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REVIEW ARTICLE

Lateralization in reverse shoulder arthroplasty: a descriptive analysis of different implants in current practice

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Abstract

Introduction Since its first description, the concept of reverse shoulder arthroplasty (RSA) has evolved. The term lateralization remains unclear and is used to describe implants that lateralize on the glenoid side, the humeral side, or both. The objective of this study was to provide a clear definition of lateralization and to measure the lateralization achieved by the most commonly used implants.

Materials and methods Twenty-eight different configurations with 22 different implants were analyzed. Glenoid, humeral, and global lateralization was measured on digitized templates. Implant lateralization was normalized to the lateral offset of the Delta III. Each implant was defined as a combination of one of two glenoid categories (medialized glenoid (MG), lateralized glenoid (LG), and one of four humeral categories (medialized humerus (MH), minimally lateralized humerus (LH), lateralized humerus (LH+). In addition, implants were separated in categories of 5-mm increments for global offset (medialized RSA (M-RSA), minimally lateralized RSA (ML-RSA), lateralized RSA (L-RSA), highly lateralized RSA (HL-RSA), and very highly lateralized RSA (VHL-RSA).

Results The global lateral offset of the Delta III was 13.1 mm; global lateral offset of all designs in this study varied between 13.1 and 35.8 mm. Regarding their global lateral offset, five implants are M-RSA (lateral offset < 18.1 mm), five ML-RSA (18.1–23.1 mm), seven L-RSA (23.1–28.1 mm), six HL-RSA (28.1–33.1 mm), and one VHL-RSA (33.1–38.1 mm).

Conclusion There is high variability in the amount of lateralization provided by the majority of RSAs currently available. This descriptive analysis can help surgeons understand the features of implants in the market based on their lateralization in order to adapt the surgical technique depending on the expected lateral offset of the design being implanted.

Keywords Shoulder arthroplasty · Lateralization · Templates · Humeral lateralization · Glenoid lateralization

Introduction

Since its first description by Grammont in 1985 [1, 2], reverse arthroplasty (RSA) has evolved, with now over 30 different designs of RSA commercially available. Grammont's design relied on four principles: (1) medialization of the joint centre of rotation by medializing the glenoid and the humerus with a straight stem and a 155° neck-shaft angle (NSA) to increase

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Table 1 Lateral offset (LO) of the different implants included in the study

Manufacturer	Implant	Humeral LO	Stem LO	Insert LO	Glenoid LO	Sphere LO	Baseplate LO	Global LO	Maximal LO	Range of LO
Arthrex	Univers 135°	8	13	− 5	12.7	12.7	0	20.7	30.8	10.1
Arthrex	Univers 155°	11.5	14.5	− 3	7.6	7.6	0	19.1	28.9	9.8
Aston	Duocentric	12.8	5.2	7.7	15.3	10.3	5	28.2	35.9	7.7
Biomet	Comprehensive	15	7.8	7.2	14.8	9.8	5	29.8	50.7	20.9
Biomet	TESS	10	11	− 1	16	9	7	26	29.3	3.3
DJO	Altivate	6.7	8.5	− 1.8	16.7	12.7	4	23.5	43.5	20.2[b]
DePuy	Delta III	3.5	7	− 3.5	9.6	7.6	2	13.1	19.7	6.6
DePuy	DeltaXtend	9	8	1	9.5	8[a]	1.5	18.5	25.9	7.4
Exactech	Equinoxe	13.5	8.7	4.8	12.9	10.9[a]	2	26.4	37.1	10.7
FH Ortho	Arrow	18.2	5.5	12.7	16.3	7.6	8.7	34.5	39.3	4.8
FH Ortho	Arrow II	15.6	5.5	10.1	16.1	7.6	8.5	31.7	36.5	4.8
Fx Solutions	Humelock Reverse	10.5	8.5	2	13.8	10.3	3.5	24.3	33.5	9.2
Fx Solution	Easytech	13.4	8.5	4.9	13.8	10.3	3.5	27.2	33.7	6.5
Lima	SMR	3	6.5	− 3.5	14	9	5	17	26.5	9.5
Lima	SMR Stemless	–	–	− 2.2	17.9	12.9	5	–	–	–
Mathys	Affinis Reverse	4.1	9.5	− 5.4	9.1	7.6	1.5	13.2	20.4	7.2
Medacta	Shoulder System 145°	9.2	7.5	1.7	14.3	10.3	4	23.5	34.5	11
Medacta	Shoulder System 155°	10.1	7.5	2.6	11.6	7.6	4	21.7	32.7	11
Strkyer	ReUnion RSA	14.6	7.5	7.1	14.7	12.7	2	29.3	44.7	16.8[b]
Tornier	Aequalis	8	7	1	7.6	7.6	0	15.6	21.9	6.3
Tornier	Aequalis II	8	7	1	7.6	7.6	0	15.6	22.9	7.3
Tornier	Aequalis II + BioRSA	8	7	1	14.6	7.6	7[c]	22.6	29.9	7.3
Tornier	Ascend Flex 127.5°	16.4	9.6	6.8	10.3	10.3	0	26.7	43.7	16.7
Tornier	Ascend Flex 132.5°	14.2	9.6	4.6	10.3	10.3	0	24.5	41.5	17
Tornier	Ascend Flex 137.5°	13.5	9.7	3.8	10.3	10.3	0	23.8	40.8	16.7
Tornier	Ascend Flex 132.5° + BioRSA	14.2	9.6	4.6	17.3	10.3	7[c]	31.5	48.5	17
Zimmer	Inverse Reverse	17.4	11	6.4	13.6	7.6	6	31	39	8
Zimmer	Trabecular Metal	7.5	7	0.5	11.5	9	2.5	19	35.5	16.5

Humeral stem lateral offset for stemless implants has been calculated differently for the 3 stemless implants:

- Biomet TESS is available with a stem which has been used to calculate the stem lateral offset of the stemless version

- FX Easytech has been overlapped to the position of the stem of the Fx Humelock to calculate the stem lateral offset

- SMR stemless: humeral stem lateral offset could not be calculated as the design of the stemmed SMR implant is too different to overlap the two templates

[a] Smallest glenosphere available: 38 mm

[b] Smallest glenosphere available: 32 mm

[c] Lateralization is not in the baseplate but on the scapular neck

the lever arm of the deltoid in active elevation and abduction; (2) positioning of the joint centre of rotation at the bone-implant interface to reduce shear forces on the glenoid implant; (3) distalization of the humerus to retension deltoid fibers; and (4) a semi-constrained configuration to provide static stability and a stable fulcrum.

