Assessment of Pulmonary Artery Stenosis Using Freehand "Flock of Birds" Digital Color Three-Dimensional Echocardiographic Reconstruction

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Abstract

Pulmonary artery (PA) trunk or branch PA stenosis is commonly found in patients with congenital heart disease. The aim of the present study was to evaluate the freehand "Flock of Birds" color Doppler three-dimensional (3D) reconstruction on a modeled-segment imitating PA stenosis. First, a PA model was created from latex tubes to simulate the main PA and its main branches with baseline cross-sectional areas (CSA) of 0.7 cm^2. A series of narrowed segments in the right and left PA were created. The cross-sections of the smallest area ranged from 0.13 to 0.59 cm^2 and stenotic segmental length ranged from 0.17 to 1.80 cm. The dimensions of these elements mounted on to the model were verified by intravascular ultrasound (IVUS) imaging. Next, pulsatile flows at 60 beats/min were generated through the system. A GE/VingMed System FiVe with magnetic locator system (Flock of Birds) on a 3.5 MHz transducer was used to acquire a freehand sweep for ECG gated 3D data acquisition of color Doppler flows through the model. The images were reconstructed by EchoPac 3D software and the morphology of the stenotic elements were determined. The results revealed that the narrowest CSA determined by the 3D color flow cast of the pulmonary artery were in excellent agreement with IVUS CSA ($r=0.98$, $p<0.001$, SEE=0.04 cm^2). The stenotic length estimated from 3D was also in good agreement with the IVUS ($r=0.98$, $p<0.001$, SEE=0.03 cm). In addition, complex morphology of the stenosis was well visualized by this technique. As a result, the noninvasive freehand digital color 3D echocardiography can be adopted for the accurate assessment of the severity and morphology of PA stenosis in patients with congenital heart diseases.

Key word : Three-Dimensional Echocardiography, Color Doppler Echocardiography, Pulmonary Artery Stenosis

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J Med Assoc Thai 2002; 85 (Suppl 4): S1259-S1265

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Pulmonary artery (PA) trunk or branch PA stenosis is commonly found in congenital heart diseases, such as tetralogy of Fallot (TOF), complex pulmonary atresia with ventricular septal defect (VSD)(1), Williams syndrome(2), or isolated pulmonary artery stenosis. In addition, PA stenosis can be acquired as a result of ductal constriction, systemic-pulmonary shunt, and palliative PA banding. Conventional two-dimensional (2D) and Doppler echocardiographic study provide some information of stenotic diameter, stenotic length and probably Doppler velocity across the stenosis if the angle of interrogation allows(3). Most patients with congenital heart diseases and PA stenosis have multiple PA branch stenoses, post-operative systemic-pulmonary shunt, or pulmonary artery banding. In these instances, Doppler flow velocity estimating pressure gradient across the PA branch stenosis may underestimate the severity due to complex anatomy and obstruction in series. Assessment for the severity of PA stenosis appeared to be more accurate with imaging for stenotic diameter of the PA branches and possibly the stenotic cross-sectional area. However, the conventional methods have limited capability to delineate the complex asymmetrical stenotic morphology of the pulmonary artery branches. Precise information of the lesion is essential for planning the intervention either transcatheter or surgical approach. 3D echocardiographic methods have been reported on the studies for intracardiac blood flow jets(4) and outflow obstruction in congenital heart disease with better accuracy and better perception of complex morphology(5). 3D echocardiographic image acquisition and reconstruction can be obtained by rotational, translational, or freehand scanning. The rotational and translational techniques require accurate motor-driven device with limited angle of interrogation of ultrasound signal. These techniques are also time-consuming. The freehand scanning with magnetic locator system has advantage of a more liberal imaging plane of acquisition even at the limited echocardiographic window on the patient's chest. The aim of the present study was to evaluate the accuracy of the freehand color Doppler 3D Flock of Birds reconstruction in a

