III. PEDIATRIC SURGERY

DETERMINATION OF THE MECHANICAL REQUIREMENTS FOR A PROGRESSIVE CORRECTION SYSTEM (PCS) OF PECTUS EXCAVATUM IN CHILDREN

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Abstract

Pectus excavatum is the most frequent deformity of the thorax. Many surgical procedures have been used for correcting this chest wall deformity. The Nuss procedure performs an instant full correction using a rigid stainless steel bar but some patients experience acute pain. We propose a new progressive correction technique for the chest deformity using an elastic rod. This method requires the specification of mechanical properties in correlation with thorax anthropometrical characteristics. The force-displacement correlation for anterior-posterior compression of the thorax was determined for forty normal male and female subjects between 4 and 16 years old.

The measurement data offer the following conclusions: displacements less than 3,1cm ….. 4cm in pectus excavatum can be corrected with the Nuss method because the pain level is not surpassed. Displacements larger than 4cm must be corrected progressively. The younger the child is, the manageable displacements imposed by the pain level are larger average displacement = 3,22cm while the older children can tolerate only shorter displacements 2,62cm.The average required force in order to obtain a displacement of up to 4cm varies with age between F=10,28 kgF at a younger age and F=13,61 kgF in older children. At a younger age one can achieve larger displacements with a smaller force, but the force required for the same correction grows linearly with age.

The correction of pectus excavatum should be achieved with a progressive correction system (PCS) that must take into account these mechanical parameters.

Key words: pectus excavatum, force-displacement correlation, progressive correction system (PCS)

Introduction

Many surgical procedures have been used for correcting the chest wall deformities [1][9][10]. Recently a new technique was introduced by D. Nuss [6] with a significant improvement of the final result, while minimizing the surgical trauma. Additional advantages are provided by the cosmetical and functional benefits. However, this technique performs an instant full correction using a rigid stainless steel bar. As a result, among other complications [4][5], some patients experience acute pain and sometimes it was necessary to remove the rigid bar. It is obvious that this method should be improved by performing a progressive correction instead of the instant one.

Objectives:

We propose a new method for correcting the chest deformity using an elastic rod instead of the rigid one currently employed in the Nuss technique.

Designing such an elastic rod requires the specification of the rod mechanical properties in correlation with thorax mechanical and anthropometrical characteristics. While geometrical requirements are relatively easy to formulate from anatomical data, mechanical properties of the thorax cannot be readily found in literature. As a result, one has to measure the force versus displacement for anterior-posterior compression of the thorax, below individual pain level.

The final result of such investigation is a quantitative description of the force-displacement correlation for different groups of age and gender.

The ideal determinations should measure the mechanical properties of the anterior wall of the thoracic cage in pectus excavatum when the deformation is the result of forces with a posterior to anterior trajectory. These cannot be experimentally tested on "in vivo" models at children. That is why we begin our study with the theoretical idea that the desired values can be approximated by the determining the forces corresponding to reverse antero-posterior deformations.

Material and method:

The experimental setup employed a force transducer (based on a strain gauge bridge) applied on the sternum with patient in supine position on a rigid surface and a device for measuring the anterior-posterior thorax displacement (Fig. 1 and Fig. 2).

Fig. 1 – Force transducer

Fig. 2 - Clinical measurement

The maximum force value was limited by the subject acute pain level. Forty normal male and female subjects between 4 and 16 years old were investigated. The force (**F**) – displacement (**d**) correlation was modeled as:

$$F = a_1 d + a_2 d^2$$

were the a_1 and a_2 coefficients are determined for each subject using a least-squares fit of experimental data [8].

The linear coefficient a_1 corresponds to the elastic properties of the thorax, while the quadratic coefficient a_2 accounts for the thorax stiffening as the displacement increases.

Results:

The force and displacement values for male and female subjects are presented in table 1, 2, 3 and 4.

