Taguchi's analysis to optimize descending aortography for patent ductus arteriosus, with clinical verification

Fu-Tsai Chiang[1,2] MD, Kuang-Hua Chu[1,3] MSc, Ching-Yuan Chen[1,4] MD, Chien-Yi Chen[5] MD, PhD, Lung-Kwang Pan[1] MD, PhD

1. Graduate Institute of Radiological Science, Central Taiwan University of Science and Technology, Takun, Taichung 406, Taiwan.
2. Department of Orthopedic Surgery, Taichung Armed Forces General Hospital, Taichung, 406, Taiwan, ROC
3. Cardiovascular Center, Taichung Veterans General Hospital, Taichung, 407, Taiwan.
4. Department of Nuclear Medicine, Buddhist Tzu Chi General Hospital, Taichung Branch, Taichung, 427, Taiwan.
5. School of Medical Imaging and Radiological Sciences, Chung Shan Medical University, Taichung, 402, Taiwan

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Corresponding author:
Prof. Lung Kwang Pan
Graduate Institute of Radiological Science,
Central Taiwan University of Science and Technology,
Takun, Taichung 406, Taiwan
lkpan@ctust.edu.tw

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Abstract

Objective: Taguchi's analysis was adopted to optimize the various factors referring to cardiac angiographic examination used to delineating ductus arteriosus in pediatric patients. **Subjects and Methods:** Thirty-six pediatric patients, 9 male and 27 female, mean age of 6.5±4.7yrs, range 0.6 to 16.6 years were included in the study from January 2004 to April 2005. All patients had patent ductus arteriosus (PDA). Taguchi's L_9 orthogonal array was used to generate nine different designs of angiographic levels. Four control factors were selected: a) body surface area (BSA), b) projection angle, c) catheter location, and d) the volume of contrast medium. Each factor was set to three different levels. Statistical analysis, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were used to estimate the optimum level of each control factor and to analyze the effect of each factor. **Results and Conclusion:** The optimal combinations that obtained the highest image quality for PDA were: a) at <0.65m^2 of BSA, b) right anterior oblique (RAO) position at 30° plus cranial position (Cr) at 15° and lateral view, c) catheter location at T2-3 and d) contrast medium volume: 1.0cc/kg. The projection angle was found to be the most significant factor to delineate ductus arteriosus using the ANOVA test and was not influenced by other factors. The setting of RAO at 30° plus Cr at 15° and the LAT view obtained the optimal image quality for PDA during descending aortography.

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Introduction

Patent ductus arteriosus (PDA) is one of the most common, about 5%-10% of congenital heart diseases in Taiwanese children. Isolated PDA incidence has been estimated about 9% to 12% of all presenting congenital heart diseases [1]. Since the first report on trans-catheter ductal occlusion of PDA by Porstmann et al. (1971) [2], many methods and devices including the Rashkind double umbrella, Sideris's buttoned device, the coil closure, and the Amplatzer device, have been widely used as alternatives to surgical ligation or division [3-10]. The lateral view of the anatomy and shape of the ductus arteriosus has been analyzed by angiographic classification by Krichenko et al. (1989) [11]. Descending aortography (DAOG) can be used to view the PDA directly and allow for the implantation of an occluder device. This therapeutic strategy requires accurate localization and precise size measurements of the PDA. The diameter of the narrowest segment of PDA in angiographic images is very important for the interventional occluder device implantation. Many factors interfere with the quality of angiographic images, including body surface area (BSA), projection angle, catheter location, and the volume of the contrast medium. The image quality can in turn influence the intervention strategy.

The Taguchi's method is one of a number of robust design techniques. It provides a systematic and efficient approach for conducting experiments to determine the optimal settings of quality characteristic and also utilizes the orthogonal array in order to study a large number of variables with a minimum number of experiments [12, 13]. Using orthogonal arrays significantly reduces the number of experiments to be conducted and also decreases the costs of research and development by simultaneously studying a large number of factors [14]. In order to analyze the results of the experiments, Taguchi's method uses a statistical measurement of performance called the signal-to-noise (S/N) ratio that takes into account both mean and variability. The S/N equation depends on the characteristics necessary to optimize the quality of the angiographic image. Furthermore, after performing the S/N ratio analysis, analysis of variance (ANOVA) needs to be employed for estimating error variance and for determining the relative importance of various factors, such as BSA, projection angle, catheter location and the volume of contrast medium.

