Article

Efficacy of Open Reduction and Internal Fixation Assisted by Handheld Ultrasound Combined with 3D Printing Technology in Treating Multiple Rib Fractures

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AIM: This study aimed to explore the efficacy of open reduction and internal fixation assisted by handheld ultrasound combined with three-dimensional (3D) printing technology in treating multiple rib fractures.
METHODS: We retrospectively analyzed the clinical data from 84 patients affected with multiple rib fractures admitted to our hospital between August 2022 and April 2024. After excluding four cases, 80 cases were included in this study. Based on the method of preoperative rib fracture localization, patients were divided into three groups: group A (n = 30), group B (n = 26), and group C (n = 24). Group A received 3D reconstruction of ribs on chest Computed Tomography (CT), group B adopted the examination of handheld ultrasound and 3D reconstruction of ribs on chest CT, and group C received handheld ultrasound, 3D reconstruction of ribs on chest CT, and 3D printing technology. The operation-related indicators (such as incision length, exposure time of surgical field, intraoperative blood loss), pulmonary function [total lung capacity (TLC), forced vital capacity (FVC), forced expiratory volume in one second/forced vital capacity (FEV1/FVC), residual volume (RV)], quality of life, degree of pain, and incidence of complications were compared among the three groups.
RESULTS: Before surgery, there were no significant differences in pulmonary function, quality of life, and degree of pain among the three groups ($p > 0.05$). However, after surgery, significant differences in the pairwise comparison of TLC, FVC, FEV1/FVC and RV were observed among the three groups ($p < 0.001$), with group C indicating the highest levels of observational indicators and group A exhibiting the lowest levels. Furthermore, a significant difference was observed in the pairwise comparison of incision length, exposure time of surgical field, and intraoperative blood loss among the three groups ($p < 0.001$). Group C had the shortest incision length, the lowest exposure time in the surgical field, and the least intraoperative blood loss, while those in group A were the opposite. After surgery, a significant difference was found in the pairwise comparison of the quality of life and degree of pain among the three groups ($p < 0.001$). Group C had the highest quality of life and the lowest degree of pain, while Group A had the opposite results. Additionally, there was no significant difference in the incidence of complications among the three groups ($p > 0.05$).
CONCLUSIONS: The open reduction and internal fixation assisted by handheld ultrasound combined with 3D printing technology revealed effective curative outcomes in treating multiple rib fractures. This method promotes the formulation of an accurate and personalized surgical plan and seems to have high clinical significance.

Keywords: ultrasonography; fracture fixation, internal; rib fractures; 3D printing technology

Introduction

A rib fracture is a common injury associated with higher morbidity and mortality rates [1]. Multiple rib fractures, often resulting from falls, motor vehicle accidents, and deceleration events, is a severe form of chest trauma. Approximately 15% of patients with blunt trauma experience multiple transverse rib fractures, with 25% of the associated morbidity and mortality rates [2,3]. Complications associated with multiple rib fractures, including atelectasis, severe pain, pneumonia, and respiratory failure, can affect the pulmonary function and long-term recovery of patients, and prolong the length of stay in the intensive care units [4,5]. Open reduction and internal fixation provide a practical treatment approach for multiple rib fractures, enhancing anatomical reduction, improving functional outcomes, and decreasing complication rates [6,7].

Accurate rib fracture localization before surgery is crucial for determining the surgical incision, which significantly affects the success of open reduction and internal fixation [8]. Three-dimensional (3D) reconstruction of ribs using chest Computed Tomography (CT) is commonly used in clinical practice to localize fracture sites. Physicians usually rely on this information to determine the location of

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incisions and formulate surgical strategies accordingly [9]. However, rib positioning can shift between the initial imaging and the time of surgery, leading to suboptimal incision placement and extended operation time [10]. Therefore, additional preoperative methods for rib fracture localization are required to improve the accuracy of surgical planning.

Ultrasonography can help diagnose and evaluate the severity of the fracture while also guiding treatment strategies [11]. This approach is adaptable for use by operators with different levels of experience across diverse clinical settings. Technological advancements have improved the diagnostic capabilities of fixed ultrasound systems and resulted in their miniaturization [12]. Handheld ultrasound devices are now widely recognized in emergency care settings, although their significance for fracture management has yet to be fully explored [13]. Moreover, 3D printing technology, which generates personalized 3D objects based on computer-aided digital designs, is an advanced manufacturing method [14]. However, its application in the preoperative planning of rib fractures remains limited [15]. Therefore, this study investigates handheld ultrasound combined with 3D printing technology for open reduction and internal fixation of multiple rib fractures, aiming to assess the efficacy and provide valuable insights for clinical practice.

Materials and Methods

Research Subjects

We retrospectively analyzed the clinical data of 84 patients with multiple rib fractures admitted to our hospital between August 2022 and April 2024. After excluding 4 cases, 80 cases were finally included in the study. Based on the method of preoperative rib fracture localization, patients were divided into three groups: group A (n = 30), group B (n = 26), and group C (n = 24). Informed consent was obtained from each study participant, and the study design adhered to the guidelines of the Declaration of Helsinki [16]. Before this study, all participants were informed about its purpose, procedures, and potential benefits. Participants were allowed to ask questions about this study. Participants fully understood the study procedure and voluntarily signed the informed consent form. For those unable to provide written consent, oral consent was obtained, recorded and confirmed by independent witnesses. Additionally, this study strictly adhered to all relevant privacy protection regulations and institutional policies to ensure the confidentiality of study participants' personal information and research data. The data were stored and analyzed anonymously to protect participants' privacy. This study has been approved by the medical ethics committee of Mindong Hospital Affiliated to Fujian Medical University (approval No.: 2021111808K). All eligible participants signed an informed consent form.

