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ORIGINAL ARTICLE

Dual mini-fragment plate fixation of midshaft clavicle fractures is biomechanically equivalent to anatomic pre-contoured plating

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Abstract

Objectives To biomechanically compare the stiffness of midshaft synthetic clavicle osteotomies fixed with either superior anatomic pre-contoured locking plates, anterior anatomic pre-contoured locking plates, or short-segment dual orthogonal mini-plate fixation.
Design and Setting Controlled laboratory study.
Specimens
Twenty-one synthetic pre-osteotomized clavicles were separated into three groups: superior plating, anterior plating, or dual-plating. Each clavicle was sequentially tested in non-destructive cycles of axial compression, three-point bending, and torsion. Load and displacement were recorded. Stiffness was calculated.
Results No statistically significant differences were found between construct stiffness during axial compression, three-point bending, or torsional testing. One superior plated clavicle suffered catastrophic failure during axial compression. One dual mini-fragment plated clavicle suffered catastrophic failure during torsion.
Conclusions Orthogonal dual mini-fragment fixation of transverse clavicle fractures is biomechanically similar to superior and anterior pre-contoured anatomic locking plate fixation. No statistically significant differences in construct stiffness were found in axial compression, three-point bending, or torsion testing. Further clinical research is required to determine the long-term stability of dual mini-fragment plate fixation.
Level of Evidence IV.

Keywords Biomechanics · Dual-plate fixation · Mini-fragment plates · Midshaft clavicle fracture

Introduction

Clavicle fractures account for 2–10% of all fractures seen in adults [1, 2]. Fractures of the middle third, or midshaft, are the most common morphology accounting for 80% of clavicle fractures. These fractures typically occur in younger active patients. Historically, these fractures were treated non-operatively as previous studies demonstrated a higher rate of nonunion associated with operatively treated clavicle fractures [3]. More recently published studies suggest unfavorable results of displaced midshaft clavicle fractures treated nonoperatively [4–7]. As a result, several studies have investigated operative fixation versus nonoperative management of displaced midshaft clavicle fractures [8–13]. The current evidence shows patients treated with open reduction and internal fixation (ORIF) have significantly lower rates of nonunion and may have better functional results and a quicker return to activities, although the clinical relevance of the latter two findings is still in question [14]. Nonetheless, this has led to an increasing proportion of these fractures being treated operatively.

Although underreported, implant prominence is likely the most common post-operative complication of operative clavicle fixation. This complication can lead to high rates of implant removal ranging from 8 to 17% [8, 10–12]. The

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variation in individual plate thickness and the positioning of the plate for operative fixation could impact rates of implant prominence requiring reoperation. A recent meta-analysis demonstrated that anteroinferior plating versus superior plating for midshaft clavicle fractures resulted in similar rates of nonunion, malunion, and implant failure [15]. However, symptomatic implants were much more common in the superior plating group than anteroinferior plating group (17% vs. 8%) and subsequent removal was also higher in the superior plating group than the anteroinferior plating group (11% vs. 5%).

Previously, a systematic review demonstrated similar biomechanical properties when comparing superior versus anteroinferior single plating of midshaft clavicle fractures [22]. However, the biomechanical stability of dual mini-fragment plating of midshaft clavicle fractures remains unclear. Previous studies have demonstrated similar stiffness values of dual-plate constructs when compared to anteroinferior or superior plating [16, 23, 24]. However, these studies use larger caliber plates (2.7 mm–2.8 mm) or long-segment fixation (10–12 holes) for their dual-plate constructs. There is a higher biologic cost of increased dissection and an ongoing risk of reoperation for symptomatic implants with use of similar caliber plates [19].

Given the low profile a mini-fragment plates, there is some concern that dual mini-fragment plate fixation of midshaft clavicle fractures would be biomechanically inferior when compared with anterior or superior locked plating. Proposed benefits of dual-mini-fragment plate fixation include previously reported lower rates of implant prominence and hardware removal [16–21]. However, no previous study has investigated the biomechanical stability of dual mini-fragment plate fixation of midshaft clavicle fractures. Thus, the aim of this study was to investigate the biomechanical properties of short-segment dual anteroinferior and superior mini-fragment orthogonal plates for treatment of midshaft clavicle fractures and compare this to conventional anatomic pre-contoured anteroinferior or superior plates in a cadaveric model. Our null hypothesis was that there is no significant difference between constructs with regards to stiffness for axial compression, torsion, and three-point bending.