Table 1. Force-displacement data for 4 to 6 years old male and female subjects.

displacement (cm) / Force (kgf)												
Age	4 years				5 years				6 years			
Gender	M(male)		F(female)		M(male)		F(female)		M(male)		F(female)	
Case number	I	II	I	II	I	II	I	II	I	II	I	II
displacement(cm)												
0,4	-	0,72	-	0,80	-	-	-	-	-	-	-	1,10
0,5	0,38	0,84	-	-	-	-	-	-	1,60	1,04	-	-
0,6	-	-	-	0,90	-	1,70	1,90	1,10	-	-	-	1,30
0,7	1,00	1,34	-	-	1,20	-	-	-	-	1,53	-	-
0,8	-	-	-	1,20	-	-	-	-	1,42	-	-	1,41
0,9	1,21	1,89	-	-	-	-	-	-	-	-	-	-
1	1,40	-	-	1,30	-	2,80	3,45	2,00	2,29	1,69	-	1,49
1,1	-	2,63	-	-	-	-	-	-	-	-	-	-
1,2	1,66	-	-	1,42	2,40	-	5,50	2,80	3,12	2,59	-	1,60
1,3	-	3,10	-	-	-	-	-	-	-	-	-	-
1,4	2,30	-	-	1,81	-	4,00	-	-	-	3,09	-	1,90
1,5	2,55	-	-	-	-	-	6,54	-	3,44	-	-	-
1,6	-	-	-	2,11	3,10	-	-	3,90	-	-	-	-
1,7	3,00	-	-	-	-	-	-	-	4,45	4,08	-	2,80
1,8	-	5,30	-	2,93	-	-	6,30	-	-	-	-	-
1,9	3,60	-	-	-	-	6,00	-	-	5,34	4,83	-	4,10
2	4,00	6,99	-	4,01	4,20	-	7,03	5,80	5,86	-	-	-
2,1	-	-	-	-	-	-	-	-	-	5,64	-	4,60
2,2	-	-	-	4,08	-	-	-	-	6,22	-	-	-

2,3	4,75	8,58	-	-	-	**7,70**	7,80	-	-	-	-	5,10
2,4	-	-	-	6,70	5,30	-	-	-	6,82	-	-	-
2,5	5,81	-	-	-	-	-	8,12	**8,40**	7,21	5,52	-	6,30
2,6	-	-	-	-	-	-	-	-	7,36	-	-	-
2,7	6,70	10	-	7,30	-	-	**9,01**	-	-	6,62	-	6,70
2,8	-	-	-	-	6,50	-	-	-	7,76	-	-	-
2,9	-	-	-	-	-	-	-	-	-	**7,25**	-	7,30
3	7,60	-	-	9,00	-	-	-	-	8,01	-	-	-
3,1	8,29	-	-	-	7,20	-	-	-	-	-	-	7,90
3,2	8,69	-	-	9,50	-	-	-	-	-	-	-	-
3,3	-	12	-	-	-	-	-	-	-	-	-	8,90
3,4	-	-	-	10,00	**8,00**	-	-	-	**9,03**	-	-	-
3,5	**10**	**14**	-	-	-	-	-	-	-	-	-	10,00
3,6	-	-	-	11,20	-	-	-	-	-	-	-	-
3,7	-	-	-	-	-	-	-	-	-	-	-	11,30
3,8	-	-	-	13,00	-	-	-	-	-	-	-	-
3,9	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	**14,30**	-	-	-	-	-	-	-	**15,20**

Average force – 10,28kgF
Average displacement – 3,22cm

Table 2. Force-displacement data for 7 to 9 years old male and female subjects.

