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Three-dimensional virtual reality simulation of periarticular tumors using Dextroscope reconstruction and simulated surgery: A preliminary 10-case study

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Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: Dextroscope® three-dimensional (3D) imaging has been extensively used to generate virtual reality (VR) workspaces for neurosurgery and laparoscopy, but few applications have been reported for orthopedic surgery. Here, we investigated orthopedic periarticular tumor surgery planning and anatomical characteristics using a Dextroscope.

Material/Methods: Patients undergoing surgery for periarticular tumors (*n*=10) between October 2008 and June 2010 were enrolled and presurgically subjected to computed tomography (CT), magnetic resonance imaging (MRI), and MRI angiography (MRI-A). Imaging data were transferred and integrated in a Dextroscope to produce a VR simulation. The presurgical 3D anatomical reconstructions and intraoperative anatomical characteristics (virtual *vs.* actual data) and surgical approach (virtual *vs.* actual situation) measurement and subjective appearance were compared.

Results: Anatomical characteristics in the area of interest and tumor diameters in all 3 planes (superior-inferior, medial-lateral, and anteroposterior) were consistent between virtual and actual data (3.92±1.22, 1.96±0.53, and 1.73±0.44 *vs.* 3.92±1.13, 1.91±0.44, and 1.81±0.41; *P*=0.99, 0.24, and 0.09, respectively). However, the virtual surgical situations were inconsistent with the actual intraoperative situation in many cases, leading to complications. The resolutions of the original CT, MRI, and MRI-A images directly correlated with 3D simulation quality, with soft tissues most poorly represented. Tumor tissue imaging quality in 3D varied extensively by tumor type.

Conclusions: Anatomical structures of periarticular tumors can be reconstructed using the Dextroscope system with good accuracy in the case of simple fenestration, increasing treatment individualization, surgical competence level, and potentially reducing intraoperative complications. However, further specialization of VR tools for use in orthopedic applications that involve specialized tools and procedures, such as drilling and implant placement, are urgently need.

MeSH Keywords: Reconstruction • Virtual Surgery • Virtual Reality Exposure Therapy • Computer Simulation

Abbreviations: **VR** – virtual reality; **CT** – computed tomography; **MRI** – magnetic resonance imaging; **MRI-A** – magnetic resonance angiography

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Background

Multimodal virtual reality (VR) imaging for presurgical visualization is increasingly common in contemporary clinical settings [1]. These techniques have been widely and successfully employed in neurosurgery and laparoscopy [2,3], but fewer than 16 cases and only 23 published articles have reported on the orthopedic applications of VR despite the potential for improvements in surgical evaluation and planning, minimization of unanticipated intraoperative variations, and improved patient outcomes [4]. These cases consisted primarily of acetabular fractures [5], total hip replacement [6], and arthroscopic knee surgery [7], representing only a few of the myriad of potential orthopedic applications.

Dextroscope® is a popular VR system for reconstruction of two-dimensional (2D) from DICOM data and three-dimensional (3D) stereoscopic virtual workspaces from magnetic resonance imaging (MRI) and computed tomography (CT) data [8–13]. The 3D user interface reflects the computer-generated scenario into the user's eyes using mirrors and time-split synchronized liquid display shutter glasses, allowing full manipulation of the 3D workspace by a hand-held pen and a virtual "tool rack" [14]. Color, transparency, segmentation, image fusion, and linear and volumetric measurements can also be manipulated and exported in an image or video format [14], allowing for complete surgical simulation.

Periarticular tumors in 10 patients were assessed by conventional MRI and CT, and the data were integrated with the Dextroscope to produce a 3D workspace to examine pathological anatomical structures. Simulated virtual and actual intraoperative anatomical characteristics and surgeries were compared to provide a preliminary evaluation of the orthopedic use of the Dextroscope for periarticular tumor treatment.

