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BIOLOGICAL IMPLICATIONS OF INTRINSICALLY STABLE SPINAL INSTRUMENTATION

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INTRODUCTION

Background

- Spinal Arthrodesis
  - First successful treatment for scoliosis
- Spinal instrumentation
  - Required to reliably obtain fusion
- Intrinsically stable instrumentation
  - Required to
    - Control three dimensional deformity and
    - Eliminate external immobilization

Possible negative consequences of intrinsically stable instrumentation on

- Fusion
- Bypassed bone and disk
- Unbypassed adjacent and periadjacent bone and disk

Purpose

Experimentally quantify biological effects of stiff, pedicle screw anchored, posterior spinal instrumentation

Hypotheses

- Anterior column growth can be controlled
- Potentially harmful biological consequences measurable
  - Generally acceptably small
  - Modifiable

METHODS

Overview

Summary

- Five published experiments
- One analysis in progress

Institutional animal care committee approval obtained for each, and for pilot studies

Experiments were designed to complement each other to gain maximum information

Animal Model

- Adult Mongrel Canines
  - Up to one year survival
- Ten to 12 week old Walker hounds (Risser 0)
  - Six months survival

Operation

None (Control)

Sham (Screws placed and removed, grafts harvested and discarded)

Instrumentation (Human size on animals ½ to ¼ as heavy)

- Anchors
  - Bicortical pedicle screws (6.25 mm diameter)
  - L3 – L5 anchors; L4 bypassed (one L1 – L3 – L5 anchors)
- Connections (Stiff)
- Longitudinal members
  - Rods (6.35 mm or 4.76 mm diameter) or plates (human size)
- Transverse connection
  - One with rods constructs

Arthrodesis (Autogenous Iliac Crest Bone Graft)

- Facets only
- Facets and posterior

Experimental design (typical one shown)
Randomized before the last non-retraceable operative step