displacement (cm) / Force (kgf)												
Age	7 years				8 years				9 years			
Gender	M		F		M		F		M		F	
Case number	I	II	I	II	I	II	I	II	I	II	I	II
displacement(cm)												
0,4	1,90	-	-	0,47	-	-	1,80	1,70	-	-	-	1,60
0,5	2,40	0,65	-	-	0,75	-	-	-	-	-	-	-
0,6	-	-	-	0,60	-	-	2,46	2,10	1,60	2,20	-	1,80
0,7	2,66	0,90	-	-	-	-	-	-	-	-	-	-
0,8	-	-	-	-	-	-	-	2,50	-	-	-	-
0,9	3,66	1,25	-	1,14	-	-	3,50	-	-	-	-	1,95
1	3,85	-	-	-	1,87	-	-	3,20	3,30	-	-	-
1,1	-	2,31	-	1,55	-	-	-	-	-	-	-	2,40
1,2	4,14	-	-	-	-	-	4,19	-	-	4,70	-	-
1,3	-	3,17	-	1,78	-	-	-	4,60	-	-	-	3,90
1,4	5,58	-	-	-	-	-	5,12	-	-	-	-	4,60
1,5	-	3,73	-	2,11	-	-	-	5,20	-	5,20	-	5,10
1,6	6,06	-	-	2,40	-	-	6,07	-	6,00	-	-	-
1,7	-	4,56	-	-	3,65	-	-	5,50	-	5,60	-	-
1,8	6,83	-	-	-	-	-	-	-	-	-	-	5,90
1,9	-	5,75	-	2,80	-	-	-	5,70	9,00	6,70	-	-
2	8,77	-	-	-	**4,55**	-	6,75	-	6,80	-	-	6,80
2,1	-	6,60	-	3,29	-	-	7,32	5,90	-	8,70	-	-
2,2	9,07	-	-	3,62	-	-	**7,05**	-	-	-	-	7,10
2,3	-	7,80	-	-	-	-	-	6,12	-	-	-	-
2,4	9,31	-	-	-	-	-	-	-	8,20	-	-	8,40
2,5	-	8,67	-	3,80	-	-	-	6,50	-	-	-	-
2,6	9,81	-	-	-	-	-	-	-	**10,0**	-	-	8,90
2,7	-	9,76	-	4,25	-	-	-	7,30	-	**11,6**	-	9,80
2,8	10,86	-	-	-	-	-	-	-	-	-	-	10,20
2,9	-	**10,18**	-	-	-	-	-	7,65	-	-	-	-
3	11,20	-	-	4,80	-	-	-	-	-	-	-	11,70
3,1	-	-	-	-	-	-	-	8,10	-	-	-	-
3,2	11,58	-	-	5,41	-	-	-	-	-	-	-	12,90

3,3	-	-	-	**6,02**	-	-	-	9,16	-	-	-	-
3,4	-	-	-	-	-	-	-	-	-	-	-	**13,80**
3,5	**12,36**	-	-	-	-	-	-	**11,00**	-	-	-	-

Average force – 9,61 kgF
Average displacement – 2,9 cm

Table 3. Force-displacement data for 10 to 12 years old male and female subjects.