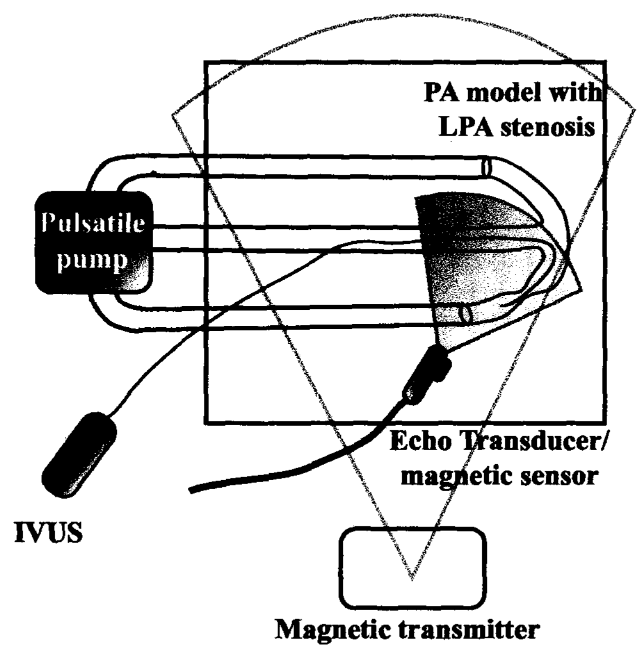

Fig. 1. **The experimental setup includes: *in vitro* pulmonary artery stenosis model, echocardiographic transducer with magnetic sensor, magnetic transmitter, intravascular ultrasound (IVUS), and pulsatile flow pump.**

modeled segment of PA stenosis for determining the stenotic cross-sectional area and stenotic segmental length.

MATERIAL AND METHOD

In vitro flow model

A PA model was created from latex tubes to simulate the main PA (VWR latex tubing 3/8" ID, 3/32" wall thickness, VWR Scientific, Inc, West Chester, PA), and left and right PA branches (VWR latex tubing 1/2" ID, 1/8" wall thickness) with baseline cross-sectional areas (CSA) of 0.7 cm^2. Thin silastic sheaths of different sizes were prepared and mounted onto the model one at a time resulting in narrowed segments in the right or left PA (Fig. 1). The cross-sections of the smallest area ranging from 0.13 to 0.59 cm^2 and obstructive segmental length of 0.17 to1.80 cm were verified by intravascular ultrasound (IVUS) imaging with the IVUS catheter (Spy, Boston Scientific, San Jose, CA) on the Sonos 100 Intravascular Imaging System (Hewlett-Packard, Andover, MA) at 30 MHz 25-30 frames/sec (Fig. 2). Pulsatile flows 50 mL/beat at 60 beats/min and systolic/diastolic flow ratio of 40 per cent/60 per cent were generated by Harvard Apparatus dual phase control blood pump (model 1423, Harvard Apparatus, Inc, Hillston, Mass) through the system. A solution of water mixed with cornstarch (1% by weight) was used as the fluid medium. The model was immersed in a water container with an echocardiographic window for imaging. A GE/VingMed System Five with magnetic locator system (Flock of Birds) on a 3.5 MHz transducer was used to acquire a freehand sweep 3D data acquisition of gray scale and color Doppler flows through the model with ECG gated at peak systole. The images were reconstructed offline by GE/VingMed EchoPac 3D software. The 3D color Doppler flow casts of the stenotic PA were reconstructed in anyplane mode. Then, the stenotic segments were identified and an adjusted plane perpendicular to the PA flow cast was slide along the flow direction to find and trace for the narrowest cross-sectional area (Fig. 3). The stenotic lengths were measured from the beginning to the end of the stenotic segment of 3D color flow cast in long axis. The average of three measurements for stenotic cross-sectional area and segmental stenotic length of each model were obtained.

Interobserver variability

To evaluate the interobserver variability on the measurement of PA stenotic cross-sectional area and stenotic length, ten randomly selected stenotic PA segments determined using 3D method by two observers were analyzed.

