direction perpendicular to the bisectrix defines the direction of the q -axis

Fig. 2 Definition of sagittal plane rotation and the translation vector $\mathbf{t}$, illustrated by the DCRA protocol. The cranial vertebra of a segment rotates and translates with respect to the caudal vertebra. Rotational motion is given by the difference of the angles $\phi_e - \phi_f$. Translational motion of the vertebral centre is given by the translation vector $\mathbf{t}$ being the difference between the position vectors $\mathbf{d}_e$ and $\mathbf{d}_f$. In the pq -system, the components of $\mathbf{t}$ are t_p and t_q .

DCRA data are given in a segmental coordinate system (Fig. 1b: p, q). The relative rotation around the transverse axis between the pq - and zy -systems can only be estimated from the exposure geometry to be in the range between 0 and 30°.

Strictly speaking (and in the absence of measurement errors), the translation vector measured by DCRA is not identical with the translation vector measured by RSA. In RSA, translation is measured between the centres of gravity of the implanted tantalum markers. In DCRA, translation is measured between the geometric centres of the vertebrae. The centres of gravity of the markers and the geometric centres of the vertebrae do not coincide. Neglect of this difference is, however, permissible if the actual rotational motion is very small or zero. In the material studied, this was effectively the case.

Employing the DCRA protocol, rotational and translational motion was measured independently by two observers. Thus, in addition to the comparison between DCRA and RSA, the results of this study also quantify the DCRA interobserver error.

Statistical tools

Sagittal plane angle

For observer 1 as well as for observer 2 the difference DCRA minus RSA is evaluated by the t -test. The

difference between both observers (DCRA interobserver error) is evaluated by the t -test as well. The level of significance is set to $\alpha = 0.05$. In both cases the error is given by the SDs of the differences.

Sagittal plane translation vector

Translation vectors are 2-dimensional quantities. To evaluate differences between DCRA and RSA or between the DCRA results of the two observers Hotelling's T^2 test [14] is employed. As the rotation between the RSA zy - and DCRA pq -coordinate systems is estimated to lie between 0 and 30°, the difference between DCRA and RSA is evaluated for both angles. The level of significance is set to $\alpha = 0.05$.

Maximum and minimum values of the error of DCRA with respect to RSA as well as the DCRA interobserver error are given by the lengths of principal axes of the error ellipsis defined by the 2-dimensional matrix of covariance. Adopting a conservative point of view, the maximum error (worst case) is quoted in the "Abstract" and "Discussion" section of this study.

Additional remark

Comparing magnitudes of translation vectors would render estimation of the relative rotation of the coordinate systems unnecessary, as vector magnitudes are independent of this orientation. If, however, true translations approach zero (as in the present material), measurement errors effect that the measured magnitude of translation vectors does not approach zero. Instead, measurement errors effect a positive bias. A minor uncertainty could result from the application of statistical tests to such biased data.

Results

Table 1 lists rotation determined by RSA together with the results measured by observers 1 and 2 employing DCRA. Table 2 lists the cohort means and SD of the difference of rotation determined by DCRA and RSA as well as the difference between the results of the two DCRA observers. There were no significant differences between the DCRA and the RSA measurements. The error (1 SD) amounted to 2.4°. There were no significant differences between the two observers employing DCRA. The DCRA interobserver error amounted to 1.8°.

Table 3 lists the components t_z , t_y of the translation vectors determined by RSA together with the components t_p , t_q of the translation vectors determined by observers 1 and 2 employing DCRA.

Table 4a, b list the cohort means of the difference of the vector components determined by DCRA and RSA.

Table 1 Rotation measured by DCRA and by RSA

Patient no.	Segment	DCRA, observer 1	DCRA, observer 2	RSA
1	C5/C6	3.48°	1.86°	-0.57°
2	C5/C6	0.95°	-3.16°	2.18°
3	C5/C6	-2.39°	-0.32°	-0.58°
4	C5/C6	-4.06°	-4.23°	-1.38°
5	C5/C6	-2.10°	-1.87°	0.53°
6	C5/C6	-0.47°	-0.21°	-0.88°
7	C6/C7	-0.43°	-0.02°	0.70°
8	C5/C6	-2.37°	-1.59°	-0.29°
9	C4/C5	1.12°	-0.16°	-1.39°

Table 2 Sagittal plane rotation

	N	Rotation	p-value
DCRA observer 1 minus RSA	9	-0.510° (2.372°)	0.537
DCRA observer 2 minus RSA	9	-0.891° (2.382°)	0.294
DCRA observer 2 minus DCRA observer 1	9	-0.381° (1.770°)	0.536

Comparison between DCRA and RSA as well as between the two DCRA measurements (interobserver study). Cohort means, SD in parentheses

This difference is calculated for (a) the case of 0° rotation and (b) the case of -30° rotation between the *pq*- and *zy*-systems. The T^2 -values and finally the *p*-values are calculated employing Hotelling's T^2 test. There were no significant differences between the DCRA and the RSA measurements. This holds for 0° as well as for a 30° rotation between the coordinate systems. Relative to RSA, DCRA measured translation with a maximum error (worst case) of 0.78 mm. Table 4c lists the difference in translation between the results of the two DCRA observers. The DCRA maximum interobserver error amounted to 0.65 mm.