The purpose of this study was to use Taguchi's method in the medical imaging field in order to introduce new insight into which factors and combinations of angiographic positions are most important in delineating ductus arteriosus during descending aortography.

Subjects and Methods

Patient population

A total of 36 patients with isolated PDA type A (of conical shape) who underwent cardiac catheterization were enrolled in this study from January 2004 to April 2005. There were 9 male and 27 female. All demographic data of the patients are expressed as mean±SD (standard deviation). The patients had a mean age of 6.5±4.7years, range 0.6 to 16.6 years, mean height of 112.2±28.5cm, range 66-166cm, and mean weight of 23.6±13.7kg, range 6.7 to 63kg (Table 1).

Table 1. *Patient demographic data*

Data	Patient Group (N=36)
M/F ratio	9/27
Age (years)	6.5±4.7[a]
Body height (cm)	112.2±28.5[a]
Body weight (kg)	23.6±13.7[a]

[a]: *Data are presented as mean value ± SD.*

Orthogonal array

The Taguchi's method utilizes orthogonal arrays to study a large number of variables with a minimum number of experiments [15, 16]. In the first series of this study, a Taguchi's standard $L_9(3^4)$ array was used to generate nine different arrangements of angiographic levels (Table 2). Each row of the matrix represents one trial. Four control factors were selected for this study, and there were three levels for each in the following combinations: a) three BSA (<0.65m^2, 0.65-1.0m^2 and >1.0m^2), body surface area (m^2)=0.007184xweight$^{0.425}$(kg)xheight$^{0.725}$(cm) [17], b) three projection angles at the anteroposterior and lateral (LAT) view, right anterior oblique (RAO) ankle at 15° plus cranial (Cr) ankle at 15° and LAT view, and RAO at 30° plus Cr at 15° and LAT view, c) three catheter locations (thoracic vertebra) T2-3 (between the T2 and T3 vertebra), T3, and T3-4 (between the 3rd and 4th thoracic vertebra) and d) three volumes of contrast medium (1.0cc/kg, 1.25cc/kg, and 1.5cc/kg). The three levels of each factor are represented by an '1', '2', or '3' in the matrix. Table 3 shows the assigned factors and levels.

Table 2. *Experimental layout using an L_9 orthogonal array; on the left side, (the numbers indicate the experiments, and the letters at the top of the column indicate the factors).*

Experimental number	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3. *Factors and levels for the angiographic image quality*

Factor	Levels		
	1	2	3
A.Body surface area (m^2)	0.65 ↓	0.65-1.0	1.0 ↑
B.Projection angle	AP+LAT[a]	RAO15°Cr15° +LAT[a]	RAO30°Cr15° +LAT[a]
C.Catheter location	T2-3[b]	T3[b]	T3-4[b]
D.Contrast media (cc/kg)	1.0	1.25	1.5

[a]: *AP=anteroposterior; LAT=lateral, RAO=right anterior oblique, Cr=cranial* [b]: *T: thoracic vertebra*

Throughout this work the following acronyms will be used: DAO (descending aorta), LPA (left pulmonary artery), PA (pulmonary artery), PDA (patent ductus arteriosus), and RPA (right pulmonary artery).

Taguchi's method

The Taguchi's method is a powerful tool for the design of a high-quality system. The basic principle of this method is to develop an understanding of the individual and combined effects of various assigned factors, such as BSA, projection angle, catheter location, and volume of the contrast medium for angiographic image quality during DAOG. This method of factor design aims to establish the optimal combination of settings and to reduce variations in image quality. The S/N ratio as statistical measurement of performance is used to analyze the results and to quantify the variation. The S/N ratio characteristics can be divided into three categories: "lower-is-better" (LB), "nominal-is-best" (NB), and "higher-is-better" (HB). In this work, the equations for the particular type of characteristics assigned in order to obtain HB optimal image quality are as follows:

$$S/N = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2} \quad (1)$$

where n is the number of observations. y is the observed data. s^2 is the variance of y. $\bar{y}$ is the average of observed data.