Statistical analysis

Data are presented as mean $\pm$ SD. Correlations between continuous variable data were determined by linear regression analyses. Statistical significance was defined as a value of $p<0.05$. The relationship and agreement between the PA stenotic

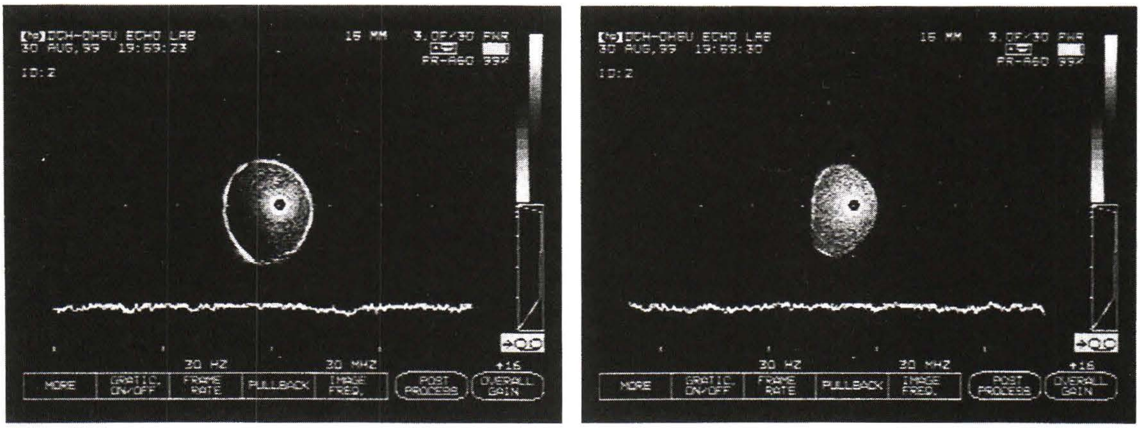

Fig. 2. Intravascular ultrasound imaging of the pulmonary artery stenotic cross-sectional area and length as a reference standard.

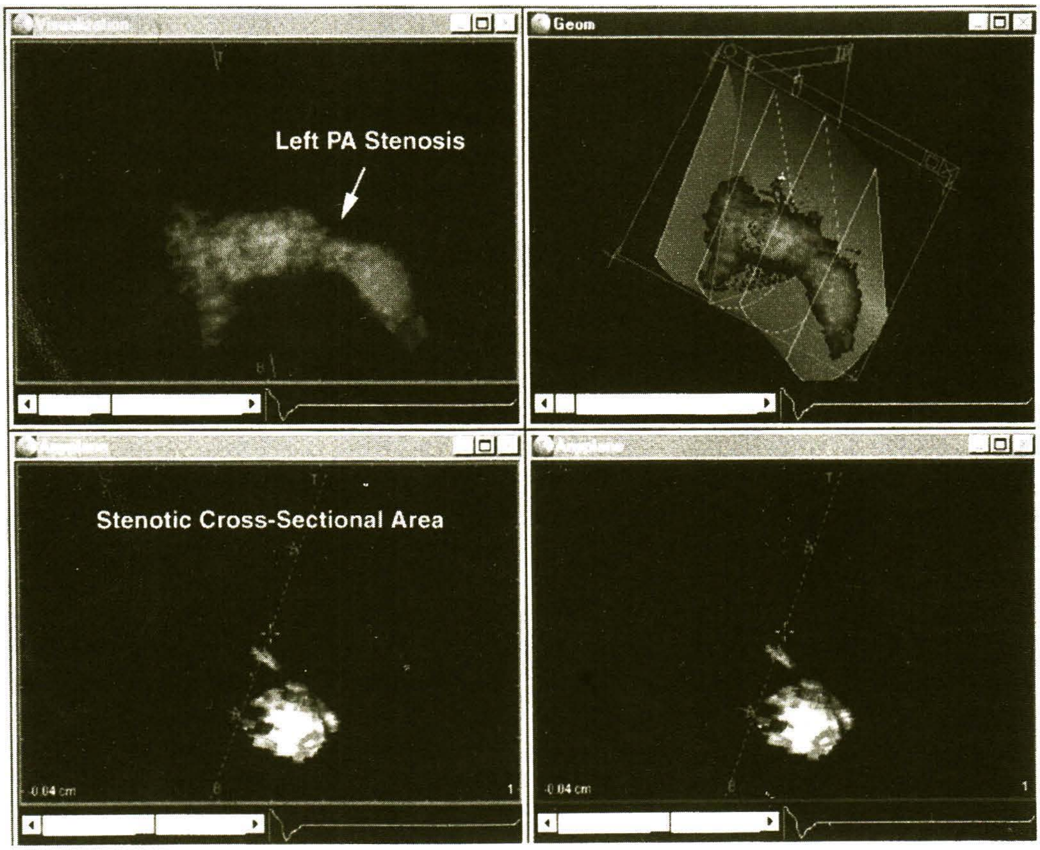

Fig. 3. Reconstructed digital color 3D Doppler flow cast inside the left pulmonary artery branch is shown. The site and severity of stenosis is clearly and easily identified.

cross-sectional areas and stenotic length by 3D and IVUS methods were tested by the method of Bland and Altman(6) using Stata 6.0 statistical software (Stata Corporation, Texas, USA).

