Fractures of the clavicle are common and account for around 3% of all adult fractures [5]. The incidence ranges from 64 to 71/100,000 per year [10,23]. Historically, midshaft clavicular fractures have been treated nonoperatively with good functional outcomes. A major complication of conservative therapy is the relatively high nonunion rate, which is reported to be 15–20% in some studies [32, 33].

In the past decade, randomized control trials have been conducted to compare operative and nonoperative therapy of midshaft clavicular fractures. A recent meta-study concludes that surgical treatment significantly reduces the nonunion rate, shortens the time to union, and, despite a slightly higher incidence of complications, leads to better shoulder functional scores in both short- and long-term follow-up [9]. Although other studies state that there is still no consensus on treatment, there has been an overall paradigm shift towards operative therapy with open reduction and plate fixation [18, 27, 29]. However, the problem of nonunion remains after both conservative and operative management.

Less is known about the results after revision of clavicular nonunions, regardless of whether the initial therapy was operative or nonoperative. Nonunion is either atrophic or hypertrophic. Most studies report a higher rate of atrophic nonunions (see Table 5). The surgical procedure usually includes a resection of the nonunion (decortication according to Judet) and (angular stable) plating combined with autologous bone grafting [20, 28]. Bony union can reliably be achieved with this technique [6, 25]. McKnight et al. compared the surgical management of midshaft clavicular nonunions with that of acute fractures and found an increased risk of short-term complications such as wound infections [21]. Long-term results are scarce. O’Connor et al. found a higher level of disability according to assessment with the Disabilities of Arm, Shoulder, and Hand (DASH) questionnaire in the operated group compared with the normal population after a mean follow-up of 42.1 months [24].

The aim of the present study was therefore to examine the clinical and radiographic results after operative revision of clavicular nonunions in a multicenter study. We hypothesized that the functional results would be similar to the noninjured side and that radiographic fracture union could be achieved in the majority of the cases.

Methods

Study design and patient cohort

Two level-1 trauma centers in northwestern Germany conducted a retrospective analysis of patients with clavicular nonunion who needed revision surgery during the past 10 years. The study was approved by the local ethics committees (2019-159-F-S/8688_BO_S_2019). All patients who underwent operative revision for clavicular nonunion in these two hospitals were included. Patients

| Table 1 | Epidemiological data of the cohort |
|---------|----------------------------------|
| Total patients | n = 31 |
| Age (years) | 52.3 ± 15.2 (range: 32–84) |
| Male vs. female | 12 (38.7%) vs. 19 (61.3%) |
| Body weight (kg) | 80.4 ± 22.1 (range: 51–160) |
| Right- vs. left-handed | 29 (93.5%) vs. 2 (6.5%) |

| Table 2 | Mean values of active range of motion |
|---------|-----------------------------------|
| Movement | Injured side | Noninjured side | p |
| Anteverision | 162 ± 22° | 170 ± 4° | 0.0953 (ns) |
| Retroversion | 39 ± 5° | 40 ± 4° | 0.9993 (ns) |
| Abduction | 163 ± 30° | 174 ± 10° | 0.0064 (**) |
| Adduction | 37 ± 8° | 39 ± 7° | 0.9746 (ns) |
| External rotation | 83 ± 13° | 85 ± 8° | 0.9692 (ns) |
| Internal rotation | 73 ± 11° | 75 ± 9° | 0.9939 (ns) |

ns Nonsignificant, **significant
In 90° abduction
with a record of pre-existing shoulder conditions (e.g., osteoarthritis), earlier operations at the injured side, or regular immunosuppressive medication were excluded. This was a two-center retrospective cohort study with a level III of evidence.

Outcome assessment

All patients underwent a structured clinical and radiological assessment. The clinical interview included a survey of the relevant epidemiological data, pre-existing illness, and individual course of treatment. Risk factors such as smoking, diabetes, and osteoporosis (when explicitly stated as a diagnosis in the patient reports) were also recorded. Pain was assessed using the Visual Analog Scale (VAS). The major outcome parameter was functional assessment using the age- and gender-adjusted Constant score according to Katolik [14].

For the radiographic follow-up, the major outcome parameter was fracture union on conventional X-rays of the clavicular in two planes (anteroposterior [ap] and tangential). This was defined by three continuous cortices. Technical aspects, such as the plate type and length as well as usage of conventional and angular stable screws, were also recorded. Furthermore, the usage of autologous bone grafting was noted. This was harvested either from the iliac crest or from the resected hypertrophic nonunion itself (decorticated bone was cleaned from soft tissue, reduced to small chips, and used for bone grafting). Additionally, complications such as wound site infections with re-operation and the occurrence of paresthesia were examined.