Grammont-style RSA has been reported to provide satisfactory results [3–5], but this design has been found to have several drawbacks. First, excessive medialization may lead to a slackening of any intact cuff, which could contribute to instability and weakness in external rotation. Second, the contour of the shoulder is somewhat altered [6, 7]. Finally, the 155° NSA and glenoid medialization led to high rates of scapular notching [5, 8] with the potential for polyethylene wear and glenoid loosening [9].

Subsequent RSA designs tried to address some of these by providing a more lateralized reconstruction. Lateralization may be increased on the glenoid side at the scapular neck [10], baseplate [11], or glenosphere [12]. Modifications of the stem design have also been proposed: (i) a change in the

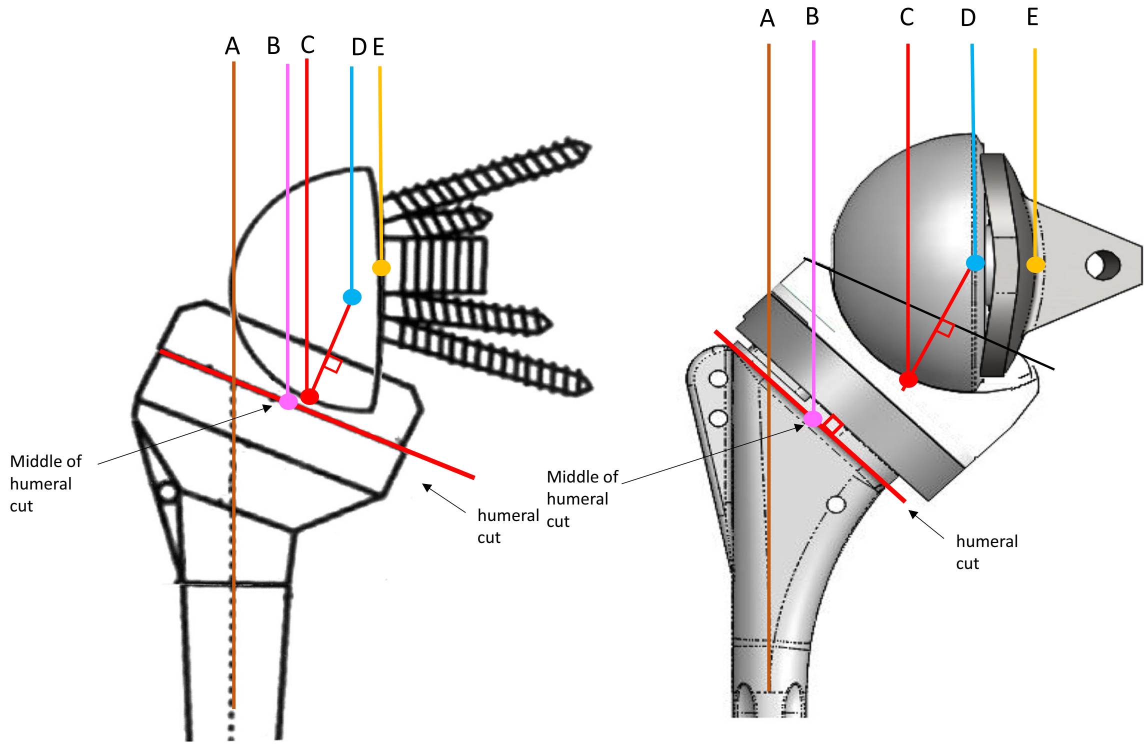

Fig. 1 Templates of a medialized implant (Delta III (DePuy, Warsaw, IN)) and of a very highly lateralized implant (arrow (FH Ortho, Heimsbrunn, France). Line A is the vertical line passing through the middle of the diaphysis of the humeral stem. Line B is the horizontal line passing through the middle of the surface of the humeral implant at the level of the humeral cut. Line C is the vertical line passing through the "pivot point" defined as the deepest point of the articular surface of the humeral insert measured perpendicular to the surface of the humeral insert. Line D is the vertical line passing through the centre of rotation of the joint. Line E is the vertical line passing through the bone-glenoid baseplate interface. Humeral lateral offset (distance AC) was defined as the sum of the humeral stem offset (distance AB) and of the humeral insert offset (distance BC). Glenoid lateral offset (distance CE) was defined as the sum of the "perceived radius of the glenosphere" (distance CD) and of the centre of rotation offset (distance DE). Global lateral offset

NSA to 145° or 135° to decrease scapular notching, (ii) curved and short stems to preserve bone stock, and (iii) onlay systems to facilitate conversion from an anatomic arthroplasty. These humeral changes translate into humeral lateralization, which introduces confounding factors when reporting results of lateralized RSAs.

The objective of this study was to provide a clear definition of lateralization (glenoid, humeral, and global) and to measure and compare lateralization values provided by the most commonly used RSA implants currently available.

Materials and methods

RSA Designs included in the study

The templates of 22 different implants were obtained from manufacturers (Table 1). All templates were analyzed using SolidWorks 2017 SPO (Dassault Systèmes, Vélizy-Villacoublay, France). A total of 28 different configurations were included, as some implants allow different neck-shaft angles and/or the addition of a glenoid bone graft.