Materials and methods

Twenty-one pre-osteotomized (midshaft; transverse orientation) synthetic left clavicles (Model 3408; Sawbones Worldwide, Vashon, WA) were utilized for biomechanical testing. Each synthetic clavicle was made of short fiber filled epoxy to simulate cortical bone (https://www.sawbones.com/biomechanical-product-info). Seven clavicles underwent fixation with 7-hole (2.7 mm/3.5 mm) anatomic pre-contoured superior clavicle plates (Stryker, Hamilton, Canada). Seven clavicles underwent fixation with 7-hole (2.7 mm/3.5 mm) anatomic pre-contoured anteroinferior plates (Stryker, Hamilton, Canada). The final seven clavicles underwent fixation with dual mini-fragment plating with two 8-hole 2.3 mm hand locking plates (Stryker, Hamilton, Canada) located superiorly and anteroinferior. The plates were placed orthogonal to each other and centered over the osteotomy site. Each plate in the three cohorts were secured with two bi-cortical bone screws and one bi-cortical locking screw on either side of the osteotomy. Plates were manually measured for implant thickness.

The plates were fixed to the clavicle specimens by three surgical residents (D.D, D.F, P.T) using standard AO compression plating techniques. All plates and screws were used only once, and the order of screw application was the same in all cases. The medial end of each clavicle was potted and cemented in place using a standardized technique. No portion of the plated clavicle was potted.

Biomechanical testing was completed at the Biomaterial Laboratory in the department of Biomedical engineering at Dalhousie University. An Instron single column force transducer (Instron Universal Testing System; Instron, Norwood, MA, USA) was used for biomechanical testing. Each specimen was cycled through a series of three testing scenarios in a standardized order. The three testing scenarios were: axial compression, superior-inferior three-point loading, and torsion. There was a minimum of five non-destructive testing cycles, with data analysis occurring on the final cycle for each scenario.

For axial testing, each specimen was placed vertically with the lateral end of the clavicle superior, and the osteotomy site parallel to the floor (Fig. 1). The clavicles were loaded in compression with a speed of 1 mm/sec to a maximum compressive load of 315 N. This load was chosen to prevent catastrophic failure of the device in the testing scenarios and has been used in previous biomechanical studies [16, 24, 25]. This load exceeds what has previously been reported for maximum dynamic forces on the clavicle during regular glenohumeral range of motion [26, 27]. Data for the axial compression test were collected for actuator displacement (mm) and load (N).

The three-point bend test was cyclic in the superior-inferior direction with a speed of 3 mm/min and a maximum deflection of 2 mm. The clavicle was oriented parallel to the floor, with the transverse osteotomy perpendicular to the floor. The medial end of the clavicle was fixed, the lateral end of the clavicle was supported on a standardized surface, and the force transducer applied a downward force immediately lateral to the fracture site (Fig. 2). Data were collected in the form of actuator displacement (mm) and load (N).

Torsional testing was performed with the clavicle parallel to the floor with the osteotomy perpendicular to the