This study found that for each type of characteristic, analyzed with the above S/N ratio equation, a higher S/N ratio is better as it resulted in better image quality for PDA during descending aortography.

Furthermore, ANOVA needs to be employed after performing the S/N ratio analysis to estimate error variance and to determine the relative importance of the four factors. The equations for assessing which factor has the most significant effect in this study are as follows:

$$SS_{Total} = \left(\sum_{i=1}^{n}\sum_{j=1}^{r} y^2_{ij}\right) - n\times r\times \bar{y}^2 \quad (2)$$

$$SS_{Factor} = \frac{n\times r}{L}\left(\sum_{k=1}^{L}\left(\bar{y}_k - \bar{y}\right)^2\right) \quad (3)$$

$$DOF_{Factor} = L-1 \quad (4)$$

$$V_{Factor} = \frac{SS_{Factor}}{DOF} \quad (5)$$

$$F_{Factor} = \frac{V_{Factor}}{V_{error}} \quad (6)$$

where SStotal is the total sum of squares and SSfactor is the factorial sum of squares. n is the number of factors combine (9 in this work), r is the number of observations. y is the observed data and $\bar{y}$ is the average of observed data. DOF is the number of degrees of freedom and VFactor is the variance of the factor. FFactor is the F ratio of the factor.

Experimental procedures

Thirty-six patients with PDA type A followed by the criteria in Table 3 underwent DAOG using a Philips INTEGRIS BH5000 digital cardioangiographic system (Best, Netherlands). An angiographic pigtail catheter (Cordis Corporation, Miami, Florida, USA), 5F (French) or 6F was introduced percutaneously through the femoral artery into the descending aorta. The contrast medium (Ultravist 370, Schering, Germany) for the DAOG was delivered by an Angiomat 6000 injector (Liebel-Flarsheim Company, Cincinnati, Ohio, USA). Images were acquired at 30 frames/s using a 1024x1024 pixel density and two 20-inch fields. Both the frontal and lateral images of the ductus at the end-systolic phase from the DAOG were chosen to determine the image quality of the PDA. The imaging quality of the DAOG was divided into three grades in each projection. Score 1 (poor quality) was assigned if only the DAO and PA were pacified but the ductus could not be seen; score 2 (fair quality) was used when the ampulla or narrowest segment of the ductus appeared in the image. Score 3 (good quality) was used when both the ampulla and the narrowest segment of the ductus could be clearly seen. All images of the DAOG were interpreted and scored by a consensus of two well-trained cardiologists, with a third cardiologist interpreting in cases of disagreement. Informed consent was obtained from the patient or the guardian of the patient. Data recorded at the time of cardiac catheterization were analyzed and reviewed retrospectively.

Results

Analysis of S/N ratio

Table 4 shows the actual data of observed scores for angiographic image quality along with their scores and computed averages, SD and S/N ratio obtained by the two cardiologists according to the Taguchi's analysis. Figure 1 implies the derived average, SD, and S/N ratio as denoted in Table 4. This study defined the HB index of S/N to obtain the image quality for PDA during descending aortography according to Taguchi (Figure 2). Table 4 revealed that the optimal levels combination obtained by the S/N ratio to get the highest image quality for PDA included: a) BSA <0.65m^2, b) RAO at 30° plus Cr at 15° and LAT view, c) thoracic vertebra (T2-3) and d) contrast medium volume, 1.0cc/kg. Thus, the optimal combination chosen was $A_1B_3C_1D_1$.

Analysis of variance (ANOVA)

In order to assess the relative importance of the factors, an ANOVA analysis was performed using Equations (2-6). Table 5 summarizes the present ANOVA results. The values of the sums of squares (SS), due to the four factors, tabulated in the third column of Table 5, are a measurement of the relative im-

Table 4. Experimental results for angiographic image quality and their corresponding S/N ratio