Definitions

Vertical lines were traced and used as a reference to measure lateral offset (LO) (Fig. 1): Line A is the vertical line passing through the middle of the humeral stem diaphysis; line B is the vertical line passing through the midpoint of the bearing of the humeral implant at the level of the humeral cut; line C is the vertical line passing through the "pivot point," defined as the deepest point of the articular surface of the humeral insert measured perpendicular to the surface of the humeral insert; line D is the vertical line passing through the centre of rotation of the joint; and line E is the vertical line passing through the medial most bone-glenoid baseplate interface. The horizontal distance between each of these lines was measured.

Humeral LO (AC) was defined as the sum of the humeral stem and humeral insert offsets (AB + BC). Glenoid LO (CE) was defined as the sum of the "perceived radius of the glenosphere" (CD) and of the centre of rotation offset (DE). Global LO (AE) was defined as the sum of the glenoid and humeral lateral offsets. Finally, Greater Tuberosity LO was defined as the distance between the medial most bone-glenoid baseplate interface and the greater tuberosity (Fig. 2).

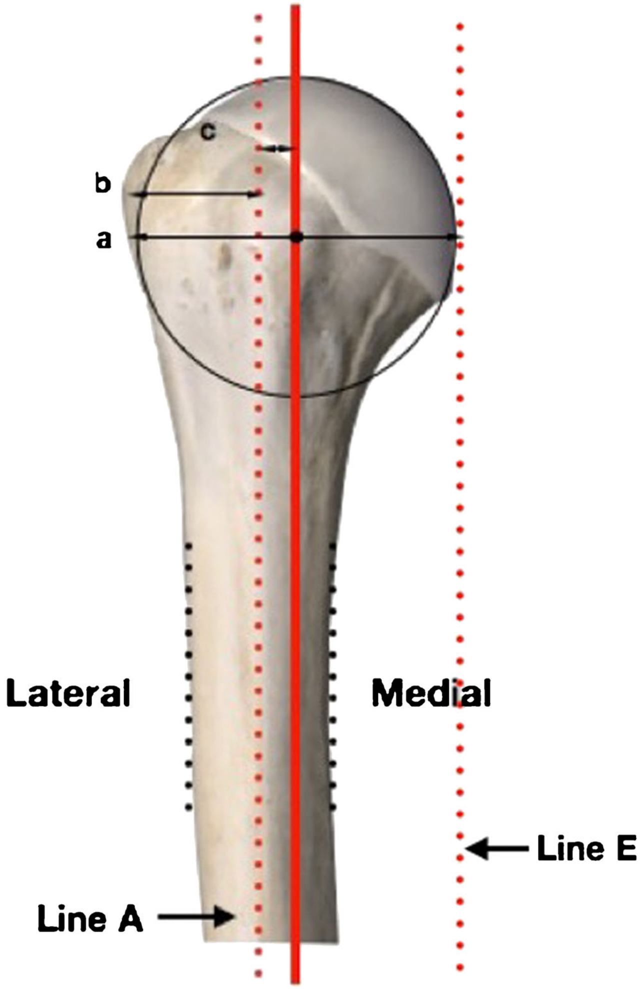

Fig. 2 The diameter of the humeral head (a) represents the distance between the glenoid (line E) and the greater tuberosity (mean overall greater tuberosity lateral offset). The humeral head has a medial offset (c) relative to the diaphyseal axis (line A) of a mean 6.9 mm. The distance between the diaphyseal axis and the greater tuberosity (b) which is equal to the radius of the humeral head minus the medial offset of the centre of rotation of the humeral head

The design of the original Grammont design (Delta III; DePuy, Warsaw, IN) was used to normalize all measurements. The relative lateralization of the implants was calculated as the difference between the LO of each particular implant and the LO of the Delta III. Implants were then classified into categories based on a classification introduced by Hamilton et al. [13] modified for this article.

Glenoid lateralization

- Medialized glenoid (MG): glenoid LO (CE) < 5 mm of Delta III
- Lateralized glenoid (LG): glenoid LO (CE) ≥ 5 mm of Delta III.

Humeral lateralization

- Medialized humerus (MH): humeral LO (AC) < 5 mm of Delta III.
- Minimally lateralized humerus (LH): humeral LO (AC) 5–9 mm of Delta III.
- Lateralized humerus (LH+): humeral LO (AC) 10–14 mm of Delta III.

Global implant lateralization

Each implant was therefore defined as a combination of one of two glenoid categories and one of four humeral categories: MGMH, MGLH, MGLH+, MGLH++, LGMH, LGLH, LGLH+, and LGLH++. However, as this classification does not give any information on the amount of global lateralization, an additional classification was created to separate implants in categories of 5-mm increments according to the value of global LO (AE) in reference to Delta III:

- Medialized RSA (M-RSA): < 5 mm of Delta III
- Minimally lateralized RSA (ML-RSA): 5–10 mm of Delta III
- Lateralized RSA (L-RSA): 10–15 mm of Delta III
- Highly lateralized RSA (HL-RSA): 15–20 mm of Delta III
- Very highly lateralized RSA (VHL-RSA): > 20 mm of Delta III

Overall medialization of the greater tuberosity LO (Fig. 2)

The diameter of the humeral head represents the distance between the glenoid (line E) and the greater tuberosity and represents the native greater tuberosity LO. As we used templates, direct measurement of the overall offset of the greater tuberosity after implantation of the different RSAs could not be measured directly but had to be calculated. The humeral head has a medial offset relative to the diaphyseal axis (line A) of a mean 6.9 mm, and the mean diameter of a humeral head is 46.2 mm [14]. Thus, the distance between the diaphyseal axis and the greater tuberosity is equal to the radius of the humeral head minus the medial offset of the centre of rotation of the humeral head: $(46.2 / 2) - 6.9 = 16.2$ mm (Fig. 2). The mean greater tuberosity LO was considered to be the global LO + 16.2 mm.