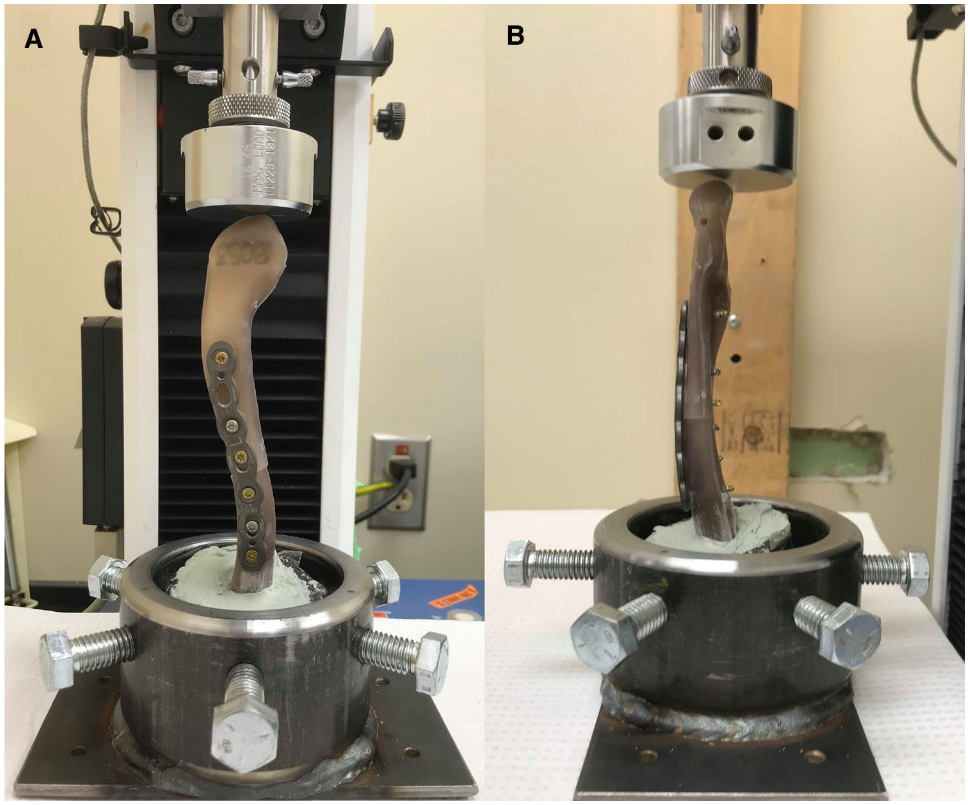

Fig. 1 Axial compression demonstration for an anatomic superior pre-contoured locking plate. **A** Anterior–posterior view, **B** Lateral view

Fig. 2 Anterior–posterior view of three-point bending testing. Load cell located immediately lateral to fracture site

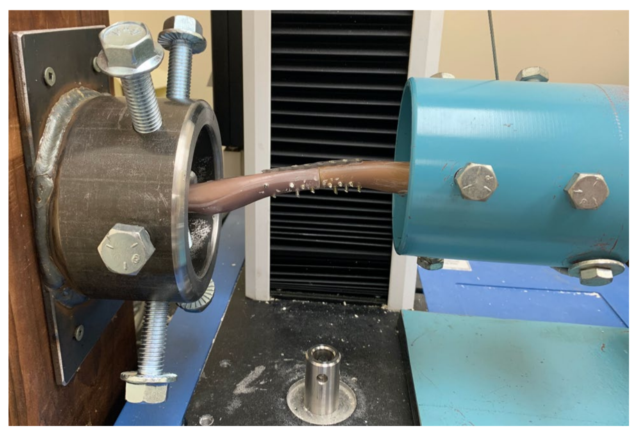

Fig. 3 Torsion testing with lateral end secured and medial end fixed to a rotational construct

floor. The lateral end of the clavicle was fixed. The medial end of the clavicle was fixed within a rotational construct that centered each specimen at a fixed point. The medial end of the clavicle was then rotated through the fracture site by applying a vertical force through a cable attached to the rotational device at a fixed point (Fig. 3). The force transducer applied a vertical force at a speed of 20 mm/min to a maximum deflection of 20 mm. Data were collected in the form of transducer displacement (mm) and load (N). The angular displacement (degrees) was calculated by performing a trigonometric analysis of the distance from the center of rotation of the device to the force application and the vertical displacement of the force transducer.

Construct stiffness was determined from load versus displacement data for the axial and three-point bending tests and torque versus rotation data for the torsional tests. All data from each scenario were grouped by plate location and fixation type. Data from the final cycle of each scenario were summed, and a mean result was provided. A one-way ANOVA with a Tukey post hoc analysis was performed on the data. Statistical significance was set at $p = 0.05$.

Results

The descriptive statistics for the axial compression, three-point bending, and torsional stiffness testing scenarios for the anterior, superior, and orthogonal dual mini-fragment plated clavicles are summarized in Table 1. The superior and anterior anatomic pre-contoured locking plates measured 3.1 mm in thickness. The mini-fragment implants used for orthogonal dual-plating measured 1.4 mm in thickness.