Group number	Factor				Observed scores				Average	SD	S/N ratio
	A	B	C	D	y1	y2	y3	y4			
1	1	1	1	1	4	4	4	4	4.00	0.00	12.04
2	1	2	2	2	5	5	4	4	4.50	0.58	12.90
1	1	3	3	3	6	6	6	5	5.75	0.50	15.11
4	2	1	2	3	3	4	3	4	3.50	0.58	10.61
5	2	2	3	1	4	5	4	6	4.75	0.96	13.17
6	2	3	1	2	6	6	5	6	5.75	0.50	15.11
7	3	1	3	2	3	4	3	4	3.50	0.58	12.90
8	3	2	1	3	5	5	4	4	4.50	0.58	12.90
9	3	3	2	1	6	4	5	6	5.25	0.96	14.03

Table 5. Analysis of variance (ANOVA) for angiographic image quality

Factors	DOF	SS	Variance	F ratio	Confidence (%)	Significant
A.Body surface area (m^2)	2	0.72	0.36	0.89	57.8	No
B.Projection angle	2	22.06	11.03	27.07	100.0	Yes
C.Catheter location	2	0.72	0.36	0.89	57.8	No
D.Contrast media (cc/kg)	2	0.06	0.03	0.07	6.7	No
Error	27	11.00	0.41		S=0.64	
Total	35	34.56	0.99		*Note: At least 95% confidence	

portance of the factors in angiographic image quality for PDA. A factor was considered significant if its confidence level exceeded 95%. Therefore, the projection angle B) explained a dominant portion of the image quality for PDA. The BSA A), catheter location C) and contrast media D) were responsible for insignificant parts of the derived image quality, namely 57.8%, 57.8% and 6.7%, respectively. An estimation of the variance ratio explained that the effect of the three factors A), C), and D) was not significant when compared to the error variance. In fact, these three factors did not yield the confidence level required for clinical procedures.

Discussion

Dominant and minor factors

In the past, the only method for closing PDA was the surgical treatment through a lateral thoracotomy [18]. Trans-catheter occluding devices, such as coils and occluders, have

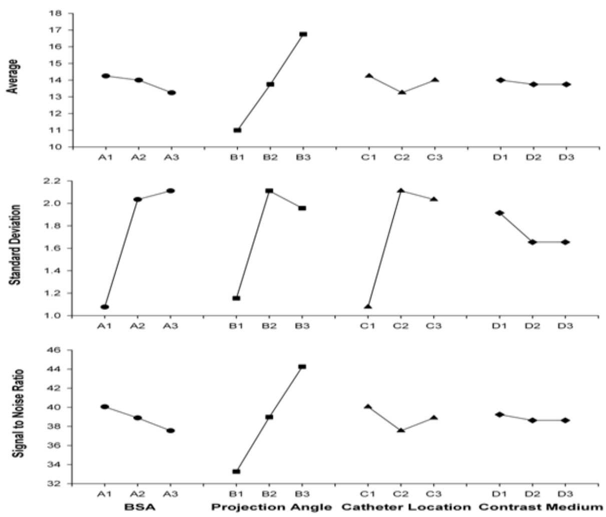

Figure 1. Shows the derived average, standard deviation, and S/N ratio of the image quality of PDA during DAOG according to Taguchi's analysis.

been widely used to seal off the defect. However, this therapeutic strategy requires accurate localization and precise size measurement for PDA during DAOG before therapeutic intervention [6-9]. Arora et al. (2013) suggest that when there was a discrepancy between clinical, radiographic and echocardiographic signs the aortogram was of significant value to diagnose significant shunting through PDA. Other uncontroled factors included the direction in which the catheter tip was oriented, the volume of the contrast medium and the precise timing of exposure of radiography [19]. Retrograde aortic angiography to demonstrate the PDA was described by Grosse C. and Grosse A. (2010). They used aortography at the anteroposterior position (AP) to attempt to visualize PDA in premature patients, but the descending aorta overlapped the PDA and they could only see the right part of cardiac image and the pulmonary artery [20, 21]. Promphan et al. (2014) used the LAO view at 60o-70o to show the PDA in pulmonary angiography, but in this method the contrast media may be injected into the PA near the opening of the ductus. The PDA and the DAO can only be viewed transiently [22]. Krichenko et al. (1989) classified the PDA angiographically using the LL view [11].

