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A mini hallux neurovascular osteo-onychocutaneous free flap for refined reconstruction of distal defects in thumbs and fingers

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ABSTRACT

Distal injury in thumbs and fingers is common in emergency. Although multiple surgical techniques have been introduced for repair purpose, it is still challenging for restoring both good function and cosmetic appearance. The present study reports our experiences on how to reconstruct amputated fingertips in thumbs and fingers using a mini hallux neurovascular osteo-onychocutaneous free flap with favorable outcomes in 15 patients (average age, 27.27 ± 5.43 years old). Follow-up period was 19.47 ± 10.18 months (range, 6–48 months). Digital function was improved indicated by the static two-point discrimination (2-PD) and key-pinch, which were 8.40 ± 1.64 mm (range, 6–12 mm) and $85.37 \pm 3.03\%$ (range, 80.2–90.6%) of that of the intact contralateral thumbs and fingers, respectively, after surgery. As to aesthetic outcomes, all reconstructed digits were self-graded as *good* by patients. 73.3% of the donor halluces were self-graded as *good* and four halluces (26.7%) were graded as *fair*. In conclusion, the mini hallux neurovascular osteo-onychocutaneous flap may be used for refined reconstruction of type I amputated injury in thumbs and fingers achieving both satisfactory functional and aesthetic outcomes.

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Introduction

Amputations, distal to the distal interphalangeal (IP) joint in thumb and fingers, are common to see but difficult to treat in emergency. In intricate circumstances, initial digital replantation and the 'pocket principle' [1] may not be feasible. Reconstruction becomes the second best for a better hand rehabilitation. The prime principle for reconstruction is 'like-with-like' to restore good functional and aesthetic outcomes [2]. Toe-to-hand transfer for thumb reconstruction was tentatively exploited in rhesus monkey [3] and human [4,5]. In 1980, Morrison et al. introduced a neurovascular wrap-around flap from the big toe and succeeded in reconstructing the shape of thumb [6]. It was modified with aim to preserve more pulp weight-bearing skin [7], produce a more normalized thumb with trimmed-toe transfer [8] and close donor site primarily without additional skin graft [9]. However, opinions differed as to which technique represented the ideal option for different amputation levels [10]. As to reconstruction of thumb defects distal to the distal IP joint, different methods, such as the mini wrap-around flap [11], hallux osteo-onychocutaneous flap [12] and partial-nail preserving transfer [13] were proposed. Among them, the hallux osteo-onychocutaneous flap was further applied to reconstruct the distal defects in fingers [14,15]. Although, the digital defects distal to the distal IP joint do not necessarily cause a dramatic impairment in hand, retaining a more refined thumb and finger function is still very advantageous [13,16]. In this study, the authors introduced a mini neurovascular hallux osteo-onychocutaneous free flap for refined repair of the defects which is distal to the distal IP joints in thumbs and fingers. Though, high level of microsurgical skills is required, the

designed flap enables to be custom-made, precise, less donor morbidity and satisfactory rehabilitation.

Patients and methods

Patients

A retrospective study was conducted on all patients who undergone reconstruction in distal thumbs and fingers using the mini hallux neurovascular osteo-onychocutaneous free flaps from January 2013 to June 2015 at the Ninth People's Hospital and Zhongye Hospital in Shanghai. The informed consent was obtained from all the patients. Type I finger injury [12,17], injured at digits distal to the distal IP joint with preservation of partial nail, nail bed and distal phalanx, was included. To better describe the fingertip defects, their injury types were categorized by the PNB classification [18,19]. This work was approved by the Institutional Review Boards of Shanghai Jiao Tong University School of Medicine and Zhongye Hospital, and it was conducted in accordance with the Declaration of Helsinki.

Operative procedures

Thorough debridement was carried out in the emergence room. The wounds were temporarily covered with biological dressings. Patients were hospitalized for antibiotics treatment and basic care for 1–2 days, followed by from-toe-to-digit reconstructive sub-emergent surgery. For considerable bad conditions in crushing cases, patients received reconstruction 2–3 months post discharge (elective surgery). Injured digits routinely received radiography for

bone defects check preoperatively. Operations were performed under joint brachial plexus anesthesia and epidural anesthesia.