A total of 20 clavicles were tested in axial compression and three-point bending. Nineteen clavicles were tested in torsion. One superior plated clavicle sustained catastrophic failure through the most lateral screw hole during axial compression, and data were not collected for three-point bending, axial compression, or torsion (Fig. 4). One dual mini-fragment plated clavicle sustained catastrophic failure with permanent deformation of the plates during torsional testing but did succeed in the testing of axial compression and three-point bending stiffness prior to failure.

Mean construct stiffness in axial compression was 396.07 N/mm for anterior plated clavicles, 431.43 N/mm for superior plated clavicles, and 423.97 N/mm for dual-plated clavicles (Fig. 5). No significant differences were found in construct stiffness in axial compression (Table 2). Mean construct stiffness in torsion was 0.31 Nm/deg for anterior plated clavicles, 0.31 Nm/deg for superior plated clavicles, and 0.27 Nm/deg for dual-plated clavicles (Fig. 6). No significant differences were found in construct stiffness in torsion (Table 2). Mean construct stiffness in three-point bending was 156.40 N/mm for anterior plated clavicles, 148.49 for superior plated clavicles, and 133.97 for dual-plated clavicles (Fig. 7). No significant difference were found in construct stiffness in three-point bending (Table 2). A Tukey post hoc analysis did not show any significant differences in construct stiffness when comparing anterior to superior, anterior to dual-plating, and superior to dual-plating constructs in each of the three testing scenarios (Table 3).

Fig. 4 Catastrophic failure of an anatomic superior pre-contoured locking plate after axial compression

Table 1 Mean stiffness values with descriptive characteristics of each specimen following axial compression, three-point bending, and torsional testing

		N	Mean	Std. deviation	Std. error	95% CI		Min	Max
						Lower	Upper		
Axial stiffness (N/mm)	Anterior	7	396.07	105.64	39.93	298.36	493.77	193.43	497.19
	Superior	6	431.43	216.71	88.47	204.01	658.85	209.41	838.40
	Dual-plate	7	423.97	160.47	60.65	275.57	572.38	205.85	649.38
Bending stiffness (N/mm)	Anterior	7	156.39	16.91	6.39	140.76	172.03	138.60	184.92
	Superior	6	148.48	36.73	14.99	109.94	187.03	110.01	195.63
	Dual-plate	7	133.97	25.31	9.57	110.56	157.38	89.61	159.97
Torque stiffness (Nm/°)	Anterior	7	0.31	0.05	0.02	0.27	0.36	0.26	0.40
	Superior	6	0.31	0.05	0.02	0.26	0.36	0.24	0.36
	Dual-plate	6	0.27	0.07	0.03	0.20	0.34	0.19	0.39