The inclusion criteria were set as follows: (1) Patients' clinical symptoms, physical signs, and preoperative examinations met the diagnostic criteria for multiple rib fractures [17]. (2) Patients had complete clinical data. (3) Patients were between 18–80 years of age. (4) Patients had a normal mental state.

Exclusion criteria included: (1) Patients were allergic to metal. (2) Patients had preoperative thoracic infection or sepsis. (3) Patients had abdominal organ injury. (4) Patients had high-level spinal cord injury, traumatic brain injury and other trauma not suitable for surgery. (5) Patients had coagulation dysfunction.

Preoperative Localization Procedures

Based on different preoperative localization methods employed in three groups, physicians assessed the surgical incision and formulated the surgical plan. Group A adopted 3D reconstruction of ribs from chest CT scans, group B received the handheld ultrasound combined with 3D reconstruction of ribs from chest CT, and group C utilized handheld ultrasound, 3D reconstruction of ribs from chest CT, along with 3D printing technology. The details are outlined as follows.

During the 3D reconstruction of ribs from chest CT, a 64-slice spiral CT scanner (Brilliance nano-CT 64 slices, Philips (China) Investment Co., Ltd., Shanghai, China) was used. Patients were positioned supine, and a volume scan was performed from head to foot after a single breath hold, capturing all ribs. The scanning parameters were set as follows: tube voltage at 120 KV, tube current at 160–250 mA, pitch at 1.375:1, layer thickness at 1 mm, and reconstruction interval of 0.5 mm. The thin-layer images were processed using volume rendering, surface reconstruction, and multiplane reconstruction, as shown in Fig. 1.

In 3D printing technology, Digital Imaging and Communications in Medicine (DICOM) files obtained from the 3D reconstruction of ribs on chest CT were imported into the Mimics system (Version: 19.0; Lot number: 20190110923, Materialise Shanghai Co., Ltd., Shanghai, China). A 1:1 scale 3D physical model was printed employing Stereolithography Apparatus (Model: BIO3D600; Shanghai Black Flame Medical Technology Co., Ltd.; Shanghai, China). Preoperative fracture localization and incision optimization were as conducted as follows. (1) Preoperative surgical rehearsal was performed *in vitro*, where the appropriate rib bone plate was selected based on the measured data, and surgical fixation was previewed on the model to formulate a surgical plan. (2) Standards of incision design were established, and incision sites were optimized. Before surgery, medical staff marked the fracture ends and rib spaces at their bedside to assess the optimal approach for surgical incision. They considered the most exposed regions of the fracture while aiming to minimize the total length of the incision. The details are shown in Fig. 2.

Furthermore, before CT 3D reconstruction of ribs, patients underwent preliminary assessment using a handheld ultrasound device (Model: H33C; Lot number: 2020061337, Chengdu Stork Healthcare Co., Ltd.; Chengdu, China).

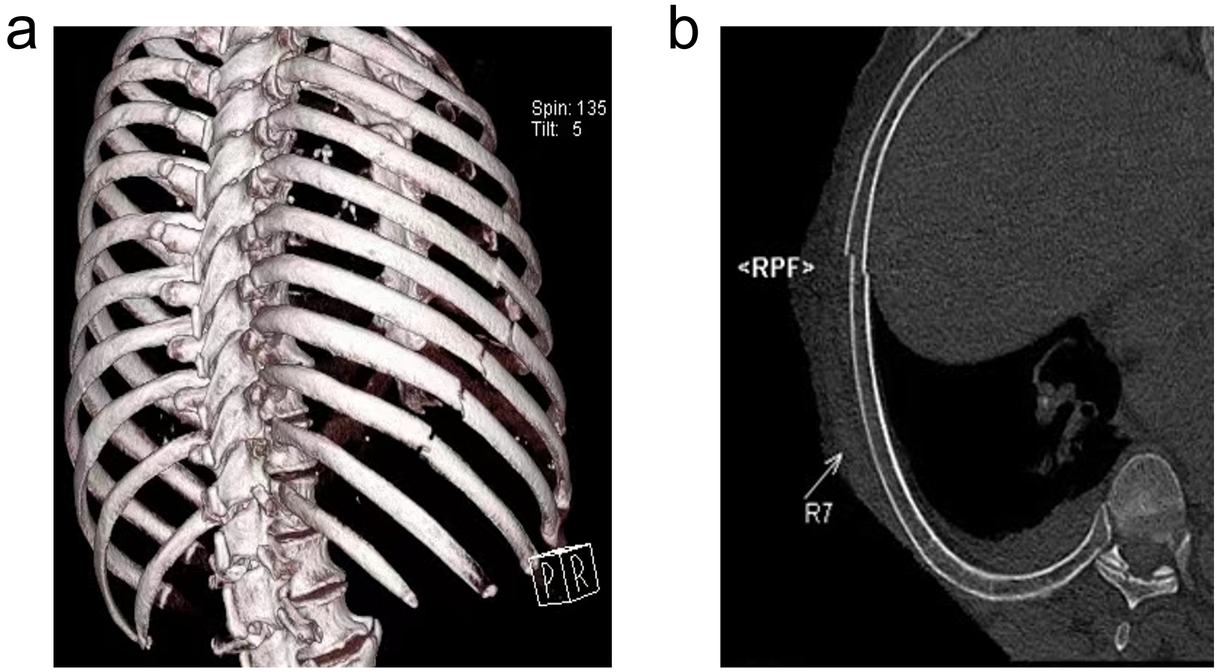

Fig. 1. Preoperative CT three-dimensional (3D) reconstruction of the ribs. (a) indicates multiple right-sided rib fractures and thoracic deformity, and (b) shows marked dislocation of the fractured sites of the ribs (Right Seventh rib). P, Posterior; R, Right; RPF, Right Principal Head Coordinate System; R7, Seventh rib; CT, Computed Tomography.