Statistical analysis

Data were collected in a Microsoft Excel data sheet. Mean and standard deviations were calculated where applicable. Statistical analysis was performed with GraphPad (GraphPad Prism 8.3.0, San Diego, CA, USA). Welch’s t test and two-
Background. Over the past decade, the treatment of midshaft clavicular fractures has increasingly shifted from conservative to operative therapy. The overall results seem to be better with surgery, although the problem of nonunion remains. The aim of this study was to report the functional results after operative revision of clavicular nonunions in two German level-1 trauma centers.

Methods. All patients who underwent surgery for clavicular nonunions during the past 10 years were invited for a structured clinical follow-up examination. The major functional outcome parameter was the age- and gender-adjusted Constant score. Additionally, radiographic fracture union was assessed with the available X-rays. Complications such as wound site infections were also monitored.

Results. In total, 31 patients were available for assessment. The mean follow-up rate was 69.7 ± 31.2 months. The mean age of the patients was 52.3 ± 15.2 years. The nonunion was classified as atrophic in 26 cases and hypertrophic in five. A total of 25 (80.6%) patients were treated with angular stable plating combined with autologous bone grafting from the iliac crest. The age- and gender-adjusted Constant score was significantly decreased compared with the noninjured side (82.2 ± 17.1 vs. 95.6 ± 10).

Radiographic union was achieved in 30 of the 31 patients (96.8%). Complications with need for surgical revision were recorded for two patients.

Conclusion. Surgery for clavicular nonunion is a safe and well-established procedure, which leads to radiographic union and good functional results for the majority of cases.

Keywords
Clavicle · Clavicle fracture · Constant score · Revision surgery · Radiographic union

Epidemiological data
The data of 31 patients were analyzed for this study. General epidemiologic data of the cohort are summarized in Table 1.

Initial treatment
The etiology was a mono-trauma of the clavicle in 28 (90.3%) patients, and only three (9.7%) patients suffered a polytrauma. In 18 (58.1%) patients the left side was injured; 14 of the 31 (45.1%) patients were treated in a primarily conservative manner, of whom four (28.6%) had to undergo surgery later than 42 days after trauma owing to secondary dislocation. For 17 patients, surgery was performed primarily within 6.6 ± 8.2 days (range: 0–35). The mean operation time was 53.3 ± 15.8 min (range: 37–80) but these data were only available for six of the operated patients. In summary, ten (32.6%) patients were treated conservatively prior to revision surgery while 21 (67.7%) patients underwent primary surgery or conversion to surgery. In seven (22.6%) surgically treated patients an angular stable plate was used, while an elastic stable intramedullary nail (ESIN) was used in five (16.1%) patients.
Revision surgery

Data on revision surgery were available for all 31 patients. The mean time from trauma to revision was 19.9 ± 20 months (range: 4–107). The nonunion was classified as atrophic in 26 (83.9%) patients and hypertrophic in five (16.1%) patients. The mean radiographic distance of the nonunion gap was 10.9 ± 6.6 mm. A loss of reduction in the operated cohort was noted in 16 (76.2%) cases while an implant breakage was present in five (23.8%) patients. The number of previously conducted operations prior to the revision surgery in one of the two hospitals ranged from 1 to 3 with a mean of 1.38 ± 0.59 operations per patient. In nine (42.9%) cases the implants were already removed.

The mean operating time of the revision was 96.3 ± 35.9 min (range: 49–174). A straight angular stable plate was used in 19 cases (61.3%), while a pre-contoured plate was utilized in 8 (25.8%) cases. The mean plate length was 8.7 ± 1.4 holes with an average of 7.5 ± 1.2 screws per plate (4.3 ± 2.5 conventional screws/3.2 ± 3 locking screws). In 25 (80.6%) patients, autologous bone grafting was used, either from the iliac crest (54.8%) or from the resected nonunion (25.8%). Representative X-rays and intraoperative images from a study patient are shown in Fig. 1.

Clinical outcome

The clinical survey and assessment were conducted with a mean follow-up of 69.7 ± 31.2 months. Eight (25.8%) of the patients reported active smoking, while 17 (54.8%) stated no pre-existing illnesses. None of the patients had a history of osteoporosis or diabetes. The majority of patients were satisfied with revision surgery. The great majority of patients were satisfied with revision surgery of clavicular nonunions can lead to satisfying midterm functional outcomes. The great majority of patients were satisfied with.