displacement (cm) / Force (kgf)												
Age	10 years				11 years				12 years			
Gender	M		F		M		F		M		F	
Case number	I	II	I	II	I	II	I	II	I	II	I	II
displacement(cm)												
0,4	1,50	-	-	1,70	1,60	1,50	-	1,70	-	-	1,50	-
0,5	-	-	-	-	1,70	-	-	-	2,60	2,30	-	-
0,6	-	1,80	-	1,90	-	1,70	-	1,70	-	-	1,93	-
0,7	-	-	-	-	-	-	-	-	-	-	-	-
0,8	-	3,30	-	2,20	2,30	2,50	-	-	-	-	3,00	-
0,9	-	-	-	-	-	-	-	2,30	3,80	3,90	3,61	-
1	-	-	-	2,90	2,90	-	-	-	-	-	-	-
1,1	2,90	-	-	-	-	3,10	-	3,05	-	-	-	-
1,2	-	-	-	3,20	3,30	3,20	-	3,10	-	-	4,38	-
1,3	-	3,30	-	-	-	-	-	-	-	-	-	-
1,4	-	-	-	3,80	3,70	-	-	3,80	-	5,80	5,25	-
1,5	-	-	-	-	-	4,70	-	-	-	-	-	-
1,6	-	4,80	-	4,20	-	-	-	4,50	6,40	-	6,32	-
1,7	-	-	-	-	4,60	-	-	-	-	-	-	-
1,8	5,10	-	-	4,80	-	5,00	-	5,10	-	-	6,95	-
1,9	-	-	-	-	-	-	-	-	-	-	-	-
2	-	6,50	-	5,90	5,30	5,90	-	6,80	-	9,00	7,94	-
2,1	-	-	-	6,30	6,30	-	-	-	8,60	-	9,39	-
2,2	-	-	-	-	-	6,80	-	-	-	-	-	-
2,3	-	-	-	6,90	-	-	-	7,30	10,3	**9,50**	10,10	-
2,4	-	-	-	-	7,80	-	-	-	-	-	10,37	-
2,5	6,80	-	-	7,50	-	7,90	-	8,00	**11,5**	-	-	-
2,6	-	10,0	-	8,80	-	-	-	-	-	-	**10,54**	-
2,7	-	-	-	9,10	8,60	8,40	-	9,30	-	-	-	-
2,8	-	-	-	-	-	-	-	-	-	-	-	-
2,9	-	-	-	10,00	9,80	10,20	-	10,60	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
3,1	9,80	-	-	11,00	10,80	11,30	-	11,80	-	-	-	-
3,2	-	13,5	-	**11,30**	-	-	-	-	-	-	-	-
3,3	-	-	-	-	**12,90**	**13,00**	-	**13,90**	-	-	-	-
3,4	-	-	-	--	-	-	-	-	-	-	-	-
3,5	-	-	-	-	-	-	-	-	-	-	-	-
3,6	-	**14,6**	-	-	-	-	-	-	-	-	-	-
3,7	**11,0**	-	-	-	-	-	-	-	-	-	-	-

Average force – 12,02 kgF
Average displacement – 3,08 cm

Table 4. Force-displacement data for 13 to 16 years old male and female subjects.

displacement (cm) / Force (kgf)																
Age	13 years				14 years				15 years				16 years			
Gender	M		F		M		F		M		F		M		F	
Case number	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
displacement(cm)																

0,4	-	1,40	-	1,70	-	-	-	2,10	2,30	2,20	-	2,70	-	-	-	2,80
0,5	1,30	1,80	-	2,10	-	-	-	-	-	2,90	-	3,10	-	-	-	-
0,6	-	-	-	-	-	-	-	2,40	-	-	-	-	3,10	-	-	3,20
0,7	-	-	-	-	-	-	-	-	2,60	3,20	-	4,60	-	1,60	-	-
0,8	2,60	2,80	-	2,80	3,10	2,60	-	2,90	-	-	-	-	-	-	-	3,90
0,9	-	-	-	-	-	-	-	-	3,11	4,05	-	4,90	-	-	-	-
1	-	-	-	3,20	-	-	-	3,60	-	-	-	-	4,50	3,00	-	4,50
1,1	-	-	-	-	-	-	-	-	3,40	4,12	-	5,40	-	-	-	-
1,2	4,40	-	-	3,80	-	-	-	4,05	-	-	-	-	-	-	-	5,09
1,3	-	4,80	-	-	5,40	-	-	-	5,60	4,80	-	-	-	-	-	-
1,4	-	-	-	4,50	-	-	-	-	-	-	-	6,21	-	-	-	6,30
1,5	-	-	-	-	-	5,70	-	4,83	5,90	5,35	-	-	-	-	-	-
1,6	-	7,00	-	5,50	-	-	-	-	-	-	-	7,20	1,60	5,60	-	6,90
1,7	-	-	-	-	7,40	-	-	-	6,80	-	-	-	-	-	-	
1,8	-	-	-	6,90	-	-	-	6,90	-	6,30	-	7,90	-	-	-	7,20
1,9	7,50	-	-	-	-	-	-	-	7,39	-	-	-	-	-	-	-
2	-	-	-	-	-	7,80	-	8,10	-	7,80	-	8,50	-	-	-	7,60
2,1	-	10,6	-	8,80	-	-	-	-	8,60	-	-	-	-	-	-	-
2,2	-	-	-	-	-	-	-	9,53	-	9,60	-	8,80	-	7,80	-	-
2,3	-	-	-	10,6	-	-	-	-	10,2	-	-	-	-	-	-	8,80
2,4	-	-	-	-	10,5	-	-	11,0	-	11,6	-	9,90	-	-	-	-
2,5	-	-	-	11,3	-	**12,0**	-	-	12,1	-	-	-	12,0	-	-	10,0
2,6	-	-	-	-	-	-	-	-	-	**13,2**	-	10,5	-	-	-	-
2,7	8,90	-	-	11,5	14,6	-	-	12,8	-	-	-	-	-	-	-	12,5
2,8	-	-	-	-	**17,0**	-	-	-	**14,6**	-	-	12,3	15,0	11,3	-	**13,0**
2,9	**11,6**	**17,0**	-	**13,1**	-	-	-	**14,0**	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	**13,82**	-	-	-	-
3,1	-	-	-	-	-	-	-	-	-	-	-	-	**17,0**	**17,0**	-	-