During this procedure, patients were positioned to avoid causing secondary injury or aggravating pain while maximizing chest exposure. A coupling agent was applied to the patient's skin, and the probe was placed directly on the chest. The probe was scanned sequentially from the back to the front along the long axis of the ribs. If a fracture was identified, medical staff marked its location and observed the surrounding soft tissues. The long axis of a normal rib cortex showed a continuous, smooth, strong echo in a linear shape, while the short axis showed a constant, circular, strong echo, accompanied by an acoustic shadow behind it. The sonogram of a rib fracture indicated continuous interruption, dislocation, and separation of the strong linear echo in the long axis of the cortical bone. The sonogram clearly showed the width of the separation at the fracture site, as well as interruptions and overlaps of the arc's strong echo in the short axis. Some patients had localized soft tissue thickening at the fracture site, with low echo areas visible in the subcutaneous and intercostal muscles, as detailed in Fig. 3.

Surgical Approaches

Patients were treated with tracheal intubation and general anesthesia. They were positioned lying on their healthy side, and their shoulder and back were cushioned high, with the upper limb on their healthy side being abducted. Routine disinfection was performed. Following the preoperative assessment of the surgical incision approach, incisions were made through the patients' skin, subcutaneous tissue, surrounding free flap, and muscle layer to expose the fracture ends. The periosteum was properly peeled off, and the fractured ends were grasped with a towel clamp to achieve anatomical reduction. Rib bone plates corresponding to the preoperative records were selected and immersed in sterile physiological saline at 0–5 °C for 2–3 minutes.

Furthermore, the embracing arm was gradually stretched using a distractor to create an opening larger than the transverse diameter of the ribs. The embracing device was then quickly removed and placed at the fracture site. Sterile gauze was soaked in saline at 40–50 °C and applied externally. The embracing arm promptly returned to its original position, achieving the goal of compression and internal fixation. Medical staff checked the stability of the embracing device, and the remaining ribs were exposed for reduction and internal fixation utilizing the same method. Once the embracing device was fixed, hemostasis was achieved at the incision site. The wound was then irrigated with normal saline and closed in layers. A closed thoracic drainage tube was also inserted. The details of the procedure are shown in Fig. 4.

Patients in all three groups received vital signs monitoring, oxygen inhalation, atomization for expelling phlegm, pain management, routine disinfection of incisions, and change of medicines. Patients were instructed to cough, expel phlegm, and mobilize early by getting out of bed. The imaging examinations were performed two weeks after surgery. The procedure is shown in Fig. 5.

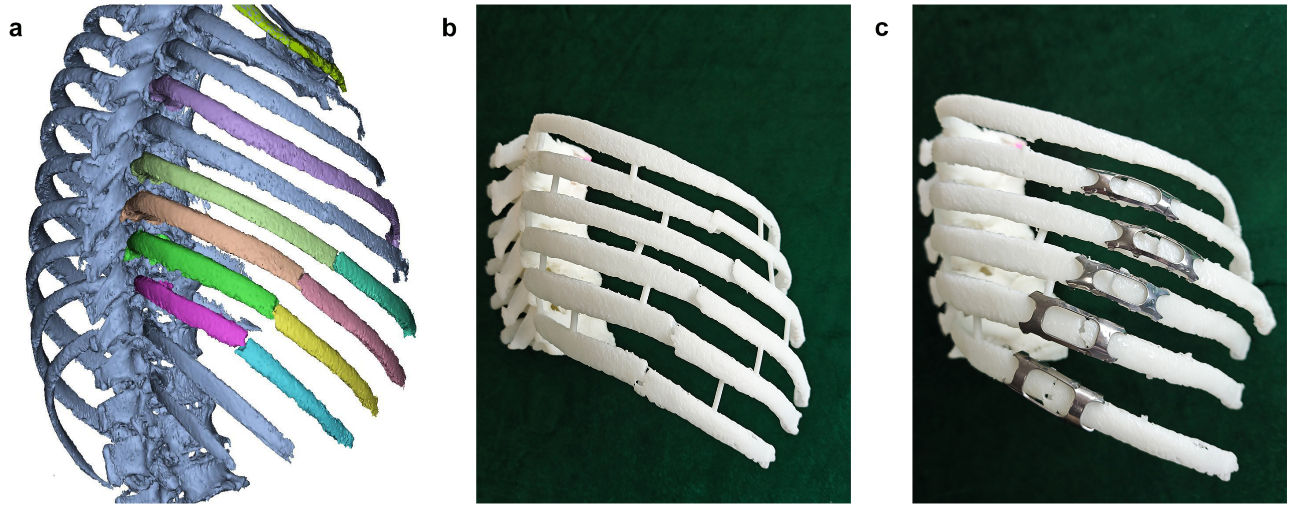

Fig. 2. Printing of a 1:1 3D physical model. (a–c) show the printing of a 1:1 3D physical model, indicating rib plate *in vitro* bonding.