Material and Methods

Subjects

Benign periarticular tumor patients (*n*=10; M: F, 4: 6; age 23–52 years; mean age 39.2 years) scheduled for curettage and artificial bone or bone cement implantation at the Department of Orthopedics between October 2008 and June 2010 were enrolled. Diagnoses of aneurysmal bone cyst in the proximal femur (5 cases), giant-cell bone tumor of the proximal tibia (3 cases), chondroblastoma in the proximal humerus (1 case), and bone cyst in the left distal tibia (1 case) were confirmed by postsurgical pathological examination. All patients were followed for a minimum of 12 months. The study was approved by the Institutional Review Board of the Huashan Hospital of Fudan University, and written informed consent was obtained from each patient.

VR image data

All patients were subjected to CT (SOMATOM Sensation® 64-Slice CT System; Siemens, Germany), MRI (GE 3.0 Tesla Signal Horizon; GE Healthcare, USA), and MRI angiography (MRI-A) 2 days prior to surgery, using 2-mm layer thickness and spacing.

Native DICOM images were converted to RadioDexter version 1.0 (Volume Interactions, Singapore) software format, preliminarily processed, loaded into the Dextroscope® (Volume Interactions, Singapore) 3D VR environment, and observed by a single operator equipped with liquid crystal stereoscopic glasses, a transmitter (left hand), and a virtual pen (right hand). Areas of interest were assigned (Figure 1A) and integrated by automated or manual 2- or multiple-point selection (Figure 1B).

The operator assigned tissue colors for visualization and segmented or rotated structures. Selective removal of skin, skeleton, tumors, vessels, and neighboring anatomical and functional structures using variant segmentation and extraction were used to reveal anatomical characteristics in the final reconstructions (Figure 2). The resulting presurgical 3D anatomical reconstructions (virtual data) were used to generate superior-inferior, medial-lateral, and anteroposterior tumor diameters, and these values were compared to intraoperative measurements (actual data).

Presurgical planning and surgical approach

The VR workspace was used to expose lesion sites according to standard surgical requirements for optimal field of view, including soft-tissue incision, bone flap fenestration, and tumor curettage, to generate individualized presurgical plans. Final output images/videos (virtual situation) were used as surgical references, and relationships between lesions and neighboring tissues were examined. Subjective image assessment by the operator and surgical precision were compared with those from the intraoperative surgical situation (actual situation). All procedures were performed by a single surgeon, who made measurements using Vernier calipers. All patients received standard postsurgical care.

Statistical analysis

Statistical analyses were performed in SPSS version 16.0 (SPSS Inc., USA). All continuous variables are presented as means ± standard deviations (SD) and analyzed using paired *t*-tests with two-tailed analysis. *P*-values less than 0.05 were considered statistically significant ($P<0.05$).

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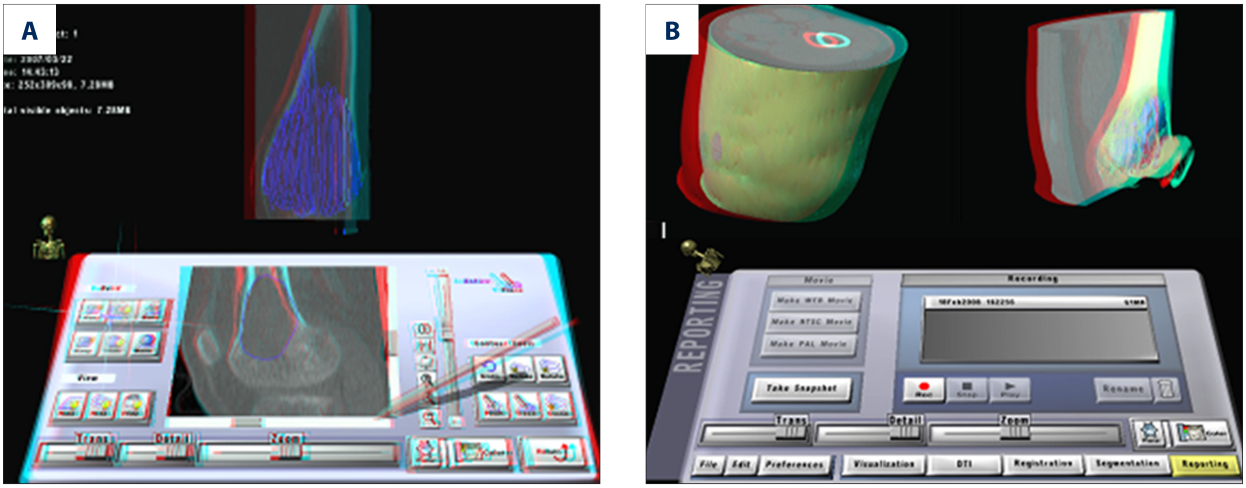