During the surgery, non-viable tissue and local scar were removed from the traumatized digits. The distal dorsal branch or the distal branch of proper palmar digital artery, the distal branch of proper palmar digital nerve, and 1–2 superficial dorsal digital veins were deliberately dissected. The flexor digitorum superficialis tendon and the distal insertion of flexor digitorum profundus on the distal phalanx were left intact. As a general principle, the non-dominant foot, mostly the left one, was chosen as the donor hallux. The nail width ($W1$), the nail length ($L1$) and the digital tip circumference ($C1$) in the intact contralateral thumb and fingers were measured. Similarly, $W2$, $L2$ and $C2$ indicated those parameters in the traumatized digits. ΔW ($W1-W2$) indicated the difference between $W1$ and $W2$, and so were the same as the ΔL and ΔC . The sizes of the mini neurovascular osteo-onychocutaneous flaps were calculated preoperatively as follows: $W=\Delta W+0.2$ cm; $L=\Delta L+0.2$ cm; $C=\Delta C+0.5$ cm, and then marked on the donor hallux (Figure 1).

Dissection was proceeded from distally to proximally, which is similar to the traditional 'retrograde approach' [20] but not totally the same. Briefly, as our targeted hallux free flap is much smaller, the dissection was initiated from the marked line at the distal toe, and went on proximally at the level of toe IP joint. Tourniquet was used intraoperatively. Nail plate, nail bed and the distal phalanx were dissected along the marked line transversely. The transverse osteotomy was performed with an oscillating saw. 1–2 dorsal digital veins were identified with a pedicle length of an approximately 1–1.5 cm. When dissection coursed to the plantar, the distal branch of plantar digital artery on the fibular side of hallux, was harvested above the level of IP joint with length of approximately 0.5–1 cm and acted as the arterial pedicle for anastomosis. It was an ultrasmall artery (Φ 0.3–0.5 mm) branching from which 1–2 mm proximal to the plantar digital arterial arch (Figure 1). The distal branch of the plantar digital nerve was exposed at a proper length which enabled tension-free for coaptation. The plantar digital arterial arch was left intact. A small portion of the distal phalanx was always included in the flap whether the distal phalangeal bone in the traumatized digits presented defects or not. It was advantageous to avoid damage to the nail germinal matrix and assure integrity of nail bed with phalanx. The neurovascular flap was checked for blood circulation by releasing the tourniquet before pedicle division, and then flaps were harvested.

After proper flap inseting, the flap was fixed longitudinally to the phalangeal bones using one to two 0.8 mm Kirschner wires (K-wire) to ensure smooth alignment of the dorsal cortex between digital phalanx and the grafted phalanx for 8 weeks. 5-0 monofilament nylon thread was used to fix nail beds between digit and grafted flap after the digital nail bed being well trimmed. Though thickness mismatch between nail beds presented, the grafted nail bed undergone atrophy within approximately 2 months before reinnervation and fit the recipient nail bed well. The vascular pedicle of distal branch of the plantar digital artery (the toe) was chosen for anastomosis to the distal dorsal or distal branch of proper palmar digital artery (the digit). The dorsal digital veins were anastomosed to the superficial dorsal digital veins in an end-to-end fashion. The distal branch of the plantar digital nerve was coaptated with the distal branch of proper palmar digital nerve in the epineurial fashion. As the artery pedicle was ultra-small, a high-power surgical microscope and 12-0 nylon micro-sutures were required. Redundant distal phalanx was trimmed using a rongeur for better primary closure in donor sites with the residual medial strip skin flap. All surgeries were performed by the same surgeons.

Postoperative regimes

Patients were treated with intravenous papaverine (30 mg, every 8 h) and subcutaneous heparin (4000 IU, once a day) injections for 2–3 days. Reconstructed digits were kept warm for better circulation using a bed-side light; flap was closely monitored by color for evidence of vascular crisis. Blood routine was examined every two days within one week. In case of external bleeding protocol for relief of early venous congestion with ≤ 7 mg/dL hemoglobin level, the blood transfusion would be performed.