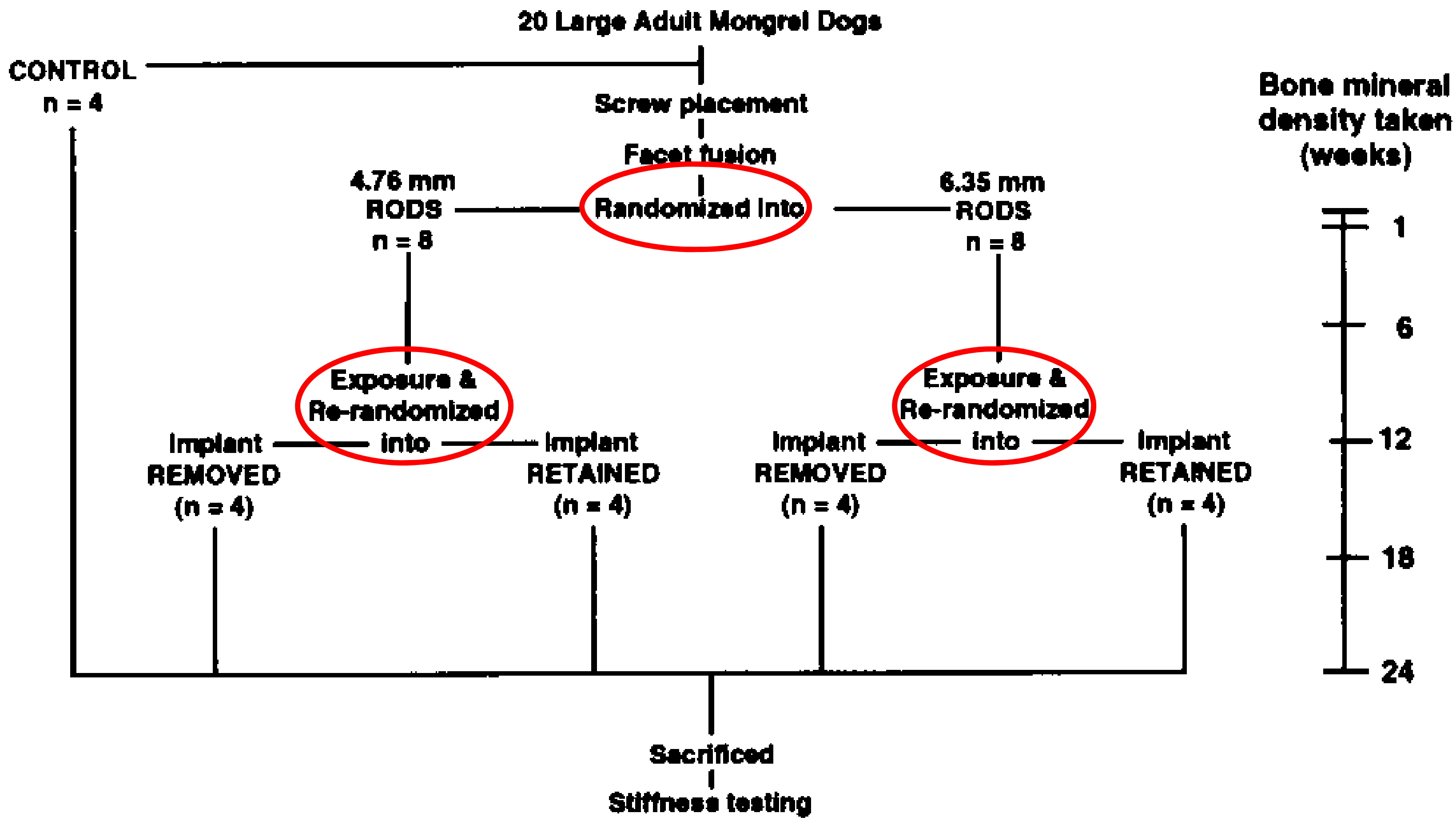
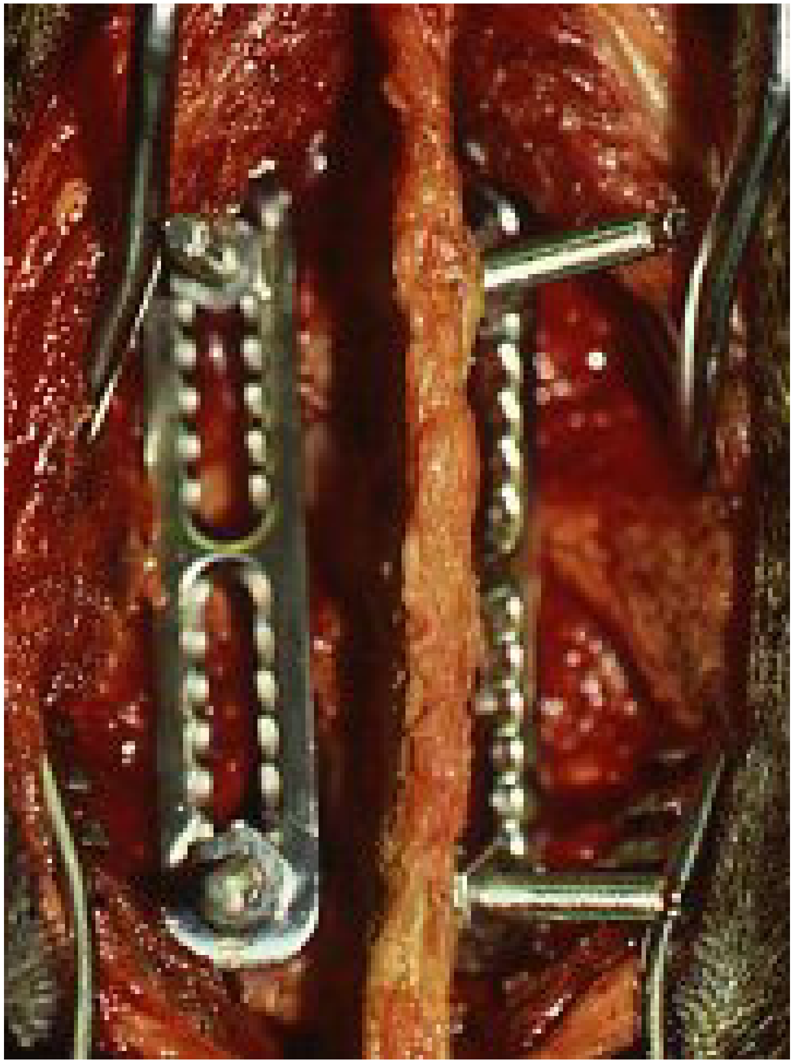