Discussion

Treatment of cervical disc disease is currently under debate. The gold standard for treating degenerative disc disease is spinal arthrodesis. Due to the risk of adjacent disc disease, new treatment strategies and techniques are rapidly developing [11, 19]. The concept of motion preservation in the spine might change the way that spine surgeons will approach these disorders in the near future. Therefore, valid non-invasive methods to document segmental motion, spinal alignment and disc height are needed to examine the effect of treatment and to test new surgical techniques.

The established RSA technique provides very precise motion data. Due to the invasive nature of the RSA technique, however, there is still interest in a protocol for measuring sagittal plane segmental motion and fusion from conventional, lateral views of the cervical spine when performing clinical studies of larger patient cohorts. DCRA provides such a protocol. Application of DCRA requires, however, the corner regions of the vertebrae being visible on the radiographs, i.e., not obscured by metal implants.

Applied to an—admittedly small—cohort with interbody fusion, DCRA measurement of sagittal plane rotational and translational motion exhibited on average no significant difference to RSA data. With respect to the gold standard RSA, rotation and translation were determined with errors of 2.4° and 0.78 mm, respectively. The corresponding DCRA interobserver errors are 1.8° and 0.65 mm. Ryd et al. [17] determined the precision (SD) of RSA when measuring rotational motion in the cervical spine in a cohort of fusion patients to range between 0.18 and 2.26°. These authors showed that RSA accuracy depends critically on the geometric configuration of the implanted markers. In unfavourable configurations, measurement accuracy in the cervical spine may fall substantially short of the values previously obtained from the lumbar spine or from rigid-body RSA laboratory studies [9, 17].

Table 3 Components of translation vectors (mm) with respect to the *zy*- and *pq*-coordinate systems measured by DCRA (observers 1 and 2) and by RSA

Patient no.	Segment	DCRA t_p , obs. 1	DCRA t_q , obs. 1	DCRA t_p , obs. 2	DCRA t_q , obs. 2	RSA t_z	RSA t_y
1	C5/C6	-1.218	-1.011	-0.581	-0.661	-0.143	0.018
2	C5/C6	0.108	-0.368	0.688	0.074	0.610	-0.113
3	C5/C6	-0.273	0.886	-0.090	-0.419	-0.106	0.191
4	C5/C6	0.978	0.180	0.842	0.234	-0.363	0.176
5	C5/C6	-0.051	0.844	0.274	-0.438	0.045	0.008
6	C5/C6	0.193	0.254	-0.074	-0.343	-0.129	0.032
7	C6/C7	0.227	0.439	0.108	-0.207	0.406	-0.382
8	C5/C6	0.218	0.166	-0.192	0.109	-0.234	0.041
9	C4/C5	-0.058	0.067	0.005	-0.518	-0.392	0.140

Table 4 Comparison of translation vectors between DCRA and RSA

(a) 0° rotation of the pq- with respect to the zy-system

	<i>n</i>	$t_{p-} t_z$	$t_{q-} t_y$	Max error	Min error	T^2	<i>p</i> -value
DCRA observer 1 minus RSA	9	0.048	0.150	0.732	0.529	0.565	0.787
DCRA observer 2 minus RSA	9	0.143	-0.253	0.482	0.355	5.946	0.143

(b) -30° rotation of the pq- with respect to the zy-system

	<i>n</i>	$t'_{p-} t_z$	$t'_{q-} t_y$	Max error	Min error	T^2	<i>p</i> -value
DCRA observer 1 minus RSA	9	0.127	0.121	0.779	0.468	0.768	0.725
DCRA observer 2 minus RSA	9	0.008	-0.275	0.528	0.266	9.419	0.066

(c) Comparison of translation vectors between the DCRA measurements of observers 1 and 2

	<i>n</i>	$t_{p2-} t_{p1}$	$t_{q2-} t_{q1}$	Max error	Min error	T^2	<i>p</i> -value
DCRA observer 2 minus DCRA observer 1	9	0.095	-0.403	0.651	0.356	4.915	0.187

Cohort means (mm), maximum and minimum error (lengths of the principal axes of error ellipses), Hotelling's T^2 , *p*-value

Therefore, if the precision of DCRA is considered adequate and when a non-invasive technique is indicated, DCRA may be utilised in cohort studies to provide reliable data required for monitoring spinal mobility. Assessing fusion, i.e., absence of motion, in the individual case is more difficult. Due to measurement errors, no method can prove motion to be zero. Only compatibility with zero may be assumed if measured motion amounts to less than two times the measurement error. In this respect DCRA is inferior to RSA.

A number of aspects should be considered when deciding whether to use RSA or DCRA in clinical studies:

- RSA measures rotation and translation in three dimensions, while DCRA just measures rotation around the transverse axis and translation in the sagittal plane.
- DCRA measures translational motion with respect to an anatomical coordinate system, while RSA measures translation along the axis of a laboratory coordinate system.
- Measurement precision of DCRA is superior to conventional protocols, but inferior to that of RSA. In most clinical situations, however, the precision of DCRA in monitoring mobility, spinal alignment and disc height should be adequate.
- RSA is an invasive and demanding technique requiring implantation of metal markers in bony structures. Cervical segment motion analysis can therefore only be made from the time of the marker implantation and post-operatively. DCRA is non-invasive and based on conventional lateral radiographs. Retrospective studies are therefore feasible.

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