Observational Indicators

The observational indicators assessed during this study were as follows:

(1) Surgical indicators: The length of the incision, exposure time of the surgical field, and intraoperative blood loss were documented and compared among the three groups.

(2) Pulmonary function indicators: The total lung capacity (TLC) (normal range: male: 5000 mL, female: 3500 mL), forced vital capacity (FVC) normal range: male (3179 $\pm$ 117) mL, female (2314 $\pm$ 48) mL, forced expiratory volume in one second/forced vital capacity (FEV1/FVC) (normal range: >70%), and residual volume (RV) (normal range: 1000–1500 mL) were assessed and compared among three groups before surgery and 10 days after surgery [18].

(3) Thoracic Trauma Severity: The severity of thoracic trauma in patients was assessed using the Thoracic Trauma Severity Score (TTSS). The TTSS consists of five key parameters: rib fracture, pulmonary contusion, PaO_2/FiO_2 ratio, age, and pleural involvement. Each parameter was scored on a scale ranging from 0 to 5, resulting in a total score ranging from 0 to 25. The TTSS was calculated by summing the scores of these five parameters, with a higher total score indicating a higher severity of thoracic trauma [19].

(4) Quality of life: The quality of life of patients was evaluated using the Generic Quality of Life Inventory-74 (GQOLI-74) [20] before surgery and 10 days after surgery. The scale included four dimensions: physical function (5 factors), psychological function (5 factors), social function (5 factors), and material life status (4 factors). Additionally, this scale included an overall quality of life factor, totaling 20 items, with a scoring range of 80 to 400 points. The formula for converting to a 0–100-point scale is: (total rough score – 80) $\times$ 100/320. A higher total score indicates a better quality of life for the patients.

(5) Pain score: The Visual Analogue Scale (VAS) [21] was utilized to evaluate the pain levels before surgery and 10 days after surgery. The VAS consists of a 10 cm horizontal line, with a segment of 0 cm indicating no pain and the other end of 10 cm representing extreme pain. The intensity of pain gradually increases along the line from 0 to 10 points. A higher score indicates that patients had more severe pain.

(6) Incidence of complications: The incidences of complications, including rib plate loosening, traumatic pneumothorax, pleural effusion, atelectasis or pneumonia, and rib collapse, were documented and compared among the three groups.

Statistical Analysis

The clinical data were analyzed using SPSS 26.0 software (International Business Machines Corporation; Armonk, NY, USA). The enumeration data were expressed as [n (%)], and the corresponding statistical tests were applied based on the characteristics of the data. (1) Fourfold table test: (i) When all theoretical numbers T $\geq$5 and the total sample size n $\geq$40, the Pearson chi-square test was used. (ii) If the theoretical number 1 $\leq$ T $<$ 5, and n $\geq$40, the chi-square test with continuity correction was used. (iii) If the theoretical number T <1 or n <40, Fisher's exact test was applied. (2) R $\times$ C table test: If cells with a theoretical number were less than 5 and constituted $\leq$20% of the total, or if T $\geq$1, the Pearson chi-square test was used. If cells with a theoretical number less than 5, constituted >20% of the total, or if T <1, Fisher's exact test was applied. Fisher's exact test for 2 $\times$ 2 tables with expected cells of less than 5, and Fisher-Freeman-Halton test for R $\times$ C tables with expected cells of less than 5. The Shapiro-Wilk test determined whether measurement data followed a normal distribution. The data conforming to normal distribution were expressed as mean $\pm$ standard deviation. Variance analysis was performed to assess the differences among multiple sets of variables, indicated by F value. The N-K test method was adopted for pairwise comparison within groups. However, data that did not conform to normal distribution were