Figure 1. Experimental design and protocol.

Craven 1994

Intra-operative Examples



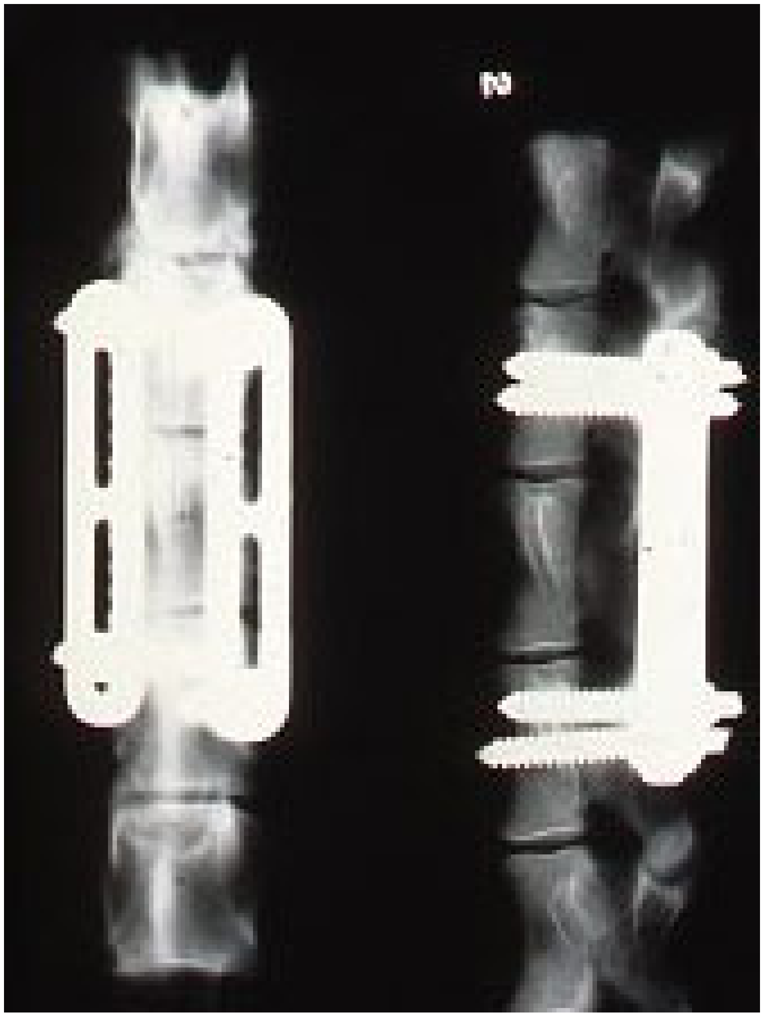
Instrumentation without Arthrodesis (Smith 1991)

Facet and Posterior Arthrodesis ready to Randomize Rod Size [Asher (Hardacker) 2007]