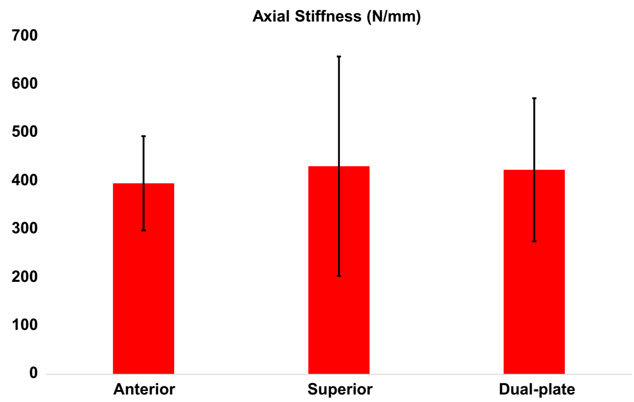

Fig. 5 Mean axial compression stiffness values with 95% confidence intervals

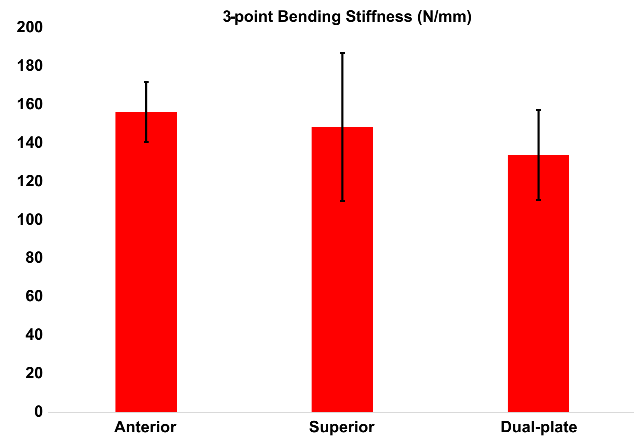

Fig. 6 Mean three-point bending stiffness values with 95% confidence intervals

Discussion

Recent evidence shows patients treated for clavicle fractures with open reduction and internal fixation (ORIF) have significantly lower rates of nonunion and may have better functional results and a quicker return to activities [14, 28]. Implant prominence is a common post-operative complication of operative clavicle fixation and can lead to high rates of implant removal ranging from 8 to 17% [8, 10–12]. One advantage of dual mini-fragment plate fixation is lower profile plates when compared with pre-contoured locking plates, and lower rates of implant prominence and hardware removal have been reported with dual mini-fragment fixation of clavicle fractures [16–21]. However, there is some concern that the low caliber of dual mini-fragment plate fixation is biomechanically inferior to anterior or superior pre-contoured locked plating. Thus, the purpose of this study was to biomechanically investigate the stiffness of dual mini-fragment fixation of transverse midshaft synthetic clavicle osteotomies and compare this to anterior and superior locked plating. The main finding of this study was that orthogonal dual mini-fragment plating of midshaft transverse clavicle fractures yields similar biomechanical properties when compared to modern anterior and superior anatomic pre-contoured locking clavicle plates in a cadaveric model. We found no significant difference in construct stiffness during axial compression, torsion, or three-point bending between the three fixation techniques. Post hoc analysis confirmed that no significant difference existed between each group.

Fig. 7 Mean torsional stiffness values with 95% confidence intervals

The current study has many limitations. The sample size was limited to a pre-testing collection of 21 synthetic clavicles, with 7 clavicles in each testing scenario. With two catastrophic failures, the sample size was further limited. However, the sample size of clavicles in this study was within the

Table 2 ANOVA testing for each specimen cohort. No statistical significance was demonstrated

		Sum of squares	df	Mean square	*F*	Sig
Axial stiffness (N/mm)	Between groups	4651.34	2	2325.67	0.087	0.917
	Within groups	456,277.99	17	26,839.88		
Bending stiffness (N/mm)	Between groups	1805.50	2	902.75	1.247	0.312
	Within groups	12,304.59	17	723.80		
Torque stiffness (Nm/°)	Between groups	0.008	2	0.004	1.243	0.315
	Within groups	0.049	16	0.003		

Table 3 Tukey post hoc test results

			Mean difference	Std. error	Sig	95% CI	
						Lower	Upper
Axial stiffness (N/mm)	Anterior	Superior	−35.36	91.15	0.921	−269.19	198.46
		Dual-plate	−27.91	87.57	0.946	−252.56	196.74
	Superior	Anterior	35.36	91.15	0.921	−198.46	269.19
		Dual-plate	7.46	91.15	0.996	−226.37	241.28
	Dual-plate	Anterior	27.91	87.57	0.946	−196.74	252.56
		Superior	−7.46	91.15	0.996	−241.28	226.37
Bending stiffness (N/mm)	Anterior	Superior	7.91	14.97	0.859	−30.49	46.31
		Dual-plate	22.42	14.38	0.290	−14.47	59.31
	Superior	Anterior	−7.91	14.97	0.859	−46.31	30.49
		Dual-plate	14.51	14.97	0.605	−23.89	52.91
	Dual-plate	Anterior	−22.42	14.38	0.290	−59.31	14.47
		Superior	−14.51	14.97	0.605	−52.91	23.89
Torque stiffness (Nm/deg)	Anterior	Superior	−0.0005	0.031	1.000	−0.080	0.079
		Dual-plate	0.0427	0.031	0.369	−0.037	0.122
	Superior	Anterior	0.0005	0.031	1.000	−0.079	0.080
		Dual-plate	0.0432	0.032	0.386	−0.039	0.125
	Dual-plate	Anterior	−0.0427	0.031	0.369	−0.122	0.037
		Superior	−0.0432	0.032	0.386	−0.125	0.039