Assessments of functional results

Overall outcomes were assessed on flap survival, episode incidences, functional and aesthetic outcomes. In all cases, static two-point discrimination (2-PD) and key-pinch strength were evaluated at follow-ups. Key-pinch power was measured by a hydraulic hand dynamometer (DeRoyal, Irvington, NY) previously described [16], and the values were presented as the percentage of the contralateral intact digits. Aesthetic outcomes both in donor hallux and the reconstructed digits were self-assessed by patients using a non-validated score scale based on: nail deformity, fingertip circumference difference and scar (Table 1). Each item was graded from 0 to 3, depending on the degree of severity.

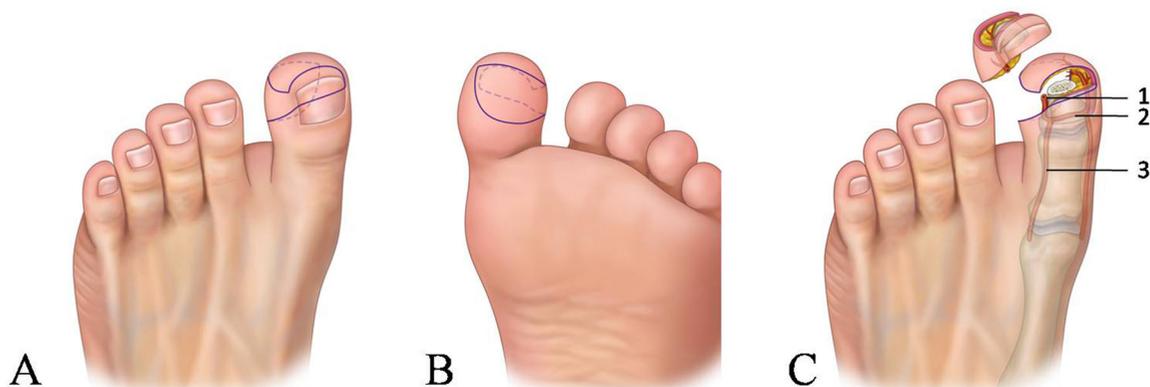


Figure 1. Schematic diagram about the designing and dissection of the hallux neurovascular osteo-onychocutaneous free flap. (A) Flap design on the dorsal hallux. (B) Flap design on the plantar hallux in pulp region. (C) Composite free flap comprised of partial nail, skin, pulp and distal phalanx. (1) The distal branch of plantar digital artery on the fibular side of hallux. (2) The plantar digital arterial arch. (3) The plantar digital artery.

The total score was from 0 to 9. Aesthetic outcomes are considered as *good* for 6–9, *fair* for 3–6 and *poor* for 0–3.

Statistical analysis

All data were presented as means ± standard deviations. Statistical significance was calculated using Student’s *t*-test via SPSS 22.0 software for Windows (SPSS Inc., Chicago, IL). A *p* value of <0.05 was considered statistically significant.

Results

A total of 15 patients, eight men and seven women, were enrolled. The average age of these patients was 27.27 ± 5.43 years

old (range, 19–36 years old). The non-devastating injuries were distributed over: six thumbs, four index fingers, four middle fingers and a ring finger. The injury causes included industrial machine pressing crush (seven cases), triangular machine belt intertwist (four cases), circular saw (three cases) and avulsion (one case). These digital injuries were classified as PNB355 type (three cases), PNB466 (four cases), PNB366 (four cases) and PNB 455 type (four cases). All flaps survived. Venous congestion occurred in one thumb repair and the flap was ultimately salvaged using the ‘external bleeding protocol’ as previously described [21,22]. Briefly, once the venous congestion was confirmed without better resolution, blood outflow from the flap using pulpar stab incision was continuously drained until flap took-in. The follow-up time period was 19.47 ± 10.18 months (range, 6–48 months). The static 2-PD was 8.40 ± 1.64 mm (range, 6–12 mm). The key-pinch was 85.37 ± 3.03% (range, 80.2–90.6%) of the contralateral intact thumbs and fingers. In terms of the aesthetic outcomes, all of the patients graded their results as *good*. The scale score was 7.29 ± 1.14 (range, 6–9). In the donor hallux, 73.3% of them (11 cases) self-graded the results as *good*. The scale score was 7.09 ± 1.04 (range, 6–8). The left 26.7% (four cases) self-graded the results as *fair* while the score was 3.75 ± 0.96 (range, 3–5).