Evaluations

Radiographic

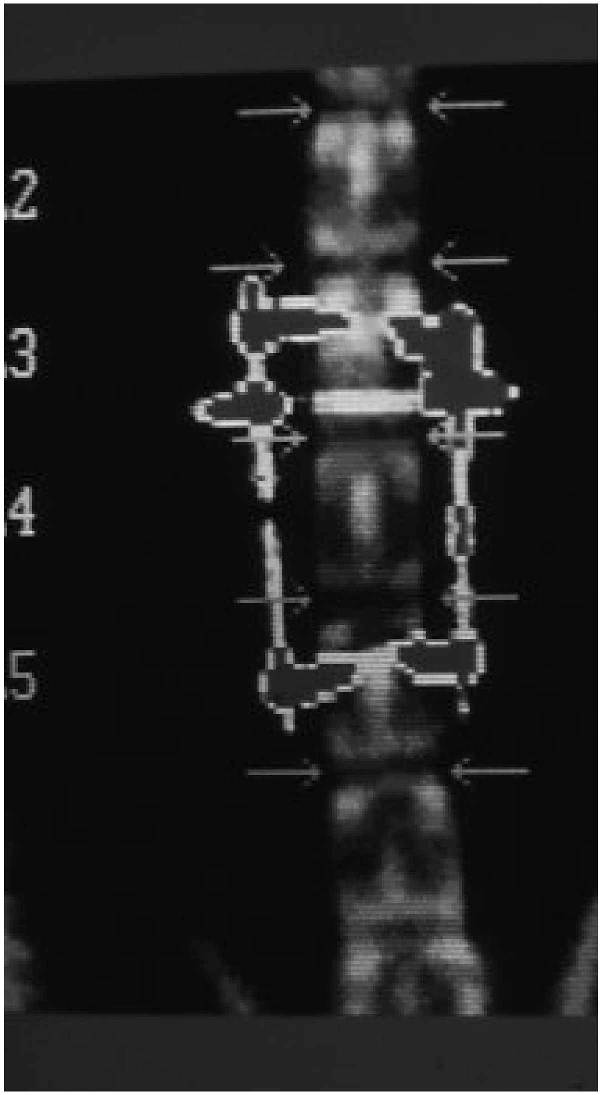
in vivo and ex vivo



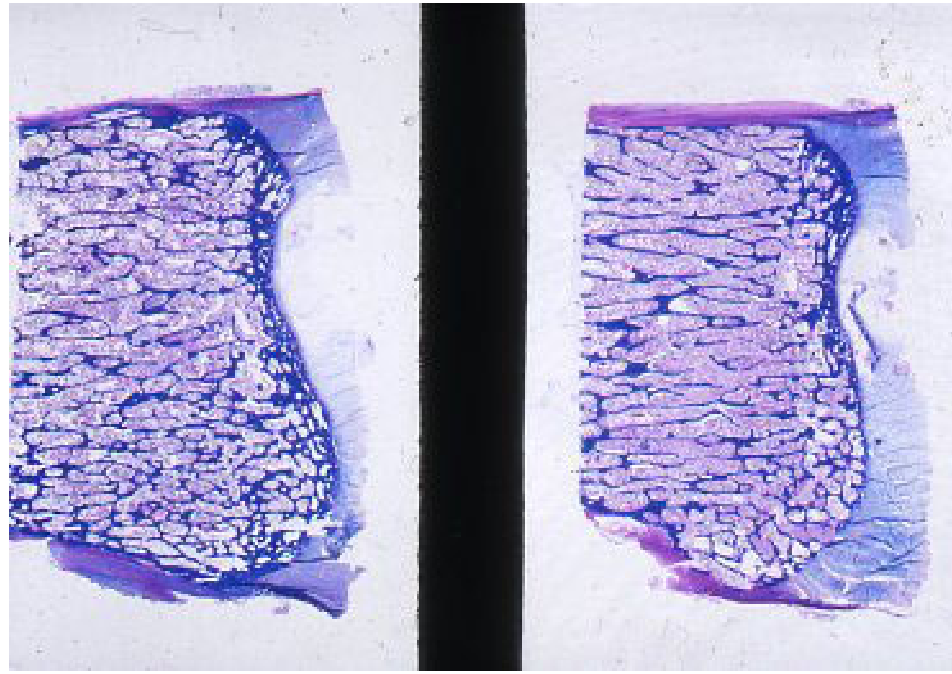
Construct integrity

Bone mineral density

DEXA, in vivo and ex vivo



Histomorphometric



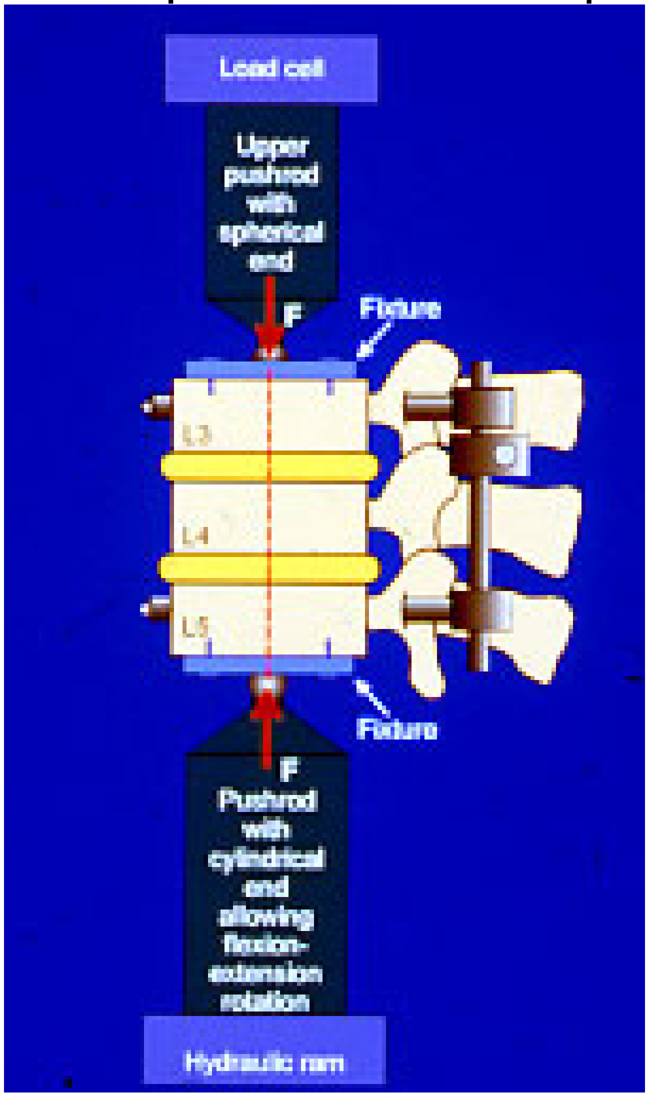
Sham

Implant without Arthrodesis

Biomechanical: Stiffness (N/mm) (ex vivo)