Measurements

For each implant, LOs were measured using the smallest available baseplate, a 36-mm glenosphere, and the thinnest polyethylene humeral insert. In addition, the maximal possible LO was also measured for each implant

Table 2 Global lateral offset (LO) and lateralization of the different implants included in the study.

Manufacturer	Implant	Global LO	Global lateralization	Mean GT LO	Mean GT medialization	Global lateralization class	Gleno-humeral construct	Glenoid contribution	Humeral contribution
DePuy	Delta III	13.1	0	29.3	− 16.9	M	MGMH		
Mathys	Affinis Reverse	13.2	+ 0.1	29.4	− 16.8		MGMH		
Tornier	Aequalis	15.6	+ 2.5	31.8	− 14.4		MGMH		
Tornier	Aequalis II	15.6	+ 2.5	31.8	− 14.4		MGMH		
Lima	SMR	17	+ 3.9	33.2	− 13		MGMH		
DePuy	DeltaXtend	18.5	+ 5.4	34.7	− 11.5	ML	MGLH	0%	100%
Zimmer	Trabecular Metal	19	+ 5.9	35.2	− 11		MGMH	32%	68%
Arthrex	Univers 155°	19.1	+ 6	35.3	− 10.9		MGLH	− 33%	133%
Arthrex	Univers 135°	20.7	+ 7.6	36.9	− 9.3		MGMH	41%	59%
Medacta	Shoulder System 155°	21.7	+ 8.6	37.9	− 8.3		MGLH	53%	47%
Tornier	Aequalis II + BioRSA	22.6	+ 9.5	38.8	− 7.4		LGMH	57%	43%
DJO	Altivate	23.4	+ 10.3	39.6	− 6.6	L	LGMH	69%	31%
Medacta	Shoulder System 145°	23.5	+ 10.4	39.7	− 6.5		MGLH	61%	39%
Tornier	Ascend Flex 137.5°	23.8	+ 10.7	40	− 6.2		MGLH+	7%	93%
Fx Solutions	Humelock Reverse	24.3	+ 11.2	40.5	− 5.7		MGLH	37%	63%
Tornier	Ascend Flex 132.5°	24.5	+ 11.4	40.7	− 5.5		MGLH+	6%	94%
Biomet	TESS	26	+ 12.9	42.2	− 4		LGLH	50%	50%
Exactech	Equinoxe	26.4	+ 13.3	42.6	− 3.6		MGLH+	25%	75%
Tornier	Ascend Flex 127.5°	26.7	+ 13.6	42.9	− 3.3		MGLH+	5%	95%
Fx	Easytech	27.2	+ 14.1	43.4	− 2.8		MGLH	51%	49%
Aston	Duocentric	28.2	+ 15.1	44.4	− 1.8	HL	LGLH	26%	74%
Strkyer	ReUnion RSA	29.3	+ 16.2	45.5	− 0.7		LGLH+	31%	69%
Biomet	Comprehensive	29.8	+ 16.7	46	− 0.2		LGLH+	31%	69%
Zimmer	Inverse Reverse	31	+ 17.9	47.2	1		MGLH+	22%	78%
Tornier	Ascend Flex 132.5° + BioR-SA	31.5	+ 18.4	47.7	1.5		LGLH+	42%	58%
FH Ortho	Arrow II	31.7	+ 18.6	47.9	1.7		LGLH+	51%	41%
FH Ortho	Arrow	34.5	+ 21.4	50.7	4.5	VHL	LGLH+	31%	69%

M medialized RSA, *ML* minimally lateralized RSA, *L* lateralized RSA, *HL* highly lateralized RSA, *VHL* very highly lateralized RSA, *MG* medialized glenoid, *LG* lateralized glenoid, *MH* medialized humerus, *LH* minimally lateralized humerus, *LH* lateralized humerus

(with the largest and/or more lateralized glenosphere, and the most lateralizing humeral insert). The difference between the maximal LO and the baseline one indicates the range of LO allowed by each implant.

Results

Overall results are detailed in Table 1.

Global lateralization (Table 2)

The global LO of the Delta III is 13.1 mm. There were 5 M-RSA implants (LO < 18.1 mm), 5 ML-RSA (LO 18.1–23.1 mm), 7 L-RSA (LO 23.1–28.1 mm), 6 HL-RSA (LO 28.1–33.1 mm), and 1 VHL-RSA implants (LO 33.1–38.1 mm). The average range of LO is 10.8 mm. The range of global LO that is possible to obtain with one given implant varies from 3.3 to 20.9 mm (Table 1).

Table 3 Glenoid lateral offset (LO) and lateralization of the different implants included in the study