Figure 1. The Dextroscope interface. (**A**) Single extraction of the area of interest using the "tool kit" (bottom) for automatic recognition and extraction of the area using bitmap grayscale ranges and (**B**) one-by-one image selection and integration, including automatic and manual operation using 2- and multiple-point methods.

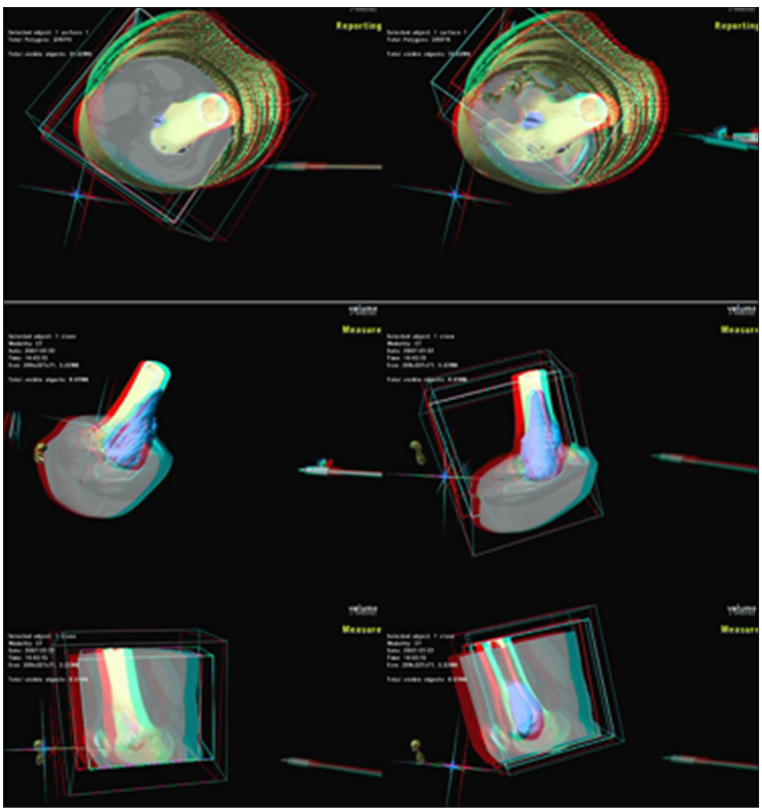

Figure 2. Removal of blocking structures and tissues to generate reconstruction images for measurement.

Results

Patient data and Dextroscope imaging

Patient data for all 10 cases are shown in Table 1. Each patient dataset yielded successful virtual and actual information for both data and situation. Imaging resolution was determined by the resolution of the original image data and was highly variable between individual tissue types based on subjective visual assessment. Optimal visual effects were achieved in the skeleton and skin, although blood vessels also exhibited relatively high-quality reconstruction images. Conversely, low-quality reconstruction was apparent in soft tissue, including muscle. The quality of tumor tissue reconstruction varied depending on the tumor characteristics (data not shown).

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Table 1. Periarticular tumor patients examined by Dextroscope.