Average force – 13,61kgF
Average displacement – 2,6cm

In figures 3 and 4 are plotted the experimental data for male and respectively female subjects. The lower and upper envelopes of the experimental data, plotted with solid lines correspond to the lower (4) and higher (16) age limits.

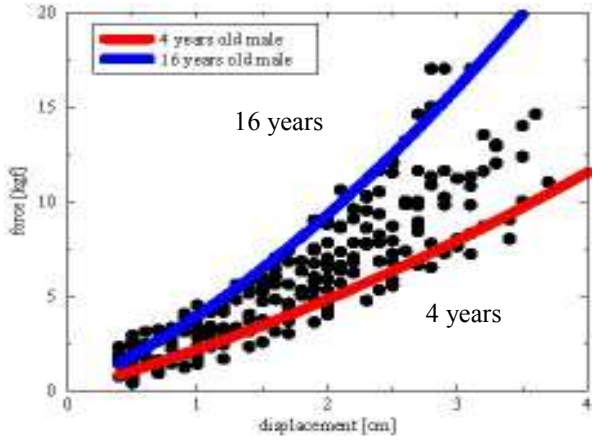

Figure 3. Force versus displacement measurements for male subjects.

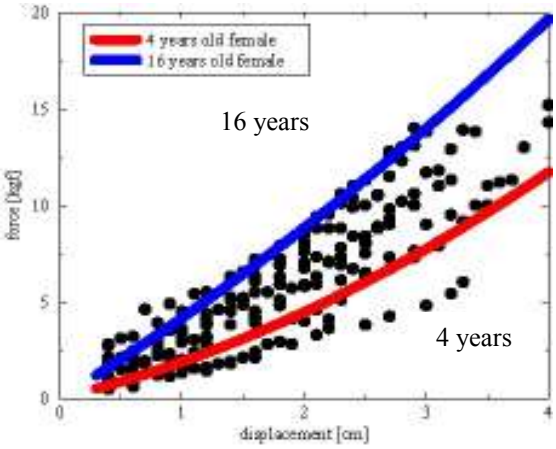

Figure 4. Force versus displacement measurements for female subjects.

When analyzing the two shown figures above we notice that:

- Force – displacement correlation is well represented by a parabolic function.
- At 4 years of age the forces needed to obtain the same displacement for male and female subjects are equal.
- At 16 years of age the same force produces a larger displacement in females. For the same displacement the males require a higher force.

One can observe that the elasticity of the thoracic wall does not depend in the first place on the consolidation (ossification) of the skeleton (that does occur quicker at females) but on the muscular mass that is more developed in males.

The values of the coefficients $\mathbf{a_1}$ and $\mathbf{a_2}$ for male and female subjects related to age are presented in tables 5 and 6.