Manufacturer	Implant	Glenoid LO	Glenoid Lat	Sphere LO	Sphere Lat	Baseplate LO	Baseplate Lat	Glenoid lateralization class
Arthrex	Univers 155°	7.6	− 2	7.6	0	0	− 2	MG
Tornier	Aequalis	7.6	− 2	7.6	0	0	− 2	
Tornier	Aequalis II	7.6	− 2	7.6	0	0	− 2	
Mathys	Affinis Reverse	9.1	− 0.5	7.6	0	1.5	− 0.5	
DePuy	DeltaXtend	9.5	− 0.1	8[a]	+ 0.4	1.5	− 0.5	
DePuy	*Delta III*	*9.6*	*0*	*7.6*	*0*	*2*	*0*	
Tornier	Ascend Flex 127.5°	10.3	+ 0.7	10.3	+ 2.7	0	− 2	
Tornier	Ascend Flex 132.5°	10.3	+ 0.7	10.3	+ 2.7	0	− 2	
Tornier	Ascend Flex 137.5°	10.3	+ 0.7	10.3	+ 2.7	0	− 2	
Zimmer	Trabecular Metal	11.5	+ 1.9	9	+ 1.4	2.5	+ 0.5	
Medacta	Shoulder System 155°	11.6	+ 2	7.6	0	4	+ 2	
Arthrex	Univers 135°	12.7	+ 3.1	12.7	**+ 5.1**	0	− 2	
Exactech	Equinoxe	12.9	+ 3.3	10.9[a]	+ 3.3	2	0	
Zimmer	Inverse Reverse	13.6	+ 4	7.6	0	6	+ 4	
Fx Solutions	Humelock Reverse	13.8	+ 4.2	10.3	+ 2.7	3.5	+ 1.5	
Fx Solutions	Easytech	13.8	+ 4.2	10.3	+ 2.7	3.5	+ 1.5	
Lima	SMR	14	+ 4.4	9	+ 1.4	5	+ 3	
Medacta	Shoulder System 145°	14.3	+ 4.7	10.3	+ 2.7	4	+ 2	
Tornier	Aequalis II + BioRSA	14.6	**+ 5**	7.6	0	7[b]	**+ 5**	LG
Strkyer	ReUnion RSA	14.7	**+ 5.1**	12.7	**+ 5.1**	2	0	
Biomet	Comprehensive	14.8	**+ 5.2**	9.8	+ 2.2	5	+ 3	
Aston	Duocentric	15.3	**+ 5.7**	10.3	+ 2.7	5	+ 3	
Biomet	TESS	16	**+ 6.4**	9	+ 1.4	7	**+ 5**	
FH Ortho	Arrow II	16.1	**+ 6.5**	7.6	0	8.5	**+ 6.5**	
FH Ortho	Arrow	16.3	**+ 6.7**	7.6	0	8.7	**+ 6.7**	
DJO	Altivate	16.7	**+ 7.1**	12.7	**+ 5.1**	4	+ 2	
Tornier	Ascend Flex 132.5° + BioRSA	17.3	**+ 7.7**	10.3	+ 2.7	7[b]	**+ 5**	
Lima	SMR Stemless	17.9	**+ 8.3**	12.9	**+ 5.3**	5	+ 3	

The Grammont style Delta III which serves as reference point has been italicized

Values of lateralization have been written in bold when they exceed 5 mm

[a] Smallest glenosphere available: 38 mm

[b] Lateralization is not in the baseplate but on the scapular neck

Glenoid lateralization (Table 3)

The glenoid LO of the Delta III is 9.6 mm. MG implants had less than 14.6 mm of glenoid LO; LG implants had a glenoid LO ≥ 14.6 mm. Eight implants lateralize on the glenoid side through the glenosphere, baseplate, or both.

Glenosphere lateralization

The glenosphere LO of the Delta III is 7.6 mm. Four implants lateralized through the glenosphere (glenosphere LO greater than that of the Delta III + 5 mm (7.6 mm + 5 mm = 12.6 mm).

Influence of the size of the glenosphere (Table 4)

An increase of the size of the glenosphere from a 36 mm to the next size available (39/40/41/42 or 44 mm) leads to a mean glenoid lateralization of 1.14 (range − 1.1–2.3) mm and a mean global lateralization of 1.44 (range − 0.4–4.3) mm.

Baseplate lateralization

The baseplate LO of the Delta III is 2 mm. Three implants lateralize through the baseplate (baseplate LO greater than that of the Delta III + 5 mm (i.e., 2 mm + 5 mm = 7 mm).

Table 4 Influence of glenosphere size on lateral offset

		Glenoid lateral offset			Global lateral offset		
Manufacturer	Implant	36 mm	Larger glenosphere: 39/40/41/42/44 mm	Lateralization	36 mm	Larger glenosphere: 39/40/41/42/44 mm	Lateralization
Arthrex	Univers 135 (39 mm)	12.7	13.8	1.1	20.7	21.8	1.1
Arthrex	Univers 155 (39 mm)	7.6	8.2	0.4	19.1	19.7	0.7
Aston	Duocentric (40 mm)	15.3	17	1.7	28.2	29.9	0.7
Biomet	Comprehensive (41 mm)	14.8	16.2	1.4	29.8	31.6	1.8
Biomet	TESS (41 mm)	16	17.3	1.3	26	28.3	2.3
DJO	Altivate (40 mm)	16.7	15.6	− 1.1	23.5	23.1	− 0.4
DePuy	Delta III (42 mm)	9.6	9.9	0.3	13.1	13.4	0.3
DePuy	DeltaXtend (42 mm)	9.5[a]	10.4	0.9	18.5[a]	19.9	1.4
Exactech	Equinoxe (42 mm)	12.9[a]	14	1.1	26.4[a]	38.1	2.3
FH Industrie	Arrow (39 mm)	16.3	17.8	1.5	34.5	36.4	1.9
FH Industrie	Arrow II (39 mm)	16.1	17.7	1.6	31.7	33.8	2.1
Fx Solutions	Humelock Reverse (40 mm)	13.8	15	1.2	24.3	25	0.7
Fx Solutions	Easytech (40 mm)	13.8	15	1.2	27.3	28.4	1.1
Lima	SMR (44 mm)	14	16	2	17	19	2
Lima	SMR Stemless (44 mm)	17.9[b]	19.1	1.2	–	–	–
Mathys	Affinis Reverse (39 mm)	9.1	9.7	0.6	13.2	13.3	0.1
Medacta	Shoulder System 145° (39 mm)	14.3	15.2	0.9	23.5	24.2	0.7
Medacta	Shoulder System 155° (39 mm)	11.6	12.2	0.6	21.7	22.5	0.8
Strkyer	ReUnion RSA (40 mm)	14.7	16.1	1.4	29.3	30.7	1.4
Tornier	Aequalis (42 mm)	7.6	9.9	2.3	15.6	19.9	4.3
Tornier	Aequalis II (42 mm)	7.6	8.9	1.3	15.6	18.9	3.3
Tornier	Ascend Flex 132.5 (42 mm)	10.3	12	1.7	27	29	2
Zimmer	Inverse Reverse (40 mm)	13.6	14.5	0.9	31	32	1
Zimmer	Trabecular Metal (36 mm)	11.5	12.5	1	19	20.5	1.5