RESULTS

The narrowest CSA determined by the reconstructed 3D color Doppler flow cast of the pulmonary artery demonstrated good agreement with the IVUS (r=0.97, p<0.001). The Bland-Altman comparison showed mean difference 0.013 (CI -0.004 to 0.029) and limits of agreement 0.047 to 0.072 (Fig. 4). The stenotic length estimated from 3D was also in good agreement with the IVUS (r=0.98, p<0.001). The Bland-Altman comparison showed mean difference 0.075 (CI 0.034 to 0.117) and limits of agreement -0.075 to 0.225. However, the stenotic length by 3D demonstrated mild overestimation and moderate variance (Fig. 5). In addition, complex morphology of the PA stenosis was well visualized by the 3D.

Interobserver variability

There was excellent agreement between the two observers' measurements of stenotic CSA and stenotic length using 3D method (r=0.98, mean difference = 0.013 $\pm$ 0.004 cm^2, 0.075 $\pm$ 0.03 cm).

DISCUSSION

PA stenosis is still a clinical challenge for diagnostic imaging and therapeutic options. Many congenital cardiac defects; such as tetralogy of Fallot, complex pulmonary atresia with VSD, or Williams syndrome, pose special problems for this entity.

Hiraishi et al(3) have demonstrated the feasibility and high accuracy of conventional 2D and Doppler evaluation for morphology of the major PA

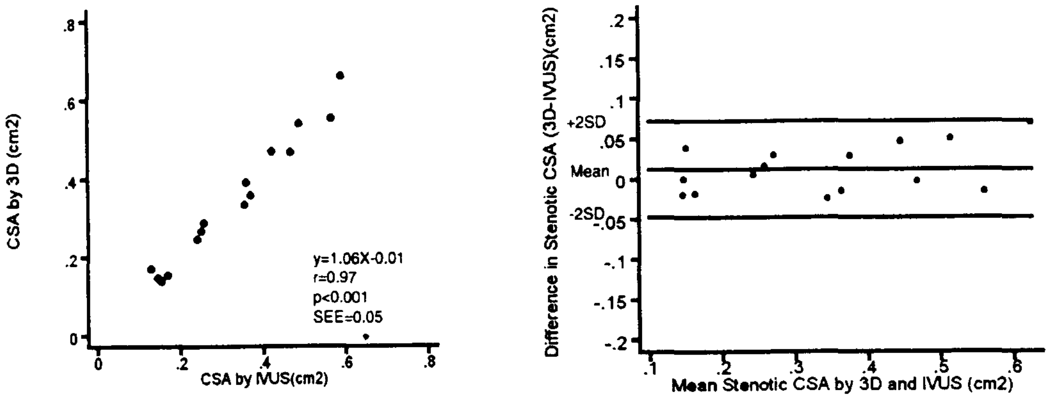

Fig. 4. **Linear regression analysis demonstrates good correlation of the stenotic cross-sectional area by color 3D and IVUS methods. The Bland-Altman plot demonstrates excellent agreement between the color 3D and IVUS method in assessing the severity of PA stenosis.**