Table 1. Self-assessment score scale for aesthetic outcomes.

Scale	Nail deformity	Fingertip circumference	Scar
0	Nail	Obvious difference	Digital dysfunction
1	Major	Moderate difference	Hypertrophic
2	Minor	Minor difference	Slight scar
3	None	Identical	Scarless

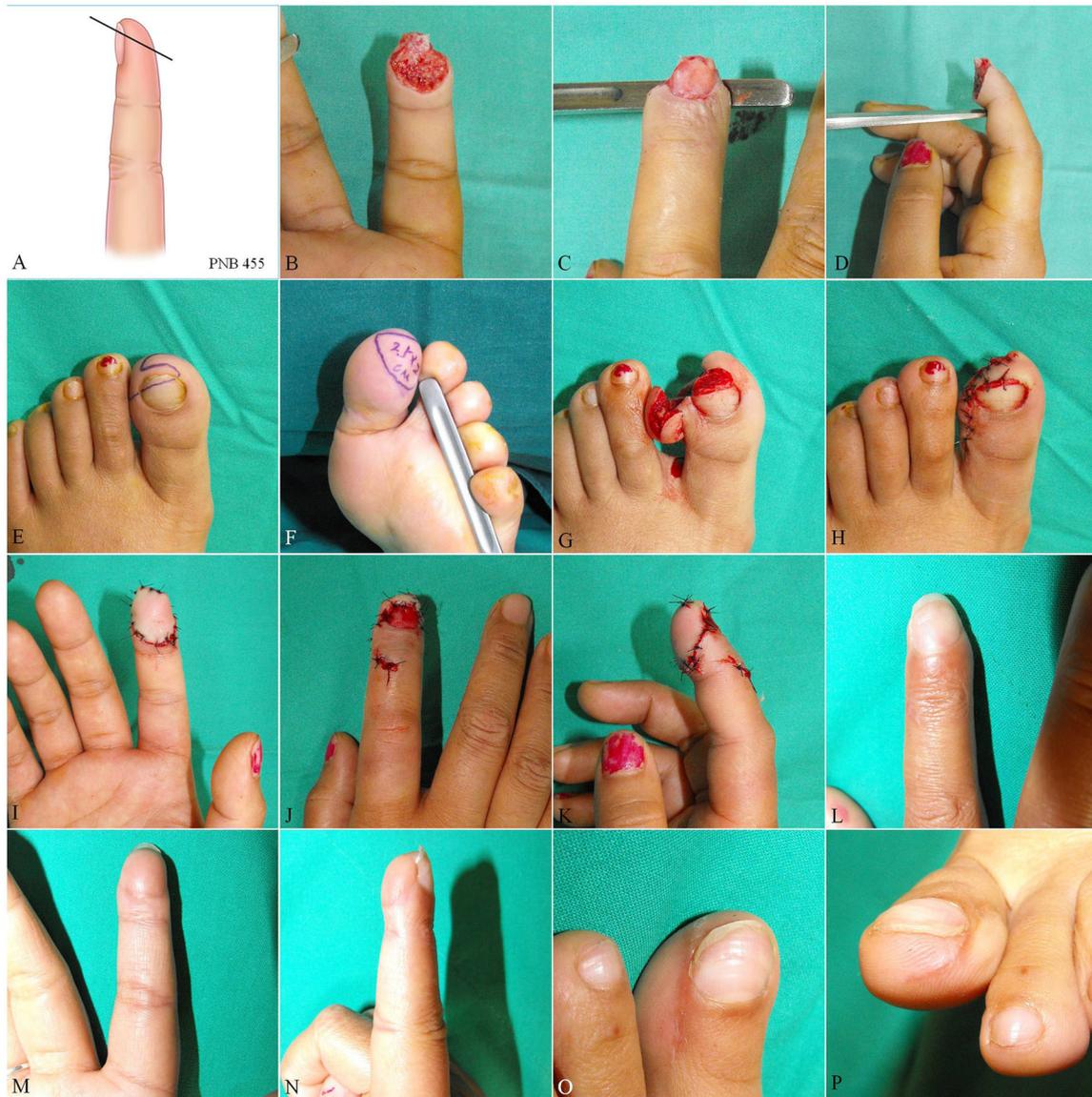


Figure 2. Refined reconstruction and rehabilitation of PNB 455 injury type in the right index finger.