No statistical significance was demonstrated between groups

range of the previously reported literature [16, 23–25]. The current study focused on a single fracture morphology. The transverse midshaft clavicle fracture is much less common than the simple oblique or comminuted clavicle fracture. However, no oblique osteotomy options existed with the synthetic clavicle manufacturer, and previous studies have similarly reported on a midshaft transverse osteotomies with [23, 24] and without [16] inferior comminution. The clavicle is a S-shaped bone making it inherently difficult to apply the axial compressive force along the true longitudinal axis. This was estimated and reproduced in each testing scenario by securing the medial end of the clavicle within the cement and aligning the specimen such that the compressive force was applied on lateral end of the clavicle with the clavicle in a vertical orientation. No trials were performed with a superiorly directed force for three-point bending. However, a superiorly directed force would not represent any physiologic loading condition that a patient would experience; therefore, it was omitted. Torsion testing was performed with a non-rotatory Instron. A rotational device was created to allow linear forces to produce angular displacement. This introduced new degrees of freedom; however, each clavicle was tested in an identical fashion. Construct stiffness was calculated through analysis of the load–displacement curves of each testing scenario. This is a surrogate measure for fracture stability. Construct stiffness is necessary in the healing of transverse fracture patterns that depend on absolute stability and primary bone healing, but may not be ideal for fractures that require relative stability and secondary bone healing such as those with comminution. Therefore, the results of this study may lack external validity for comminuted clavicle fractures.

Several other studies have investigated the biomechanical properties of various fixation constructs for clavicle fractures [22, 29–32]. To our knowledge, only three previous biomechanical studies exist that have compared dual-plating to single plate constructs for fixation of clavicle fractures with mixed results [16, 23, 24]. Prasarn et al. [16] examined the biomechanical properties of dual-plating transverse osteotomies in synthetic clavicles utilizing 2.7 mm reconstruction plates superior and 2.4 mm locking compression plate anteroinferior. They found no significant difference between their dual-plating construct and a previously published cohort utilizing superior or anterior-inferior 3.5 mm locking plates during axial compression or torsional testing [25]. Similarly, Ziegler et al. [24] demonstrated no significant difference in construct stiffness between dual mini-fragment plate fixation and either superior or anteroinferior plating for axial compression, torsion, three-point bending, or three-point load to failure. However, Boyce et al. [23] demonstrated lower stiffness and strength with dual orthogonal mini-fragment plate fixation when compared with traditional superior plating. This study is unique in that is uses the smallest caliber plates (1.4 mm in thickness) [16, 23, 24] ever tested for dual mini-fragment plating of clavicle fractures. Additionally, this study also uses shorter segment fixation (8-holes) [16, 23] and compares it to modern anatomic pre-contoured locking plates.

Implant prominence and irritation requiring reoperation is a relatively common complication with operative fixation of clavicle fractures. Dual-plate fixation of clavicle fractures may have the added benefit of less soft-tissue stripping secondary to smaller length plates as well as less implant prominence without sacrificing stability. A recent retrospective review compared rates of union and symptomatic implant removal in operative diaphyseal clavicle fractures treated with either dual mini-fragment plating (2.7 mm, 2.4 mm, or 2.0 mm) and pre-contoured superior or anterior plating (3.5 mm) [19]. Although not statistically significant, implant removal for symptomatic implants was less common in dual mini-fragment plating than pre-contoured superior or anterior plating (8.3% vs. 20.2%), and there was no significant difference in nonunion ($p = 0.45$). Similarly, Lee et al. [21] compared dual-plating with 2.7 mm reconstruction plates to superior or anterior 3.5 mm locking compression plates. They reported a symptomatic implant removal rate of 9% in the single plated group compared to 0% in the dual-plating group; however, this difference was not statistically significant.

Conclusion

In conclusion, orthogonal dual mini-fragment fixation of transverse clavicle fractures is biomechanically similar to superior and anterior pre-contoured anatomic locking plate fixation in a cadaveric model. No statistically significant differences in construct stiffness were found in axial compression, three-point bending, or torsion testing. Dual mini-fragment plate fixation is a possible option for fixation of transverse clavicle fractures.

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Declarations

Conflict of interest Ferguson D.P. declares he has no conflicts of interest. Baker H.P. declares he has no conflicts of interest. Dillman D. declares he has no conflicts of interest. Theriault P. declares he has no conflicts of interest. Trask K. declares she has no conflicts of interest. MacDonald S. declares she has no conflicts of interest. Trenholm A. declares he has no conflicts of interest.

Ethical approval This article does not contain any studies with human participants performed by any of the authors.

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