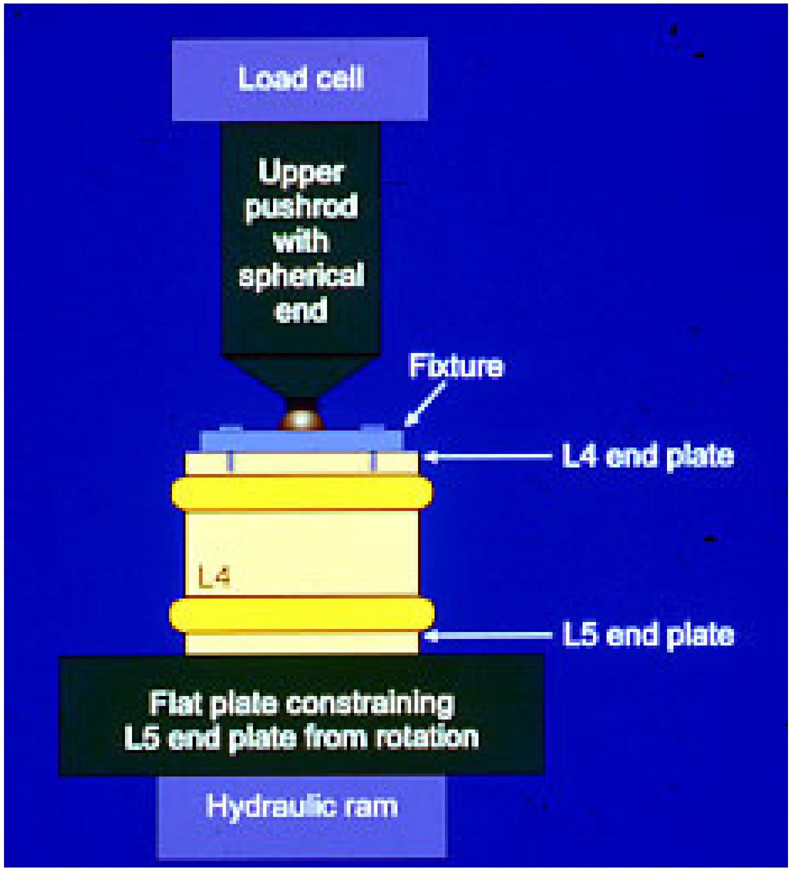
Flexion-Compression

Spinal column and portions of it



Compression

Body and Discs



Statistics

- Paired *t* test and Sign Rank Test (non-parametric)
- Regression models
- Alpha < 0.05
- Power