Radiological outcome

The mean radiological follow-up after revision surgery was 49 ± 30 months (range: 2–120). Fracture union was seen in 30 (96.8%) patients while no implant breakage, loosening, or loss of reposition were detected. Ossifications were present in 23 (74.2%) patients.

Initial treatment: nonoperative vs. operative

A total of ten patients underwent nonoperative treatment, while 21 were operated on (initial treatment before revision surgery). We compared these groups in terms of the major outcome criteria. Epidemiological data are summarized in Table 3. The conservative group included significantly more smokers.

The main clinical and functional outcome parameters are summarized in Table 4. Apart from the number of operations, no significant differences were detected. There were also no differences in all of the other aforementioned parameters (data not shown).

Discussion

The most important finding of our study is that revision surgery of clavicular nonunions can lead to satisfying midterm functional outcomes. The great majority of patients were satisfied with
the revision surgery and were able to return to work and sport. Radiographic union was reached in 30 out of 31 patients and the overall complication rate was low.

Longer-term follow up data on the functional outcome after surgical treatment of clavicular nonunions in large cohorts are rarely reported. We identified a total of 15 studies over the past 25 years that included the assessment of functional results through either the Constant or DASH score (Table 5).

In summary, the majority of the available studies are retrospective analyses with limited cohort sizes. Rollo et al. presented a larger study population with 57 consecutive cases [26]. Although we were not able to significantly increase the cohort size compared with the available literature, we report the results of two different study centers. Interestingly, our cohort is older on average than any of the aforementioned studies (52.3 ± 15.2 years). The clinical follow-up and the rate between atrophic and hypertrophic nonunions are comparable to those in the literature. Furthermore, similar to the available functional outcome assessment data, the Constant score is significantly decreased compared with the noninjured side (95.6 vs. 82.2). The difference is greater than the accepted threshold for the minimal clinically important difference for the Constant score [17]. Additionally, the range of motion for abduction was decreased in our study. Nevertheless, bony union was achieved in 96.8% of the cases and only two complications requiring revision surgery were recorded.

Additionally, our study provides detailed information on the technical aspects of the surgical revision. Huang et al. reported a mean operation time of 96 min, which is comparable to our data and longer than the average operation time for the initial fixation of a clavicular fracture in our cohort (53.3 ± 15.8 min; p = 0.0002; [11]). Also, the plate length seems to be longer in the revision case compared with the initial surgery (8.1 ± 1.2 vs. 8.7 ± 1.4).

The comparison between initially nonoperative and operative treatment revealed no difference in the outcome measures. Interestingly, significantly more smokers were seen in the conservative cohort. This is inline with studies that identified smoking as an independent risk factor for the development of a nonunion [12].

The case presented in Fig. 1 is a good example of a typical failure of primary clavicular fracture fixation and secondary development of complications like infection and nonunion. In these cases, in which stability of the fixation seems to be the major issue, double plating is a good option to increase the overall fixation stability [15, 22].

**Limitations**

There are several inherent limitations to our study. Firstly, this is a retrospective cohort analysis solely reporting functional and radiographic outcomes. Like other comparable studies published previously, we were not able to recruit a larger cohort, although we did manage (for the first time) to report results from two centers. In addition, the indication for the index therapy (conservative vs. operative) remained unclear and was based on the decision of the treating surgeon. Similarly, the surgeon decided on the need for a bone graft in the revision situation. Therefore, the revision procedures were not standardized.
Table 5  Summary of available studies with outcome assessment based on the Constant or DASH score