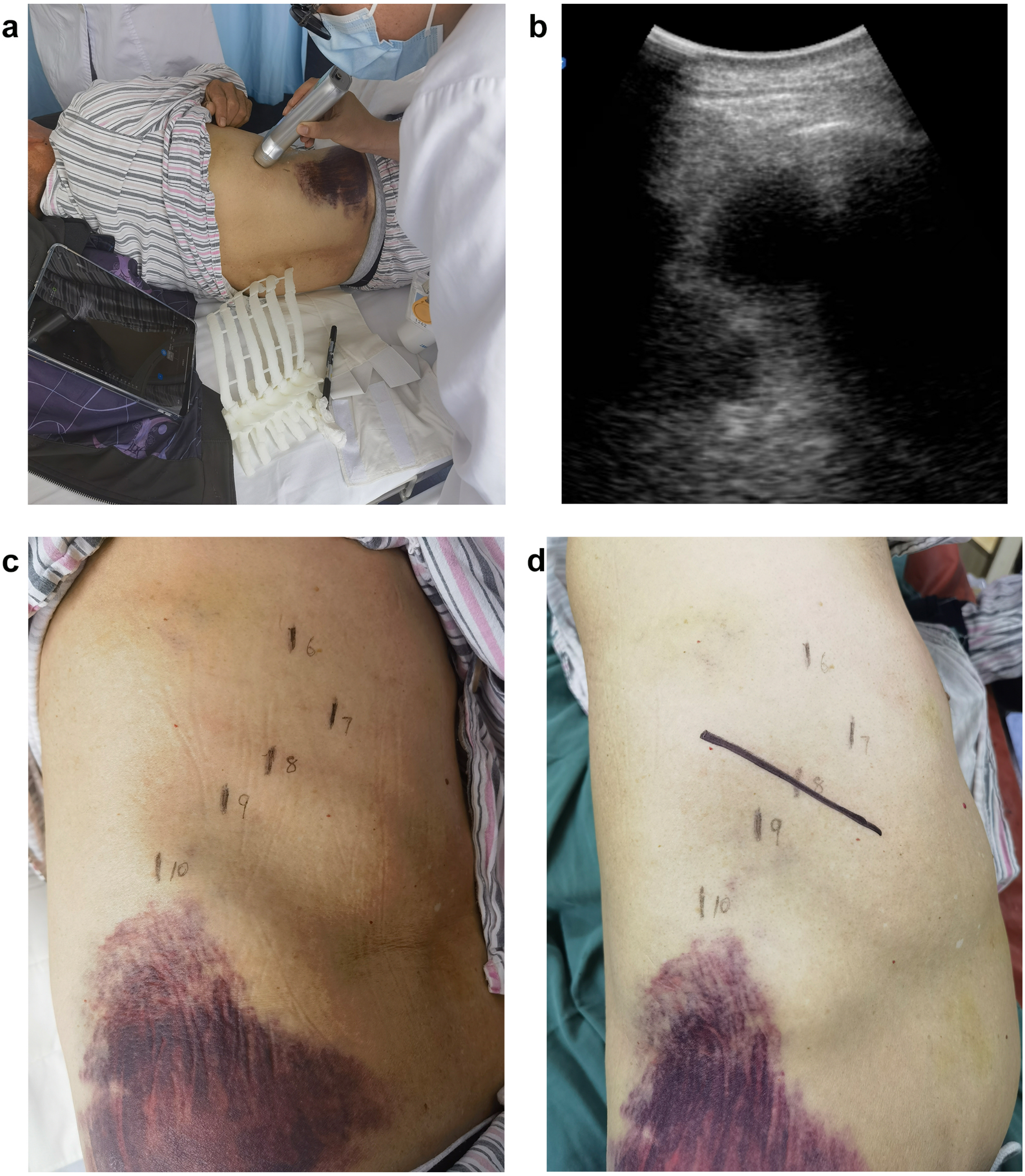

Fig. 3. Preoperative planning approach. (a–d) show preoperative planning approach of handheld ultrasound localization of fracture sites. The 6, 7, 8, 9, and 10 in (c,d) represent the 6th, 7th, 8th, 9th, and 10th ribs, respectively.

expressed as M (P_{25}, P_{75}). Kruskal-Wallis test evaluated differences among multiple sets of variables, with results expressed by the H value. The Bonferroni method was used for pairwise comparison within groups. A $p < 0.05$ indicated a statistically significant difference.

Results

Comparison of Baseline Characteristics among the Three Groups

There was no significant difference regarding age, sex, body mass index (BMI), and other baseline data among the three groups ($p > 0.05$). A comparison of baseline characteristics among the three groups is shown in Table 1.

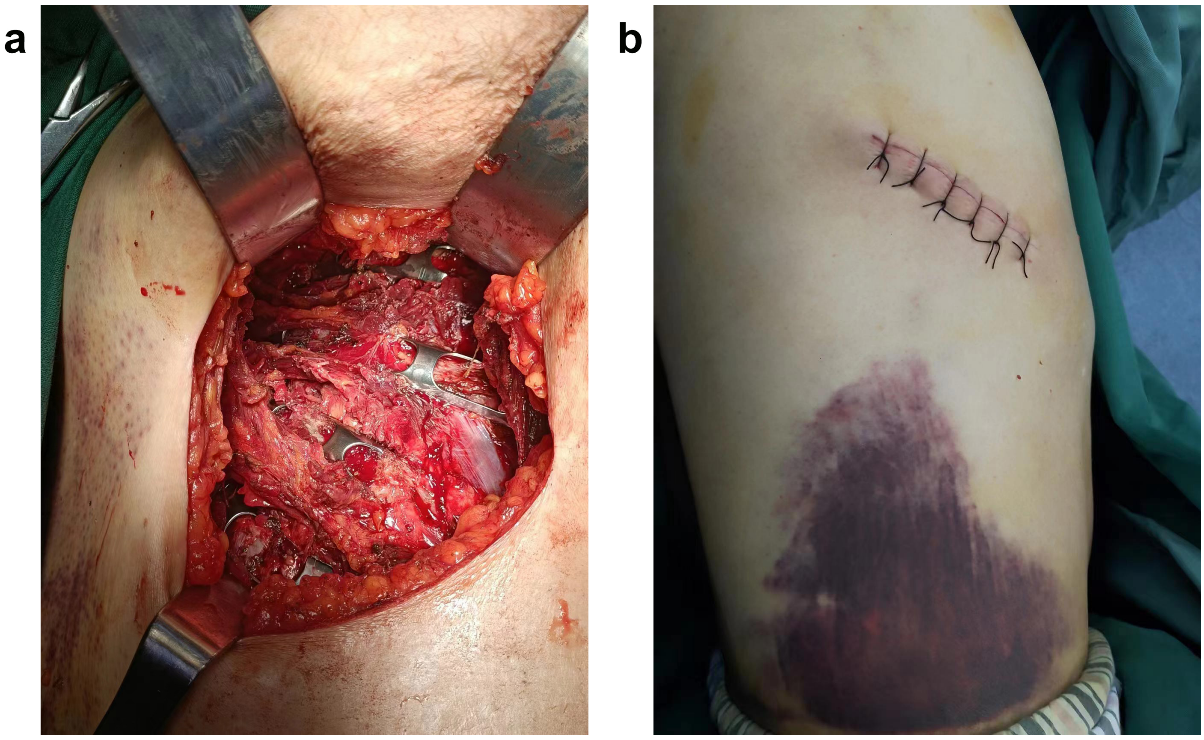

Fig. 4. Open reduction and internal fixation. (a,b) These figures show open reduction and internal fixation.