  - Study group numbers most commonly 4 or 6
  - To prevent Type II error (false negative),
    - 25-30 (an unrealistic number) would be necessary

RESULTS

I. Growing Spine

A. Sagittal angulation

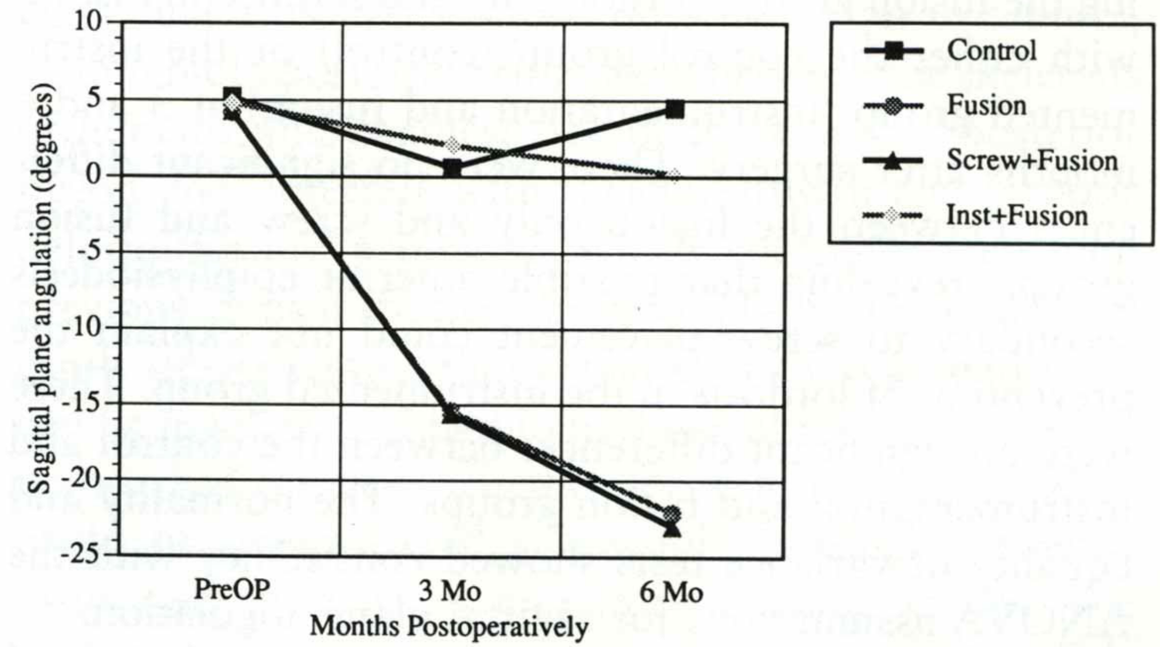
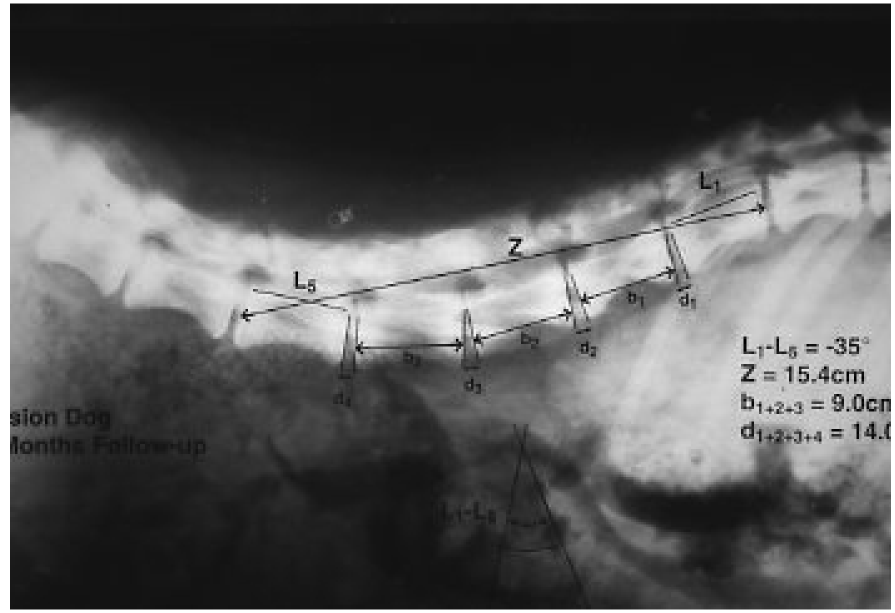