[a] 38 mm

[b] 40 mm

Humeral lateralization (Table 5)

The humeral LO of the Delta III is 3.5 mm. Nine implants were MH (humeral LO < 8.5 mm), seven were LH (humeral LO 8.5–13.5 mm, and 7 were LH+ (humeral LO 13.5–18.5 mm). Humeral lateralization is influenced by stem design, NSA, and onlay versus inlay design. The mean NSA of implants that do not lateralize on the humeral side is 149.1° (range 135°–155°) versus 133.6° (range 127.5°–135°) for those that do. All LH+ implants have an onlay design, versus only 13% of the MH and LH implants. Mean insert lateralization is + 11 mm (range 7.3–17.7 mm) in onlay implants, versus +2.22 mm (range − 1.9–5.5 mm) in inlay implants. The offset of the Delta III humeral insert is − 3.5 mm. Humeral insert offset varies from − 3.5 to 14.2 mm.

Overall medialization of the greater tuberosity LO (Table 2)

M-RSAs lead to a mean overall *medialization* of the greater tuberosity of 12.2 mm (range 11.5–16.9 mm). ML-RSAs lead to a mean overall *medialization* of the greater tuberosity of 10.2 mm (range 7.4–11.5 mm). L-RSAs lead to a mean overall *medialization* of the greater tuberosity of 4.9 mm (range 2.8–6.6 mm). HL-RSAs lead to a mean overall *medialization* of the greater tuberosity of − 0.25 mm (range −1.7–1.8 mm).

Table 5 Humeral lateral offset (LO) and lateralization of the different implants included in the study

Manufacturer	Implant	Inlay/ onlay	Stem NSA	Insert NSA	Humeral LO	Humeral Lat	Stem LO	Stem Lat	Insert LO	Insert Lat	Humeral lateralization class
Lima	SMR stemless	Inlay	135	140	–	–	–	–	− 2.2	+ 1.3	MH
Lima	SMR	Inlay	150	150	3	− 0.5	6.5	− 0.5	− 3.5	0	
DePuy	*Delta III*	*Inlay*	*155*	*155*	*3.5*	*0*	*7*	*0*	*− 3.5*	*0*	
Mathys	Affinis Reverse	Inlay	155	155	4.1	+ 0.6	9.5	+ 2.5	− 5.4	− 1.9	
DJO	Altivate	Inlay	135	135	6.7	+ 3.2	8.5	+ 1.5	− 1.8	+ 1.7	
Zimmer	Trabecular Metal	Inlay	143	150	7.5	+ 4	7	0	0.5	+ 4	
Arthrex	Univers 135°	Semi-Inlay	135	135	8	+ 4.5	13	**+ 6**	− 5	− 1.5	
Tornier	Aequalis	Inlay	155	155	8	+ 4.5	7	0	1	+ 4.5	
Tornier	Aequalis II	Inlay	155	155	8	+ 4.5	7	0	1	+ 4.5	
Tornier	Aequalis II + BioRSA	Inlay	155	155	8	+ 4.5	7	0	1	+ 4.5	
DePuy	DeltaXtend	Inlay	155	155	9	**+ 5.5**	8	+ 1	1	+ 4.5	LH
Medacta	Shoulder System 145°	Semi-Inlay	150	145	9.2	**+ 5.7**	7.5	+ 0.5	1.7	**+ 5.2**	
Biomet	TESS	Inlay	150	150	10	**+ 6.5**	11	+ 4	− 1	+ 2.5	
Medacta	Shoulder System 155°	Semi-Inlay	150	155	10.1	**+ 6.6**	7.5	+ 0.5	2.6	**+ 6.1**	
Fx Solutions	Humelock Reverse	Inlay	145	145	10.5	**+ 7**	8.5	+ 1.5	2	**+ 5.5**	
Arthrex	Univers 155°	Semi-Inlay	155	155	11.5	**+ 8**	14.5	+ 7.5	− 3	+ 0.5	
Aston	Duocentric	Onlay	145	145	12.8	**+ 9.3**	5.2	− 1.8	7.7	**+ 11.2**	
Fx Solutions	Easytech	Onlay	145	145	13.4	**+ 9.9**	8.5	+ 1.5	4.9	**+ 8.4**	
Tornier	Ascend Flex 137.5°	Onlay	137.5	145	13.5	**+ 10**	9.7	+ 2.7	3.8	**+ 7.3**	LH+
Exactech	Equinoxe	Onlay	132.5	145	13.5	**+ 10**	8.7	+ 1.7	4.8	**+ 8.3**	
Tornier	Ascend Flex 132.5°	Onlay	132.5	145	14.2	**+ 10.7**	9.6	+ 2.6	4.6	**+ 8.1**	
Tornier	Ascend Flex 132.5° + BioRSA	Onlay	132.5	145	14.2	**+ 10.7**	9.6	+ 2.6	4.6	**+ 8.1**	
Strkyer	ReUnion RSA	Onlay	135	135	14.6	**+ 11.1**	7.5	+ 0.5	7.1	**+ 10.6**	
Biomet	Comprehensive	Onlay	135	147	15	**+ 11.5**	7.8	+ 0.8	7.2	**+ 10.7**	
FH Ortho	Arrow II	Onlay	135	155	15.2	**+ 11.7**	5.5	− 1.5	10.1	**+ 13.6**	
Tornier	Ascend Flex 127.5°	Onlay	127.5	145	16.4	**+ 12.9**	9.6	+ 2.6	6.8	**+ 10.3**	
Zimmer	Inverse Reverse	Onlay	135	155	17.4	**+ 13.9**	11	+ 4	6.4	**+ 9.9**	
FH Ortho	Arrow	Onlay	135	155	18.2	**+ 14.7**	5.5	− 1.5	12.7	**+ 16.2**	

The Grammont style Delta III which serves as reference point has been italicized

Values of lateralization have been written in bold when they exceed 5 mm

VHL-RSAs lead to a mean overall *lateralization* of the greater tuberosity of 4.5 mm.