| Author                        | Year | n   | Mean age (years) | Follow-up (months) | Atrophic vs. hypertrophic | Constant score | DASH score | Union rate (%) | Complication |
|-------------------------------|------|-----|------------------|--------------------|-------------------------|----------------|------------|----------------|--------------|
| Olsen et al. [25]             | 1995 | 15  | 34               | 24.8               | 9 vs. 6                 | 87.9           | NA         | 94             | None         |
| Bradbury et al. [3]           | 1996 | 32  | NA               | 72                 | 21 vs. 10               | 85             | NA         | 97             | 1            |
| Wentz et al. [31]             | 1999 | 22  | 18–33            | NA                 | 19 vs. 3                | 97             | NA         | 100            | None         |
| Kabak et al. [13]             | 2004 | 33  | 39.3/43.6        | 44.2               | NA                      | NA             | 14.8/6.7   | 100/87.5       | 6            |
| O’Conner [24]                 | 2004 | 24  | 38               | 42.1               | 14 vs. 10               | NA             | *          | 92             | 2            |
| Endrizzi et al. [7]           | 2008 | 45  | 38.7             | NA                 | NA                      | NA             | 14.6       | 93             | 3            |
| Khan et al. [16]              | 2008 | 11  | NA               | 36                 | 4 vs. 5                 | NA             | 24         | 100            | 2            |
| Huang et al. [11]             | 2009 | 21  | 32               | 65.7               | 17 vs. 4                | 91             | NA         | 100            | 1            |
| Baker et al. [1]              | 2010 | 15  | 39               | 12                 | NA                      | NA             | 14.5       | 100            | None         |
| Stufkens et al. [30]          | 2010 | 21  | 48.2             | 30                 | NA                      | NA             | 22.8       | 100            | 2            |
| Faraud et al. [8]             | 2014 | 21  | 47               | 41                 | 16 vs. 5                | 84             | 17         | 90             | 6            |
| Beirer et al. [2]             | 2017 | 11  | 44               | 27                 | NA                      | NA             | 82         | 100            | 1            |
| Rollo et al. [26]             | 2017 | 57  | 35               | 42                 | 35 vs. 22               | NA             | 16.7       | 98             | 1            |
| Chen W. et al. [4]            | 2018 | 17  | 44               | 38.5               | 8 vs. 9                 | 75.5           | 19.9       | 100            | None         |
| Marsalli et al. [19]          | 2019 | 14  | 44.9             | 77                 | NA                      | 87.5           | NA         | 86             | 2            |

NA not available

*No single value stated

Practical conclusion

- Operative treatment for clavicular nonunion with iliac bone grafting and plate fixation is a well-established and safe procedure.
- Radiographic union and good functional outcomes can regularly be achieved.
- Our study showed that this also applies to an older patient cohort.
- In order to compare outcomes between initial conservative and operative treatment, significantly larger cohorts are needed.

Corresponding address

Dr. med. Philipp A. Michel, M.Sc.
Department of Trauma, Hand and Reconstructive Surgery,
University Hospital Münster
Waldeyer Str. 1, 48149 Münster, Germany
Philipp.Michel@ukmuenster.de

Funding. Open Access funding provided by Projekt DEAL.

Compliance with ethical guidelines

Conflict of interest. P.A. Michel, B. Schliemann, M.J. Raschke, J.C. Katthagen, L.F. Heilmann, F. Dyrska, F. Sax, M. Warnhoff, H. Lill and R.-O. Dey Haza declare that they have no competing interests.

All procedures performed in studies involving human participants or on human tissue were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975 (in its most recently amended version). The ethics committee of the Westfälische Wilhelms University (2019-159-F-S) as well as the ethics committee of the medical school of Hannover (8688_BO_5, 2019) approved the study. Informed consent was obtained from all individual participants included in the study.