Table 5. Values for $\mathbf{a_1}$ and $\mathbf{a_2}$ coefficients at male subjects

Age (years)	$\mathbf{a_1}$		$\mathbf{a_2}$	
	I	II	I	II
4	0,770	2,000	0,600	0,560
5	1,700	2,350	0,200	0,420
6	2,550	2,070	0,070	0,140
7	4,320	1,020	-0,200	0,870
8	1,380	-	0,450	-
9	3,600	2,730	0,050	0,560
10	2,630	2,450	0,110	0,480
11	1,980	2,080	0,510	0,500
12	3,790	4,450	0,270	-0,100
13	3,400	2,530	0,120	1,150
14	2,300	2,170	1,170	1,010
15	2,590	3,015	0,860	0,662
16	3,590	3,440	0,590	0,640

Table 6. Values for $\mathbf{a_1}$ and $\mathbf{a_2}$ coefficients at female subjects

Age (years)	$\mathbf{a_1}$		$\mathbf{a_2}$	
	I	II	I	II
4	-	0,454	-	0,772
5	4,533	1,163	-0,475	0,871
6	-	0,610	-	0,690
7	-	1,150	-	0,180
8	4,320	3,220	-0,460	-0,135
9	-	2,260	-	0,523
10	-	2,100	-	0,440
11	-	1,800	-	0,650
12	3,260	-	0,410	-
13	-	2,700	-	0,650
14	-	2,640	-	0,755
15	-	5,010	-	-0,270
16	-	4,220	-	0,031

The corresponding linear and quadratic coefficients are plotted versus age in the fig 5 and 6 for male and female subjects, by considering a linear regression in age.

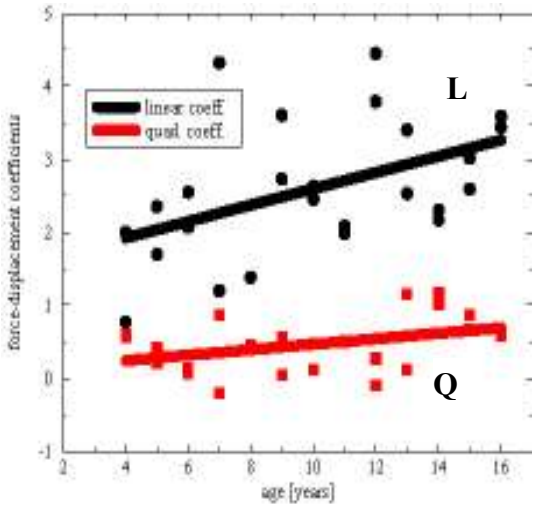

Figure 5. Coefficients a_1 (linear L) and a_2 (quadratic Q) for male subjects.

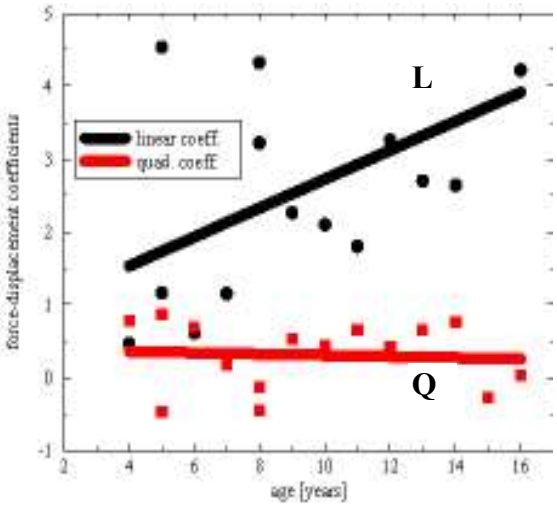

Figure 6. Coefficients a_1 (linear L) and a_2 (quadratic Q) for female subjects.

The level of pain recorded during the experiment was noted at d<4cm with variable limits:

- 4-6 years old : 2,3-4 cm average 3,22cm
- 7-9 years old : 2-3,5 cm average 2,9 cm

- 10-12 years old : 2,3-3,7 cm average 3,08 cm
- 13-16 years old : 2,8-3,1 cm average 2,62 cm

It can be seen that the linear coefficient significantly increases with age, showing an increase in thorax rigidity with age. Limit force – displacement curves for 4 and 16 years subject are plotted in fig 3 and 4 using the corresponding $\mathbf{a_1}$ and $\mathbf{a_2}$ coefficients determined by linear fits in fig 5 and 6.