Case no.	Gender	Age (yrs)	Diagnosis	Affected side	Location	Condition*	Follow-up (mo)
1	M	41	Aneurysmal bone cyst	L	Proximal femur	–	12
2	F	43	Aneurysmal bone cyst	R	Proximal femur	Psoriasis	15
3	M	23	Chondroblastoma	L	Proximal humerus	–	26
4	F	35	Giant-cell tumor of bone	R	Proximal tibia	–	16
5	F	48	Bone cyst	L	Distal tibia	Sjögren's syndrome	18
6	M	39	Aneurysmal bone cyst	R	Proximal femur	–	22
7	F	30	Giant-cell tumor of bone	L	Proximal tibia	–	14
8	F	49	Aneurysmal bone cyst	L	Proximal femur	Diabetes	17
9	M	52	Aneurysmal bone cyst	R	Proximal femur	–	18
10	F	32	Giant-cell tumor of bone	L	Proximal tibia	Hypertension	17

M – male; F – female; R – right; L – left. * Pre-existing conditions or complications.

Table 2. Dextroscope VR (virtual data) *vs.* intraoperative (actual data) tumor size.

	Diameter*		
	Vertical	Transverse	Anteroposterior
Virtual data (n=10)	3.92±1.22	1.96±0.53	1.73±0.44
Actual data (n=10)	3.92±1.13	1.91±0.44	1.81±0.41
t-value	<0.01	1.25	1.92
P-value	0.99	0.24	0.09

* Diameters are means ±SD (cm).

All patients exhibited good joint function, no local tumor recurrence, and no distant metastasis during follow-up (mean, 17.5 months; range, 12 to 26 months). In all patients, virtual and intraoperative data for anatomical structures were not significantly different based on subjective visual assessment and tumor diameter measurements ($P>0.05$) (Table 2). The virtual and actual situations closely matched; however, subjective image assessment and surgical precision of the virtual situation exhibited notable discrepancies from the actual situation.

Typical clinical applications

Patient 1. A male patient with an aneurysmal bone cyst in the left proximal femur is shown. Anatomical structures surrounding the bilateral hip joints, skin, skeleton, muscles, pelvic organs, femoral artery, and femoral vein were successfully reconstructed and multi-modal 3D VR images were produced (Figure 3). The lateral approach was simulated, and bone flap fenestration and tumor curettage were performed (Figure 4). Intraoperative complications were primarily caused by underestimation and imprecise analysis of the anatomical details of the lesion area. Some discrepancies were observed between the virtual and actual situation.

Patient 3. A male patient with chondroblastoma in the left proximal humerus is shown. Anatomical structures of the proximal humerus were reconstructed, revealing skin and muscles (Figure 5). Skin incision was simulated, and the tumor surface of the proximal humerus was exposed via the deltopectoral approach. Front fenestration, focus curettage, and allogeneic/autologous bone grafts were performed. Virtual and actual situations were highly consistent.

Discussion

All 10 cases presented with benign periarticular tumors that were modeled successfully with the Dextroscope, with no