Discussion

The position of the joint centre of rotation and humerus varies substantially amongst different RSA designs. The results of our study demonstrate a wide range in lateral offset, from the initial medialized concept designed by Grammont (13.1 mm) to more lateralized designs (up to 35.8 mm). The distribution between glenoid and humeral lateralization also varies substantially between different designs and their numerous possible configurations (Fig. 3).

Medialized implants follow Grammont's principles, leading to both humeral and glenoid medialization. These implants represent now a minority. Medialized designs may lead to poor restoration of internal and external rotation [8, 15, 16] (possibly due to a slackening of the remaining cuff or peripheral impingement), scapular notching [17] (potentially leading to osteolysis, loosening, polyethylene wear, and tuberosity resorption [3, 5, 8, 15, 18–24]), instability [8] (subsequent to slackening of the remaining cuff and maybe to the loss of the physiological wrapping angle of the deltoid from 48° to 8° [25]), and loss of contour of the shoulder [8, 15, 20, 21]. The biomechanical effects of global lateralization have been investigated in numerous in vitro studies. However, although global lateralization may have common biomechanical theoretical effects, whether this lateralization takes place on the glenoid or humeral side may have different implications.

Some implants lateralize almost exclusively on the glenoid side. Glenoid lateralization can be achieved by modifying the shape of the glenosphere [26, 27], lateralizing the baseplate [11, 28], or increasing the length of the scapular neck with a bone

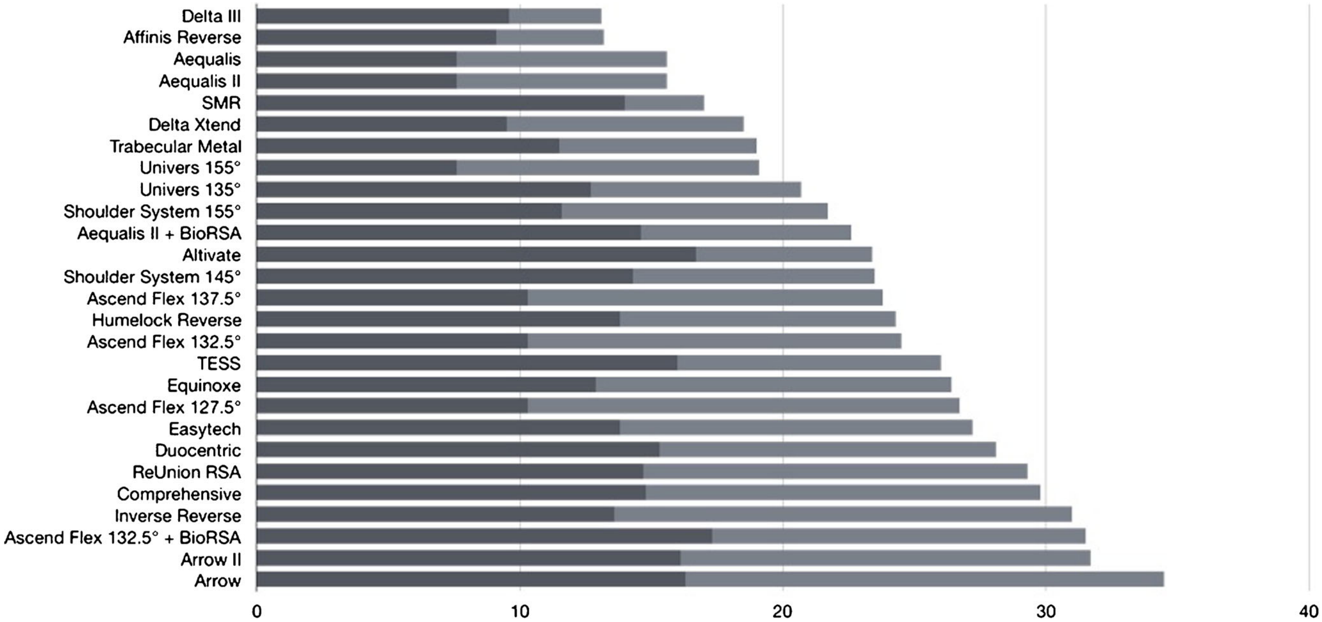

Fig. 3 Distribution of glenoid and humeral lateral offset. M medialized RSA, ML minimally lateralized RSA, L lateralized RSA, HL highly lateralized RSA, VHL very highly lateralized RSA

graft [10, 29]. Lateralization on the glenoid side decreases scapular notching (the humeral polyethylene bearing is more distant from the scapular pillar [10, 11, 28]) and increases impingement-free motion [7, 30]. However, since the centre of rotation of the joint ends closer to the deltoid line of pull, the moment arm of the deltoid in elevation and abduction decreases [13] and therefore the force required for the deltoid to perform abduction increases [31]; it may also increase acromial stress [32, 33]. In addition, the glenoid implant is subjected to substantial shear forces, which could facilitate glenoid loosening [26]. Finally, the amount of glenoid lateralization is limited by glenoid bone erosion, inclination, or retroversion [26]. None of the implants investigated in this study lateralizes more than 8.3 mm on the glenoid, a value that may be useful to keep in mind.