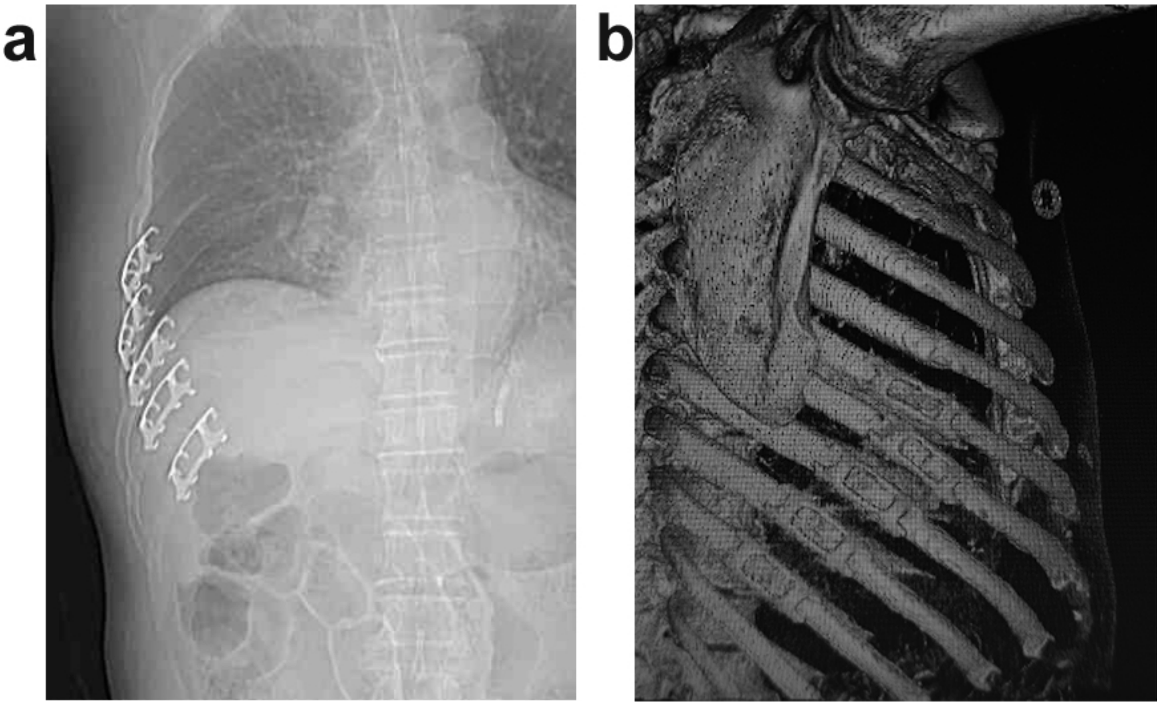

Fig. 5. Chest X-ray of postoperative reexamination. (a,b) These figures indicate chest X-ray of postoperative reexamination. CT shows no loosening of the rib plate, no deformity of the thorax, and stable chest wall.

Comparison of Surgical Indicators among the Three Groups

There was a significant difference in the pairwise comparison of incision length, exposure time of surgical field, and intraoperative blood loss among the three groups ($p <$ 0.001). Group C had the shortest incision length, the least exposure time in the surgical field, and the lowest intraoperative blood loss. In contrast, group A demonstrated the opposite results, as detailed in Table 2.

Table 1. Comparison of baseline characteristics among the three groups [M (P_{25}, P_{75}), n (%)].

Variables	Group A (n = 30)	Group B (n = 26)	Group C (n = 24)	χ^2/H	p-value
Age [years old, M (P_{25}, P_{75})]	47.00 (40.00, 58.00)	44.00 (30.75, 56.00)	48.00 (36.00, 55.50)	1.339	0.512
Sex				0.142	0.932
Male	19 (63.33)	16 (61.54)	14 (58.33)		
Female	11 (36.67)	10 (38.46)	10 (41.67)		
BMI [kg/m^2, M (P_{25}, P_{75})]	21.60 (19.10, 22.48)	21.45 (20.10, 22.83)	20.90 (18.95, 22.23)	1.752	0.416
Causes of fracture				0.251	0.993
Traumatic factors	18 (60.00)	15 (57.69)	14 (58.33)		
Pathological factors	6 (20.00)	5 (19.23)	4 (16.67)		
Aging factors	6 (20.00)	6 (23.08)	6 (25.00)		
Number of rib fractures [number, M (P_{25}, P_{75})]	5.50 (3.75, 8.00)	6.50 (5.00, 9.00)	5.50 (4.00, 8.00)	2.821	0.244
Sites of fracture				0.054	0.973
Unilateral	13 (43.33)	12 (46.15)	11 (45.83)		
Bilateral	17 (56.67)	14 (53.85)	13 (54.17)		
TTSS [points, M (P_{25}, P_{75})]	18.00 (14.00, 19.00)	16.50 (15.00, 18.25)	18.00 (15.25, 20.00)	1.724	0.422

BMI, body mass index; TTSS, Thoracic Trauma Severity Score.