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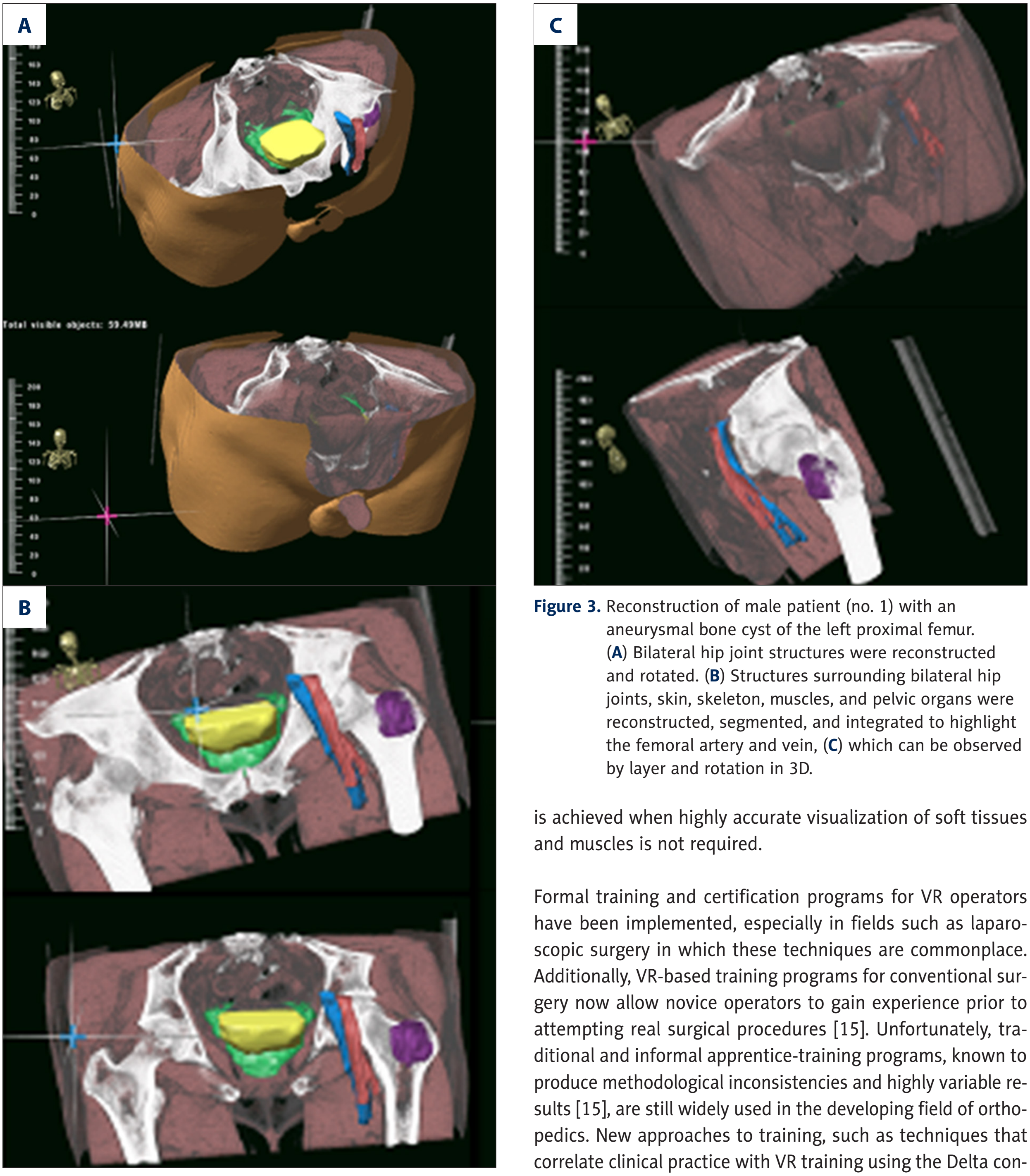

Figure 3. Reconstruction of male patient (no. 1) with an aneurysmal bone cyst of the left proximal femur. (**A**) Bilateral hip joint structures were reconstructed and rotated. (**B**) Structures surrounding bilateral hip joints, skin, skeleton, muscles, and pelvic organs were reconstructed, segmented, and integrated to highlight the femoral artery and vein, (**C**) which can be observed by layer and rotation in 3D.

significant differences between virtual and actual tumor size measurements or subjective visual assessments ($P<0.05$). Using this VR environment, a step-wise approach was used to examine the skeleton, blood vessels, and musculature in each level to aid in surgical planning. Notably, the resolution (quality) of the 3D reconstruction models of variant tissue and tumor types was highly variable, suggesting that maximum effectiveness is achieved when highly accurate visualization of soft tissues and muscles is not required.