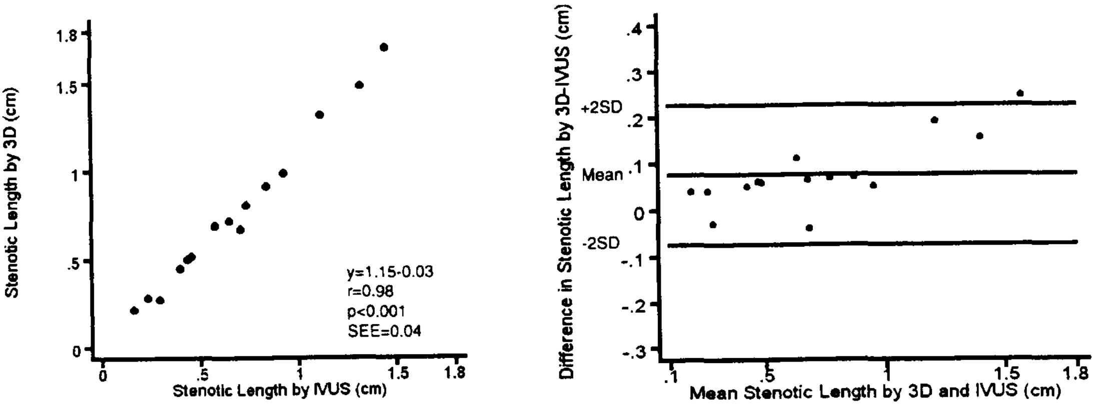

Fig. 5. **Linear regression analysis demonstrates good correlation of the segmental stenotic length by color 3D and IVUS methods. The Bland-Altman plot demonstrates good agreement between the color 3D and IVUS method in assessing the length of PA stenosis.**

branches. However, the results showed a slight underestimation in comparison to the angiographic measurement. The conventional technique requires the operator to sweep for the biggest PA diameter to obtain the most reliable data. Automated cardiac flow measurement has been reported for assessing flow volume and stenotic effective orifice area in a vessel such as descending aorta in coarctation of aorta[7] However, this method required Doppler angle of interrogation as parallel to the flow as possible. In contrast, our color 3D data acquisition using magnetic locator system (Flock of Birds) allows a freehand sweep to fully cover the entire PA branches with color Doppler information of the flow inside the PA. The reconstructed 3D images demonstrate the gray-scale PA wall and a unique color flow cast. This may provide an advantage of the ability to view and trace for cross-sectional area or the stenotic diameter in order to avoid the underestimation. The present results demonstrated the high accuracy of estimating the cross-sectional area of the PA stenosis. However, estimated PA stenotic length demonstrated mild underestimation with more variability of measurement. The limitation of lateral resolution inherent to the current echocardiographic technology may contribute to this shortcoming.

Noninvasive echocardiographic method for assessing the PA stenosis would be useful for detecting the significant stenosis and prompt for either transcatheter(2,8,9) or surgical intervention(10) to relieve the narrowing. In addition, the noninvasive echocardiographic method would be useful for the frequent follow-up assessment after interventions.

A recent report on three-dimensional contrast-enhanced magnetic resonance angiography (MRA) demonstrated promising accuracy for branch PA morphology and stenosis(11). MRA is, however, expensive to utilize and is not implemented in portable systems. Additionally, the relatively slow speed of the MRA image acquisition may require the patient on general anesthesia to control for moving and respiratory artifacts. This may pose a special risk of complication especially in patients with cyanotic congenital heart disease.

Therefore, the 3D method can be adopted as an informative, noninvasive investigation for patients with PA stenosis. However, this study was performed in a model with an ideal echocardiographic window that the imaging transducer could align for any optimal angle of echocardiographic and Doppler interrogation. Study in patients with PA stenosis might be limited by narrow high intercostal space or sternum. Suprasternal view may offer good echocardiographic window in some patients. According to the current echocardiographic capacity, color Doppler 3D for PA stenosis is still limited to imaging for the major branches of the pulmonary artery. The higher generation of the pulmonary artery arborization has not yet been able to achieve.

Freehand "Flock of Birds" digital color 3D echocardiographic imaging noninvasively allows accurate assessment of the severity and morphology of the modeled PA stenosis. Further study in patients with PA stenosis is suggested to determine the clinical applicability of this technique.