Open Access. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. Baker JF, Mullet H (2010) Clavicle non-union: autologous bone graft is not a necessary augment to internal fixation. Acta Orthop Belg 76(6):725–729
2. Beirer M, Banke U, Harrasser Net al (2017) Mid-term outcome following revision surgery of clavicular non- and malunion using anatomic locking compression plate and iliac crest bone graft. BMC Musculoskelet Disord 18:129
3. Bradbury N, Hutchison J, Hahn D et al (1996) Clavicular nonunion. 31/32 healed after plate fixation and bone grafting. Acta Orthop Scand 67:367–370
4. Chen W, Tang K, Tao X et al (2018) Clavicular non-union treated with fixation using locking compression plate without bone graft. J Orthop Surg Res 13:317
5. Court-Brown CM, Caesar B (2006) Epidemiology of adult fractures: a review. Injury 37:691–697
6. Ebrahaim NA, Mekhail AO, Darwich M (1997) Open reduction and internal fixation with bone grafting of clavicular nonunion. J Trauma 42:701–704
7. Endrizzi DP, White RR, Babkian GM et al (2008) Nonunion of the clavicle treated with plate fixation: a review of forty-seven consecutive cases. J Shoulder Elbow Surg 17:951–953
8. Faraud A, Bonneville N, Allavena C et al (2014) Outcomes from surgical treatment of middle-third clavicle fractures non-union in adults: a series of 21 cases. Orthop Traumatol Surg Res 100:171–176
9. Guerra E, Previtali D, Tamborini S et al (2019) Midshaft clavicle fractures: surgery provides better results as compared with nonoperative treatment: a meta-analysis. Am J Sports Med 47:3541–3551
10. Herteleer M, Hoekstra H, Nijs S (2018) Diagnosis and treatment of clavicular fractures in Belgium between 2006 and 2015. J Shoulder Elbow Surg 27:1512–1518
11. Huang TL, Lin FH, Hsu HC (2009) Surgical treatment for non-union of the mid-shaft clavicle using...
a reconstruction plate: scapular malposition is related to poor results. Injury 40:231–235
12. Jarvis NE, Halliday L, Sinnott M et al (2018) Surgery for the fractured clavicle: factors predicting nonunion. J Shoulder Elbow Surg 27:e155–e159
13. Kabak S, Halici M, Tunec M et al (2004) Treatment of midclavicular nonunion: comparison of dynamic compression plating and low-contact dynamic compression plating techniques. J Shoulder Elbow Surg 13:396–403
14. Katolik LI, Romeo AA, Cole BJ et al (2005) Normalization of the constant score. J Shoulder Elbow Surg 14:279–285
15. Katthagen JC, Schliemann B, Michel PA et al (2019) Clinical application and outcomes of upper extremity double plating. Z Orthop Unfall. https://doi.org/10.1055/a-0862-1070
16. Khan SA, Shamshery P, Gupta V et al (2008) Locking compression plate in long standing clavicular nonunions with poor bone stock. J Trauma 64:439–441
17. Kukkonen J, Kauko T, Vahlberg T et al (2013) Investigating minimal clinically important difference for constant score in patients undergoing rotator cuff surgery. J Shoulder Elbow Surg 22:1650–1655
18. Lenza M, Buchbinder R, Johnston RV et al (2019) Surgical versus conservative interventions for treating fractures of the middle third of the clavicle. Cochrane Database Syst Rev 1:CD9363
19. Marsalli M, Rojas JT, Barahona M (2019) Acute surgery vs. non-union surgery of displaced midshaft clavicle fractures: a case-control study. Cureus 11:e5480
20. Martetschläger F, Gaskill TR, Millett PJ (2013) Management of clavicle nonunion and malunion. J Shoulder Elbow Surg 22:862–868
21. McKnight B, Heckmann N, Hill JR et al (2016) Surgical management of midshaft clavicle nonunions is associated with a higher rate of short-term complications compared with acute fractures. J Shoulder Elbow Surg 25:1412–1417
22. Michel PA, Katthagen JC, Heilmann LF et al (2019) Biomechanics of upper extremity double plating. Z Orthop Unfall. https://doi.org/10.1055/a-0862-6334
23. Nordqvist A, Petersson C (1994) The incidence of fractures of the clavicle. Clin Orthop Relat Res 300:127–132
24. O’Connor D, Kutsy S, McCabe JP (2004) Long-term functional outcome assessment of plate fixation and autogenous bone grafting for clavicular nonunion. Injury 35:575–579
25. Olsen BS, Vaesel MT, Soejbjerg JD (1995) Treatment of midshaft clavicular nonunion with plate fixation and autologous bone grafting. J Shoulder Elbow Surg 4:337–344
26. Rollo G, Vicenti G, Rotini R et al (2017) Clavicle aseptic nonunion: is there a place for cortical allogenic strut graft? Injury 48:560–565
27. Schneider F, Bransford R, Harvey E et al (2019) Operative treatment of displaced midshaft clavicle fractures: has randomised control trial evidence changed practice patterns? BMJ Open 9:e31118
28. Schnetzke M, Morbitzer C, Aytaç S et al (2015) Additional bone graft accelerates healing of clavicle non-unions and improves long-term results after 8.9 years: a retrospective study. J Orthop Surg Res 10:2
29. Smeeming DPJ, van der Ven DJC, Hiebrink F et al (2017) Surgical versus nonsurgical treatment for midshaft clavicle fractures in patients aged 16 years and older: a systematic review, meta-analysis, and comparison of randomized controlled trials and observational studies. Am J Sports Med 45:1937–1945
30. Stufkens SA, Koen P (2010) Treatment of midshaft clavicular delayed and non-unions with anteroinferior locking compression plating. Arch Orthop Trauma Surg 130:159–164
31. Wentz S, Eberhardt C, Leonhard T (1999) Reconstruction plate fixation with bone graft for mid-shaft clavicular non-union in semi-professional athletes. J Orthop Sci:269–272
32. Woltz S, Stegeman SA, Krijnen P et al (2017) Plate fixation compared with nonoperative treatment for displaced midshaft clavicular fractures: a multicenter randomized controlled trial. J Bone Joint Surg Am 99:106–112
33. Zlowodzki M, Zelle BA, Cole PA et al (2005) Treatment of acute midshaft clavicle fractures: a case-control study. J Orthop Trauma 19:504–507