Formal training and certification programs for VR operators have been implemented, especially in fields such as laparoscopic surgery in which these techniques are commonplace. Additionally, VR-based training programs for conventional surgery now allow novice operators to gain experience prior to attempting real surgical procedures [15]. Unfortunately, traditional and informal apprentice-training programs, known to produce methodological inconsistencies and highly variable results [15], are still widely used in the developing field of orthopedics. New approaches to training, such as techniques that correlate clinical practice with VR training using the Delta consensus approach, have recently been proposed, but they have not yet been applied in orthopedic surgery [16]. Periarticular tumor treatment strategies involving conventional regimens of radiotherapy, chemotherapy, biotherapy, molecular-targeted therapy, and surgery may be dramatically improved by standardization and wide implementation of the VR surgical protocols. However, further exploration will be required to generate clinically applicable orthopedic recommendations and training programs for VR applications.

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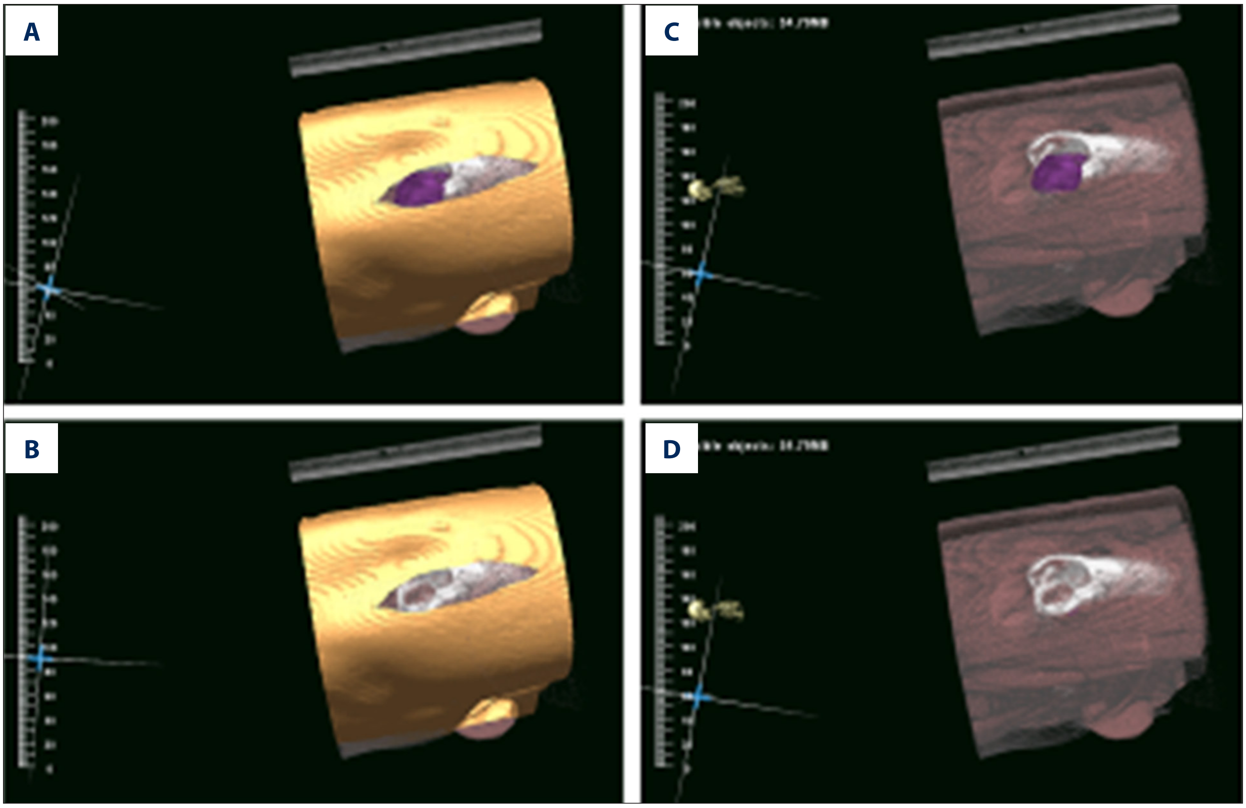

Figure 4. Lateral incision (patient no. 1) simulated in the lateral decubitus position. Skin and abductor muscle are incised layer-by-layer showing the bone flap fenestration (**A**), phyma curettage (**B**), and hidden skin (**C** and **D**).