(Received for publication on September 23, 2002)

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การประเมินความตีบของหลอดเลือดแดงในปอดด้วยคลื่นเสียงสะท้อนหัวใจ 3 มิติชนิดสี โดยการกวาดมืออย่างอิสระ

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การตีบของหลอดเลือดแดงในปอด หรือที่แขนงของหลอดเลือดดังกล่าว เป็นปัญหาที่พบบ่อยอย่างหนึ่งของโรคหัวใจแต่กำเนิด โดยเฉพาะอย่างยิ่งเป็นปัญหาแทรกซ้อนในโรคหัวใจแต่กำเนิดชนิดเขียว ทำให้การดูแลรักษาให้การไหลเวียนเลือดใกล้เคียงภาวะปกติเป็นไปได้ยาก คณะผู้วิจัยได้ศึกษาความแม่นยำของการประมวลภาพสามมิติจากการตรวจคลื่นเสียงสะท้อนหัวใจดอปเปลอร์ชนิดสีแบบดิจิทอลโดยวิธีกวาดมืออย่างอิสระ (freehand "Flock of Birds") ในการประเมินความตีบ เพื่อประโยชน์ในการวางแผนการรักษา ผู้วิจัยได้สร้างแบบจำลองแขนงหลอดเลือดแดงในปอดที่มีขนาดพื้นที่หน้าตัด 0.7 ตร.ซม. และทำให้เกิดรอยตีบแคบขนาดพื้นที่หน้าตัดตั้งแต่ 0.13–0.59 ตร.ซม. และมีความตีบเป็นแนวยาวตั้งแต่ 0.17–1.80 ซม. ได้ใช้การตรวจคลื่นเสียงสะท้อนจากภายในหลอดเลือดเป็นค่าสำหรับอ้างอิงความถูกต้องของการประเมินความตีบ ใช้ปั๊มสูบฉีดแบบเป็นคลื่นให้กำเนิดปริมาณเลือดไหลเวียนสู่แบบจำลอง การตรวจความตีบของหลอดเลือดใช้หัวตรวจขนาด 3.5 เมกะเฮิร์สที่ติดกับอุปกรณ์ตรวจรับสัญญาณคลื่นแม่เหล็กไฟฟ้าเข้าสู่เครื่องตรวจคลื่นเสียงสะท้อนหัวใจเพื่อกำหนดตำแหน่งการวางตัวในระนาบ 3 มิติของหัวตรวจโดยใช้การกวาดมืออย่างอิสระ กำหนดจังหวะการจับภาพโดยใช้สัญญาณคลื่นไฟฟ้าหัวใจที่ตำแหน่งการบีบตัวเต็มที่ ข้อมูลที่ได้นำมาประมวลเป็นภาพสามมิติโดยโปรแกรม EchoPac 3D แล้ววัดความตีบที่ตำแหน่งต่าง ๆ ผลการศึกษาพบว่าภาพหล่อ (cast) สัญญาณสีสามมิติของเลือดที่ไหลผ่านภายในหลอดเลือดเข้าปอดสามารถแสดงพื้นที่หน้าตัดและระยะความยาวของการตีบของหลอดเลือดแดงปอดได้ใกล้เคียงกับค่าอ้างอิง ที่วัดได้จากการตรวจคลื่นเสียงสะท้อนภายในหลอดเลือด ($r=0.98$, $p<0.001$, SEE=0.04 cm^2 และ $r=0.98$, $p<0.001$, SEE=0.03 cm ตามลำดับ) นอกจากนี้ยังสามารถแสดงถึงกายวิภาคที่ซับซ้อนของความตีบได้อย่างชัดเจน การประมวลภาพสามมิติจากการตรวจคลื่นเสียงสะท้อนหัวใจระบบดิจิทอลแบบสีโดยการกวาดมืออย่างอิสระสามารถประเมินความรุนแรงของความตีบของหลอดเลือดแดงในปอดได้อย่างถูกต้องแม่นยำ ดังนั้นจึงสามารถนำวิธีการดังกล่าวมาประยุกต์ในการตรวจวินิจฉัยผู้ป่วยที่มีการตีบของหลอดเลือดในปอดได้ต่อไปในอนาคต

คำสำคัญ : การตรวจคลื่นเสียงสะท้อนหัวใจแบบ 3 มิติ, การตรวจคลื่นเสียงสะท้อนหัวใจดอปเปลอร์ชนิดสี, หลอดเลือดแดงในปอดตีบ

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** ศูนย์บริบาลคลินิกสำหรับผู้ป่วยโรคหัวใจแต่กำเนิด, มหาวิทยาลัยโอเรกอนเฮลธ์แอนด์ไซนส์, เมืองพอร์ทแลนด์, รัฐโอเรกอน, สหรัฐอเมริกา