Table 2. Comparison of surgical indicators among the three groups [M (P_{25}, P_{75})].

Variables	Group A (n = 30)	Group B (n = 26)	Group C (n = 24)	H	p-value
Length of incision (cm)	8.50 (8.00, 9.25) *	7.00 (6.00, 8.00) §	4.00 (3.25, 6.00) ‡	57.408	<0.001
Exposure time of surgical field (min)	124.00 (117.75, 132.00) *	106.00 (97.50, 114.50) §	95.00 (89.00, 100.75) ‡	50.237	<0.001
Intraoperative blood loss (mL)	216.00 (201.75, 227.25) *	184.00 (165.25, 200.50) §	142.00 (116.50, 155.50) ‡	57.763	<0.001

* indicates a significant difference between group A and group B ($p < 0.05$). ‡ shows a significant difference between group A and group C ($p < 0.001$). § indicates a significant difference between group B and group C ($p < 0.01$).

Comparison of Pulmonary Function in the Three Groups

Before surgery, there were no substantial differences in the TLC, FVC, FEV1/FVC, and RV levels among the three groups ($p > 0.05$). However, after surgery, significant differences were found in the pairwise comparison of TLC, FVC, FEV1/FVC, and RV levels among the three groups ($p < 0.001$), with group C showing the highest levels and group A exhibiting the lowest levels. A comparison of pulmonary function indicators is shown in Table 3.

Comparison of Quality of Life and Pain Levels among the Three Groups

Before surgery, there were no significant differences in the quality of life and pain levels among the three groups ($p > 0.05$). However, after surgery, a significant difference was observed in the pairwise comparison of the quality of life and pain levels among the three groups ($p < 0.001$), with group C exhibiting the highest quality of life and the lowest degree of pain and group A demonstrating the lowest quality of life and the highest degree of pain. The comparison of quality of life and pain levels is detailed in Table 4.

Comparison of the Incidence of Complications among the Three Groups

There were no significant differences in the incidence of complications among the three groups ($p > 0.05$), as detailed in Table 5.

Discussion

This study explored the efficacy of open reduction and internal fixation assisted by handheld ultrasound combined with 3D printing technology in treating multiple rib fractures. By comparing the observational indexes across different groups, it was observed that group C had the shortest length of incision, the shortest exposure time of surgical field, and the least intraoperative blood loss, followed by group B and group A. Group C also showed the best quality of life and pulmonary function, followed by group B and group A. Furthermore, group C had the lowest degree of pain, followed by group B and group A. By comparing the effects of groups A and B, the study found that handheld ultrasound may provide an auxiliary benefit in open reduction and internal fixation. Moreover, the comparison between group B and group C suggested that open reduction and internal fixation assisted by 3D printing technology seemed to have a significant positive impact. Analyzing these two auxiliary methods can offer valuable insights that can contribute to the clinical improvement of surgical procedures.

Compared to traditional ultrasound machines, handheld ultrasound offers advantages, like portability, cost-effectiveness, and clear imaging quality, rendering it convenient for rapid diagnosis and management. Therefore, this allows medical staff to diagnose and locate rib fractures without repositioning patients [22]. For patients with multiple rib fractures, especially those with Posterior rib frac-

Table 3. Comparison of pulmonary function indicators among the three groups [M (P_{25}, P_{75})].

Variables	Time	Group A (n = 30)	Group B (n = 26)	Group C (n = 24)	H	*p*-value
TLC (mL)	Before surgery	2266.50 (2102.75, 2432.75)	2320.00 (2129.25, 2381.25)	2315.00 (2067.00, 2416.00)	0.025	0.988
	After surgery	2584.50 (2508.25, 2693.50)	2750.00 (2606.75, 2895.00)	2966.00 (2888.00, 3104.00)	47.620	<0.001
FVC (mL)	Before surgery	1227.50 (1090.00, 1316.00) *	1280.50 (1188.75, 1394.50) §	1266.00 (1107.75, 1406.00) ‡	1.934	0.380
	After surgery	1500.00 (1404.50, 1645.50) *	1676.00 (1577.75, 1750.25) §	1754.50 (1631.50, 1835.00) ‡	31.645	<0.001
FEV1/FVC (%)	Before surgery	44.50 (42.75, 47.25)	44.00 (42.00, 48.00)	45.00 (43.25, 49.75)	0.987	0.610
	After surgery	48.00 (45.75, 51.00)	54.50 (52.00, 58.00)	71.50 (67.00, 73.00)	63.115	<0.001
RV (mL)	Before surgery	507.00 (476.50, 532.25) *	505.50 (473.25, 525.75) §	503.00 (480.50, 538.25) ‡	0.475	0.796
	After surgery	547.50 (525.50, 572.75) *	599.00 (576.75, 630.00) §	744.50 (669.50, 813.00) ‡	57.352	<0.001

TLC, total lung capacity; FVC, forced vital capacity; FEV1/FVC, forced expiratory volume in one second/forced vital capacity; RV, residual volume. * indicates a significant difference between group A and group B ($p < 0.05$). ‡ shows a significant difference between group A and group C ($p < 0.001$). § indicates a significant difference between group B and group C ($p < 0.01$).

Table 4. Comparison of quality of life and degree of pain among the three groups [M (P_{25}, P_{75})].