It is widely accepted that MRI T1-weighted images are the most accurate for identifying intramedullary tumors, tumor infiltration into soft tissue, and relationships with important vascular and nervous structures [17–19]. However, CT scanning is superior to MRI for identifying lesions in bone structures, and MRI-A excels at identification of tumor blood supplies [17–19]. Considering the particularities of periarticular tumor surgery, detailed combination of these images by a trained VR operator can aid in limb salvage operations and preservation of joint function. Numerous methods for 3D virtual workspace construction have been reported, but the Dextroscope has been the most prominent in contemporary literature over the past decade because it is easy to use and can comprehensively combine multiple image types to achieve a virtual 2D or 3D workspace [20]. For contemporary clinical treatment of periarticular tumors, the Dextroscope is the logical approach due to its simplicity, comprehensive multi-image integration, and wide availability.

As specialized VR systems and software become increasingly available, the discrepancy between virtual and actual surgical situations is shrinking rapidly, particularly in neurosurgical and laparoscopic fields [16,21]. In orthopedics, the accuracy of virtual 3D imaging remains limited due to imaging resolution limitations and operating procession, particularly for soft tissues, minor nerves, or blood vessels. For instance, the femoral artery branch in patient no. 1 in the present study was very difficult to visualize and process. Recently, new "advanced" VR, also termed "augmented reality," systems have been developed that involve sophisticated integrations of stereoscopic evaluation and computational analysis abilities, allowing for fully immersive VR models that offer more capabilities than actual reality [21]. These approaches may be useful for the future development of more accurate applications involving periarticular tumor assessment, particularly in cases where quantitative blood flow analysis may be critical to prevent complications or ensure complete tumor removal.

The Dextroscope system is not specifically designed for orthopedic surgery, and it can only be used for simple procedures, such as fenestration. The system also cannot provide corresponding haptic feedback, which has recently become a research focus of neurosurgery and endoscopy [20,22]. While validation methodologies for surgical simulation using VR have been established in other fields, they are also urgently required in orthopedic surgery using VR [23]. Vankipuram et al. [24] reported the only study of VR validation, demonstrating that VR could effectively be used as a tool to train novice surgeons in orthopedic drilling. More advanced software add-ons and standardization of simulation methods are urgently required in the field of orthopedics to address specific issues, such as the use of orthopedic-specific implants and tools such as drills.