We have presented the experimental method in evaluating the image quality of optimization for PDA during DAOG. The goal of the Taguchi's method is to find the optimum conditions and to estimate their numerical factors. However, the Taguchi's system contains much more information because it can calculate the numerical factors not only for the optimum conditions but also for any combination of the factors [23, 24]. The projection angle is found to be the most significant factor, not influenced by other factors, to delineate the ductus using the ANOVA test. Other factors like the BSA, catheter location for thoracic vertebra and the volume of contrast medium have only a minor contribution in image quality.

The PDA cannot be visualized well by the projection angles AP and RAO at 15° and Cr at 15° because of the overlap of the descending aorta. By using RAO at 30° and Cr at 15° angulation, the location of the ductus is placed to the lateral aspect of DAO and is viewed directly, so it can be well visualized. Today's medical community seeks to obtain high quality images at a lower cost, which is a challenge of both economy and technology. The 1.0cc/kg volume of contrast medium is much less than 1.25cc/kg and 1.5cc/kg, while it allows for better quality images, it improve patients safety, especially for patients with acute renal failure or pulmonary edema which can be induced if more contrast media is injected. The Taguchi method is widely used by quality control engineers to design robust products. This technique can be successfully applied to optimize the factors for PDA during descending aortography.

Optimal verifications

To determine the optimal conditions and to compare the results with those expected, it is essential to perform the confirmation experiment in a practical manner. If the generated design fails to meet the specified requirements, the process must be reiterated using a new study until the required criteria are satisfied. In the present study, the verification experiment was performed by setting the design factors combination as: $A_1B_3C_1D_1$.

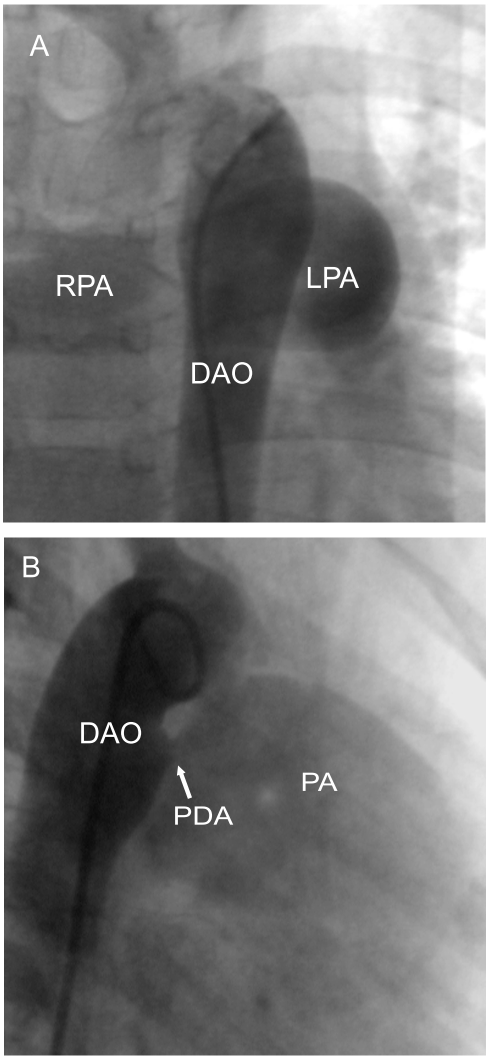

Figure 2. Revealed the retrograde descending aortogram. (A) conventional set (AP view), only the DAO and PA were opacified but the PDA cannot be seen. (B) optimal set (RAO 30° plus Cr 15° view) for comparing, both the ampulla and narrowest segment of the ductus could be clearly visualized. This was important from the clinical viewpoint for PDA treated during interventional therapy.

Conclusion

By using the Taguchi method to optimize the image quality for PDA during DAOG, we demonstrated the advantages of the method over the most conventional cardio-angiography. Another advantage of this method was that the optimization and the determination of assigned factors of the assay could be carried out in one step. The optimal factor settings for DAOG included: a) BSA: <0.65m^2, b) projection angle: RAO at 30° plus Cr at 15° and LAT view, c) catheter location: thoracic vertebra T2-3 and d) volume of contrast medium: 1.0cc/kg from the optimization.

These optimal settings yielded the highest score average and S/N ratio. The ANOVA analysis used herein revealed that the dominant factor was projection angle without interactions with BSA, catheter locations, and contrast media, which were minor factors in delineating the ductus during descending aortography.

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