Discussion

Pectus excavatum is the most frequent malformation of the chest wall [7].

Although the Nuss technique is new in the medical practice, it proved his undoubted superiority compared with all the other previous techniques. Recently published studies compare different subjects and present the advantages and disadvantages of the method [2][3].

One major disadvantage noted in the literature is the after surgery pain that in some cases lead to prolonged epidural anesthesia or even to the extraction of the Nuss bar. This is the result of a force that determines the deformation of the anterior thoracic wall surpassing the patient's bearable pain level [5].

The main idea of our study is that a progressive correction instead of the instant one will raise the level of after surgery comfort for the patients.

In order to design such a bar that will accomplish a progressive correction it is necessary to know the values of the force (F) that makes the right adjustments in order to obtain the desired final correction.

The main result of the present investigation is a quantitative analytical description of the force – displacement dependence for different age groups and male – female subjects.

Force – displacement correlations were obtained below the pain level. The correlation between F and d for d larger the pain level can be analyzed by the graphical representation of these functions and can be individualized for every patient.

These data define the mechanical (elastic) requirements for designing the elastic rod to be used in our progressive correction system (PCS).

Conclusions:

1. Displacements smaller than 3,1cm …. 4cm in pectus excavatum can be corrected with the Nuss procedure because the pain level is not surpassed.
2. Displacements larger than 4cm must be corrected progressively to prevent acute pain.
3. The younger the child is, the manageable displacements imposed by the pain level are larger (average d=3,22cm), while the older children can tolerate shorter displacements (average d=2,62cm).
4. The average needed force in order to obtain a displacement of up to 4cm varies with age between F=10,28 kgF at a younger age and F=13,61 kgF in older children.
5. At a younger age we can obtain larger displacements with a smaller force (F) and at an older age the forces grow linearly with age.
6. In female patients the correction can be obtained more easily even at an older age.
7. The correction of pectus excavatum should be achieved with a progressive correction devise that must take into account these parameters.

References

1. Fufezan V, Tepeneu P. A simplified surgical procedure for the correction of pectus excavatum. Timisoara Medicala tom XXXI 1986, Supplement pp 62-67
2. Miller KA, Ostlie DJ, Wade K et all. Minimally invasive bar repair for correction of pectus excavatum. Journal of Ped. Surgery 2002 Jul 37(7):1090-2
3. Miller KA, Woods RK, Sharp RJ et all. Minimally invasive repair of pectus excavatum; a single institution's experience. Surgery 2001 Oct 130(4):652-7; discussion 657-9
4. Moss RL, Albanese CT, and Reynolds M. Major complications after minimal invasive repair of pectus excavatum: case report. Journal of Ped. Surgery 2001 Jan (1):155-8
5. Nuss D, Croitoru DP, Kelly RE Jr. et all. Review and discussions of the complications of minimal invasive excavatum repair. Eur Journal of Ped. Surgery 2002 Aug 12(4):230-4
6. Nuss D, Kelly RE Jr, Croitoru DP et all. A 10 years review of minimal invasive technique for the correction of pectus excavatum. Journal of Ped. Surgery 1998 Apr. 33(4):545-552
7. Popoiu CM, Popoiu A. Malformatiile peretelui toracic anterior la copil – diagnostic si tratament. Ed. Eurostampa Timisoara, 2002, pp 138-147
8. Press WH, Tenkolsky SA, Vetterling WT, Flannery BP. Numerical recipes, Cambrige University Press, 1996
9. Ravitch MM. The operative treatment of pectus excavatum. Ann Surg. 129:429-444, 1949
10. Ravitch MM. Pectus excavatum In: Ravitch (Ed) Congenital deformities of the chest wall and their operative correction. W.B. Saunders, Philadelphia, pp 78-205, 1985

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