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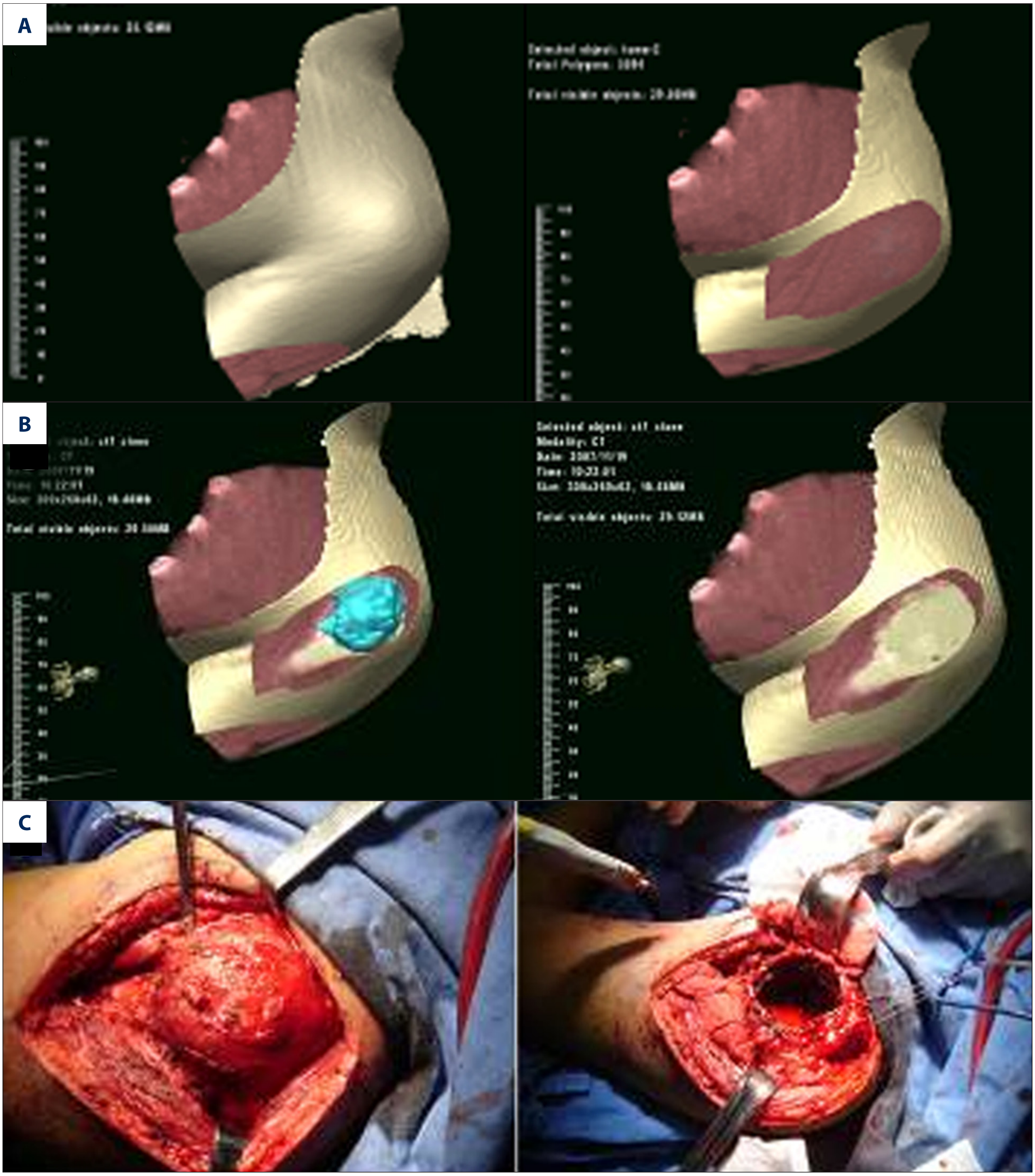

Figure 5. Reconstruction of male patient (no. 3) with chondroblastoma of the left proximal humerus. (**A**) 3D reconstruction of the anatomical structures of the proximal humerus with alternately exposed skin and muscles. (**B**) Simulated incision in the lateral decubitus position showing skin and abductor muscle incisions to expose the area of interest (tumor surface on the proximal humerus). (**C**) The actual surgical situation (shown) was highly consistent with the simulated virtual situation.

There are several limitations of our study. Most importantly, the number of patients was very small, which prevented us from performing advanced statistical analyses and introduces the possibility of a type II statistical error.

Conclusions

The findings in these cases indicate that the Dextroscope system is capable of improving results in patients with basic fenestration by providing 3D VR workspaces that approximate actual periarticular tumor size and surgical situation based on tumor measurements and subjective visual assessments. However, this method is at best preliminary and requires further refinement of specialized tools before VR can be widely applied to many orthopedic surgery types, such as upper cervical and pelvic tumor surgeries.

Conflict of interest

The authors declare that they have no conflict of interest.

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