The general average scale score was 6.00 ± 1.65 (range, 3–8). The main complaint was the nail atrophy, observed in three donor halluces [23].

Case reports

Case 1

A 29-year-old female had a palmar oblique amputation with injury type of PNB 455 [18,19] (Figure 2(A)) in the right index finger (Figure 2(B–D)). Replantation was impossible as the distal amputation was unfound. Radiography, tetanus antitoxin, analgesic, antibiotics, biological dressing and laboratory tests were routinely administered. Sub-emergent reconstructive surgery was performed. A size of 2.5×2.0 cm osteo-onychocutaneous free flap was designed preoperatively in the left hallux (Figure 2(E,F)). Composite flap was dissected and checked for blood perfusion by releasing of tourniquet intraoperatively (Figure 2(G)). The donor site was primarily closed with the medial flap strip after flap harvest (Figure 2(H)). After proper flap fixation, the vessels and nerve were repaired. The injured index finger was well reconstructed and reperfusion was robust immediately (Figure 2(I–K)). At follow-

up of 16 months, satisfactory shape in the pulp and nail was achieved (Figure 2(L–N)). No obvious morbidity was found in the donor hallux (Figure 2(O,P)). Static 2-PD was approximately 9 mm. Key-pinch strength was 82% of that of the intact left index finger. The highest score, nine points, was recorded for both the donor and recipient sites.

Case 2

A 32-year-old male suffered from a crush injury by a press machine in the right distal index finger. The injury type in this case was designated as PNB 355 (Figure 3(A)). He previously received stump revision in a different hospital and now presented shortened digit, nail atrophy and scar contracture (Figure 3(B–D)). In normal population, the length of index finger (red line) was a little bit shorter than the length of the ring finger (black line). Δ in Figure 3(B) shows the substantial length finger difference in this patient. Although no obvious functional impairment was clarified, the patient himself had a high expectation and demand for a refined digit. The elective surgery was performed. A size of 2.2×3 cm osteo-onychocutaneous flap was preoperatively designed in the ipsilateral hallux (Figure 3(E,F)). Two-thirds of the



Figure 3. Reconstruction and rehabilitation of PNB 355 injury type in the right index finger.

hallux nail and partial distal phalanx were included in the composite flap. Flap dissection and blood perfusion were emphasized intraoperatively (Figure 3(G)). The donor site was primarily closed (Figure 3(H)). After flap fixation and stabilization with a K-wire, vessels and nerve were repaired simultaneously. The injured digit was well reconstructed with good reperfusion and shape (Figure 3(I,J)). At follow-up of 48 months, the reconstructed right index finger presented with satisfactory pulp contour, nail and circumference (Figure 3(K-M)). No notable deformity was observed in the donor hallux except a slight scar (Figure 3(N,O)). Noteworthy, as demonstrated by postoperative radiography, the length of the defected phalanx in the digit was well reconstructed (Figure 3(P)).

Static 2-PD was approximately 7 mm. Key-pinch was 78% of that of the intact left index finger. The patient was much satisfied with the overall cosmetic and functional outcomes with score 8 for the reconstructed digit and 9 for donor hallux. No complication or complaint was filed.

Case 3

A 34-year-old male had an avulsion injury with type of PNB 466 (Figure 4(A)) in the right thumb, which was demonstrated by pulp and nail defects as well as exposed phalanx (Figure 4(B-D)). Two K-wire were used for stabilization of IP joint and restrained joint



Figure 4. Refined reconstruction and rehabilitation of PNB 466 injury type in the right defected thumb.

movement. Sub-emergent surgery was performed three days after primary debridement. A 2.6 × 3.2 cm size of osteo-onychocutaneous flap was designed in the left hallux (Figure 4(E–G)). The composite flap was harvested from the donor hallux (Figure 4(H)), and donor site was primarily closed (Figure 4(I,J)). The injured index finger was reconstructed using the mini free flap (Figure 4(K–N)). At the follow-up of 16 months, satisfactory pulp contour and nail shapes were achieved (Figure 4(O–R)). Slight nail atrophy and scar were found in the donor hallux (Figure 4(S,T)). Static 2-PD was approximately 8 mm. Key-pinch strength was 88% of that of the intact left index finger. Scores 9 and 6 were self-assessed for the reconstructed thumb and donor hallux, respectively.