Parameters	Time	Group A (n = 30)	Group B (n = 26)	Group C (n = 24)	H	*p*-value
GQOLI-74	Before surgery	36.50 (32.00, 38.25)	37.00 (35.25, 38.25)	36.00 (32.00, 38.00)	0.651	0.722
	After surgery	64.50 (57.75, 67.25) *	67.50 (65.75, 70.25) §	75.00 (72.25, 78.00) ‡	50.120	<0.001
VAS	Before surgery	8.00 (8.00, 9.00)	8.00 (7.00, 8.25)	8.00 (7.00, 9.00)	2.899	0.235
	After surgery	7.00 (6.00, 7.25) *	6.00 (5.00, 7.00) §	4.50 (4.00, 5.00) ‡	39.671	<0.001

GQOLI-74, Generic Quality of Life Inventory-74; VAS, Visual Analogue Scale. *indicates a significant difference between group A and B ($p < 0.05$). ‡ shows a significant difference between group A and group C ($p < 0.001$). § indicates a significant difference between group B and group C ($p < 0.01$).

Table 5. Comparison of the incidence of complications among the three groups [n (%)].

Variables	Group A (n = 30)	Group B (n = 26)	Group C (n = 24)	Fisher	*p*-value
Rib plate loosening	0	1 (3.85)	0		
Traumatic pneumothorax	0	0	0		
Pleural effusion	1 (3.33)	0	1 (4.17)		
Atelectasis or pneumonia	4 (13.33)	3 (11.54)	2 (8.33)		
Rib collapse	0	0	0		
Total incidence	5 (16.67)	4 (15.38)	3 (12.50)	0.262	0.928

tures, setting a suitable examination position without anesthetic can be challenging, which may reduce the accuracy of CT localization. However, handheld ultrasound allows for accurate localization and marking on the body surface, offering flexibility and convenience. This method is less affected by respiratory movements and is suitable for patients with multiple injuries [23].

Additionally, ultrasound is effective in diagnosing complications, such as muscle hematoma and vascular injury, addressing the limitation of CT in evaluating muscle injuries and providing valuable information for preoperative surgical planning [24]. Li W *et al.* [25] reported that ultrasound-assisted preoperative localization reduces both operation time and intraoperative bleed loss. Similarly, Martin TJ *et al.* [26] observed that ultrasound-guided rib fracture localization enhances surgical outcomes by reducing incision length and shortening operation time. These observations align with the results of our study.

3D printing technology is becoming commercially feasible and is now used for preoperative planning and intraoperative templates. Patient-specific models generated with 3D printing can improve the accuracy of surgical localization, speed up the surgery, and reduce radiation exposure [27]. There is a known correlation between limb swelling, incision angle, and wound complications after open reduction and internal fixation [28]. The 3D models provide tactile feedback and direct operation, enhancing physicians' understanding of anatomy and basic pathology. Using 3D printing technology in surgery, surgeons can better understand the morphology of fractures and develop more detailed and reliable preoperative plans [29]. The locking plate created with 3D printing technology aligns well with the ribs and sternum, eliminating the need for intraoperative adjustments and substantially reducing the steps of intraoperative fracture reduction. The conventional locking plate, which often needs reshaping during the surgical procedure, increases the risk of tissue damage and complications while increasing operation time [30]. Zhou XT *et al.* [31] reported that using 3D printing technology to make rib models and prefabricated titanium alloy locking plates provides precise and minimally invasive personalized treatment for rib fractures.

Similarly, Hung CC *et al*. [32] indicated that 3D printing technology improves the accuracy of preoperative planning and surgery, reducing both operation time and the incidence of complications in fracture cases. Li K *et al*. [33] showed that 3D-printed models can reduce operation time, promote wound healing, and minimize patient pain and trauma. A prospective randomized controlled study conducted by Wang J *et al*. [34] further validated the significance of 3D printing technology in fracture surgeries, indicating shorter operation time, fewer complications, better quality of fracture healing, and faster functional recovery, making it suitable for clinical application.

However, no substantial difference in the incidence of complications was found among the three groups in this study, which may be attributed to the small sample size and limited number of study subjects.

Despite its promising clinical outcomes, this study has certain limitations. (1) As a retrospective study, the data were extracted from existing records, which may introduce selection bias and limit the ability to infer causality. Future prospective studies are needed to address these limitations. (2) The sample size was restricted by time, manpower, and financial resources, potentially leading to insufficient statistical power. Subsequent studies should include a larger sample size for more effective outcomes. (3) The short follow-up period did not allow for evaluating long-term outcomes. Future studies need to extend the follow-up period to comprehensively evaluate the long-term clinical efficacy of open reduction and internal fixation assisted by handheld ultrasound combined with 3D printing technology in treating multiple rib fractures.

Conclusions

In conclusion, open reduction and internal fixation assisted by handheld ultrasound combined with 3D printing technology have demonstrated ideal curative outcomes in treating multiple rib fractures. This therapeutic method accelerates the rehabilitation of patients, reduces pain and complications, and improves overall quality of life, making it a valuable approach for broader clinical applications.

Availability of Data and Materials

The datasets used and analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

JL and ZL—designed the research study; QC, XX, YZ—performed the research; MZ and DZ— analyzed the data. XX drafted this manuscript. All authors contributed to important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study has been approved by the medical ethics committee of Mindong Hospital Affiliated to Fujian Medical University (approval No.: 2021111808K). All eligible participants signed an informed consent form. Informed consent was obtained from each study participant, and the study design adhered to the guidelines of the Declaration of Helsinki.

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Conflict of Interest

The authors declare no conflict of interest.

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