Humeral side lateralization can be achieved by various means. First, the stem may be modified from straight to curved [34]. Second, the humeral bearing may be embedded in the metaphysis (inlay) or rest on the humeral osteotomy (onlay) [13]. Shifting from an inlay to an onlay system lateralizes the humerus by displacing the stem away from the glenosphere. Implants evaluated in this study that lateralize on the humeral side have an onlay design (Table 4). Benefits of onlay systems include preservation of metaphyseal bone, ease of conversion [35], and additional modularity of the LO by medializing or lateralizing the connection between the humeral insert and stem (BC distance). Modification of the NSA from 155° to 145° or 135° has been described as a cause and/or a means of humeral lateralization. This study shows that the modification of the neck-shaft angle only leads to minimal lateralization: + 3.2 mm between the humeral stem of the Delta III and the stem of the Altivate, which have a similar inlay design with a straight stem but different NSAs. The lateralization created by modifying the NSA is so minimal that it can be compensated by modifying the shape of the insert and the position of

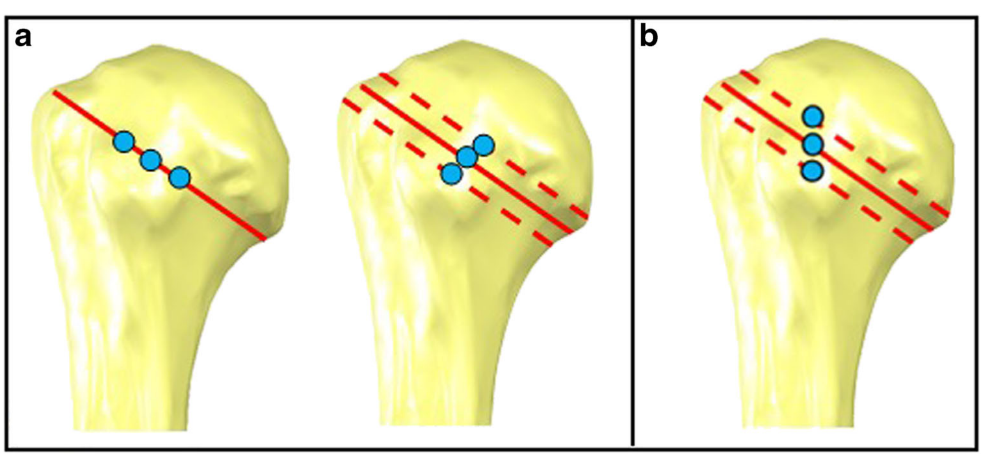

Fig. 4 In stemless implants, stem lateralization does not exist but can be replaced by the surgeon's choice of humeral cut. Indeed, line B can vary greatly by modifying the height of the humeral cut and the medio-lateral position of the stemless implant (**a**). This is not true with a stemmed implant, as in this setting, height of the humeral cut does not modify lateral offset (**b**)

the connection between the insert and the stem (Arthrex). Therefore, it seems reasonable to consider that the angle of the humeral cut and the angle of the humeral insert have little influence on humeral and on global LO. However, humeral inserts with 135° angle decrease the risk of scapular notching without increasing instability [36].

Humeral lateralization (whether in the stem or in the humeral insert) has several advantages. It restores a more anatomical position of the humerus and therefore of the lesser and greater tuberosities, which improves the length/tension curve of the remaining cuff [37]. Better resting tension of the remaining cuff increases compressive forces on the joint and improves stability [38]. A more lateral position of the greater tuberosity increases the abductor lever arm and the wrapping angle of the deltoid [25], which could increase compressive forces [6, 31, 39].

Three stemless implants have been included in our analysis. In these implants, stem lateralization can be introduced by the surgeon's choice of the location of the humeral cut. Indeed, line B can vary greatly depending on the height of the cut and the mediolateral position of the implant (Fig. 4).

Lateralization in both the humerus and the glenoid (LGLH and LGLH+) combines the beneficial effects of both glenoid and humeral lateralization, but the risk is to lateralize excessively. Indeed, VHL implants lead to a mean greater tuberosity lateralization of 5.2 mm, which can be particularly problematic in smaller patients [14] or in the presence of soft tissue contractures; resultant joint overstuffing may lead to poor motion, polyethylene wear [31, 38], difficulty to reduce the joint, nerve stretching, difficulty to repair the subscapularis [37, 40], and acromial impingement. Therefore, if the objective is to restore an anatomical insertion of the remaining rotator cuff tendons and anatomical wrapping angle of the deltoid, mean greater tuberosity lateralization should be around 0 mm, which corresponds to HL implants. In addition, as the diameter of humeral heads has a 17-mm span, a similar 17-mm range should be available in order to restore anatomy in all patients.

Modification of the size of the glenosphere from a 36-mm diameter to a greater diameter has been considered a means of lateralization. However, our study shows that the modification from a 36-mm glenosphere to a 42-mm glenosphere leads only to a + 1-mm increase in global lateral offset. Berhouet et al. [41] found that a 7-mm glenoid lateralization on a 36-mm glenosphere led to a significant increase in impingement-free external and internal rotation in an experimental model. The increase was even greater when the glenosphere was changed from a 36 to a 42-mm diameter. This shows that the improvement in axial (internal and external) rotation found in their study is probably due to a three-dimensional effect. Indeed, the main limitation of our study is to analyze a three-dimensional dynamic question using only static two-dimensional measurements. In addition, as templates were used, the actual distance between the humeral stem and the greater tuberosity could only be estimated based on previous anatomical studies. Similar three-dimensional studies are warranted to understand the true effect on soft tissue tension of different designs of RSA. Finally, and most importantly, this study provides theoretical data which needs to be correlated to clinical studies.

In conclusion, although it seems that some degree of lateralization is beneficial when performing a RSA, the ideal amount of global lateralization and the ideal contribution from the glenoid or from the humerus remain unknown. It probably varies depending on patient anatomy, quality and quantity of any remaining cuff, deltoid quality, and the amount of distalization of the humerus (arm and deltoid lengthening). This descriptive analysis can potentially help surgeons with implant selection as well to adapt the surgical technique depending on the expected lateral offset of the design being implanted (larger humeral cut, glenoid tilt, more glenoid reaming).

Compliance with ethical standards Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

Conflict of interest Philippe Valenti and Jean-David Werthel receive royalties for shoulder prosthesis design from FH Orthopedics. Gilles Walch receives royalties for shoulder prosthesis design from Wright Medical. Joaquin Sanchez-Sotelo receives royalties for shoulder prosthesis design from Stryker.

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