Discussion

Reconstruction and rehabilitation of distal amputations in distal thumbs and fingers are very challenging. To be both functional and aesthetic, the reconstructed digits are better to be a replica of what is missing. Conception of thumb reconstruction using the second toe was first introduced by Nicoladoni [4]. The toe-to-hand transfer technique has been considered as the first option represented by hallux neurovascular wrap-around free flap [6] and some modifications [7–9,13] using the hallux osteo-onychocutaneous flap and the medial pulp flap from the second toe to reconstruct massive defects in fingers. In 1989, Koshima et al. used the same composite flap for reconstruction of distal finger defects [14]. Similar methods were reported afterwards [13,15,24,25]. Though skin flaps can also be used to restore defects in hand [26,27], they were devoid of nail and fingerprint despite of much decreased protective sensation.

Osteo-onychocutaneous flap, as well as part-nail preserving transfer [13], is essentially similar to the conventional wrap-around flap [6]. The mini neurovascular osteo-onychocutaneous flap introduced here shared the same strategy but with differences. First, this flap was pedicled by an ultra small (Φ 0.3–0.5 mm) artery, ensuring the flap being dissected smaller and more precisely to match the fingertip defects without secondary pulp plasty. Moreover, compared with longitudinal osteotomy usually performed using conventional methods, the transverse osteotomy pattern was designed for better custom-made repair. This can cause less deformity to the donor nail bed and germinal matrix. Amputation revision was frequently performed in case that digit was injured distally but without obvious function impairment. However, for those who had high expectation of refined rehabilitation both in function and shape, the mini neurovascular osteo-onychocutaneous free flap presented in this study could potentially be an extra choice.

In the previous report, the second toe was regarded as the preferred donor for reconstruction of the distal finger defects [12]. Fingertip defects distal to the distal IP joint were classified as two types, and type I usually involves minor tissue deformity in nail plate, nail bed and distal phalanx, which required smaller flap for reconstruction. The mini osteo-onychocutaneous flap could be custom-made and match smaller digital defects. Partial-nail preserving flap from the hallux was regarded as the most appropriate option when there was an at least 3 mm difference in width between defected thumb and donor hallux [13]. Such width difference is more significant between the donor hallux and fingers (not thumb). It could be reasonably speculated that the mini hallux osteo-onychocutaneous free flap would be more proper for reconstruction of type I digital injury in fingers.

According to the PNB classification as indicated by Muneuchi et al. [19], the 15 patients involved in this study were exactly

supposed to be the most suitable to receive surgical repair. Technically, we strongly suggest including a partial distal phalanx in harvest of the composite flap, as it will facilitate to prevent swiveling instability, bone resorption or nail deformity [7]. Nail atrophy was observed in three donor halluces, caused by potential damage to the nail germinal matrix when larger nail size was expected during the extensive nail bed harvest. Considering the fact that transferred flap will get atrophy gradually during the first year after surgery, and decreases approximately 15% of its primary volume within 3 years [28], extra 2–5 mm larger in the circumference, width and length of the osteo-onychocutaneous flap was designed for compensation of the future tissue shrinkage.

Though, favorable static 2-PD was achieved, there may still be a room for improvement on nerve coaptation. The ulnar side of thumb and the radial side of fingers are usually dominant for pinch and touch. Therefore, we deemed that, for the purpose of optimal innervation and rehabilitation, it might be better to harvest the neurovascular osteo-onychocutaneous flaps from the ipsilateral hallux for thumb repair, and harvested flaps from the contralateral hallux for finger repair.

Conclusions

Distal defects of type I injury in thumbs and fingers can be reconstructed with good functional and aesthetic outcomes using the mini hallux neurovascular osteo-onychocutaneous free flap.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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