Figure 2. Changes in sagittal plane angulation (degrees curvature L1–L5) over time elapsed since surgery. Negative values represent the development of lordosis.

C and I+F vs. F and S+F $p < 0.01$

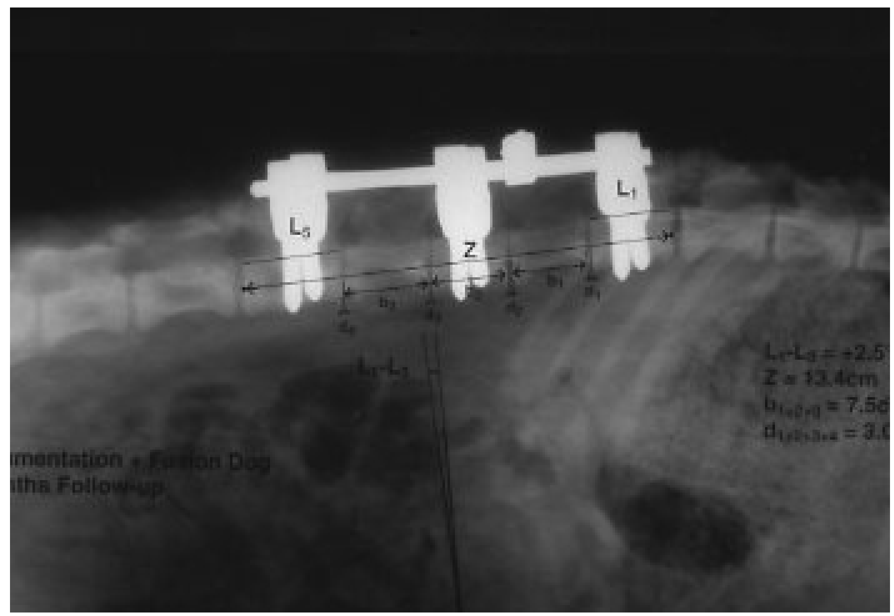
Kioschos 1996

Control



L1-L5 posterior fusion

Representative lateral lumbar spine radiographs of Walker Hounds [10-12 weeks old (Risser 0) at baseline] at six months follow-up



L1-L5 Instrumentation and fusion

Kioschos 1996

B. Body and disk growth

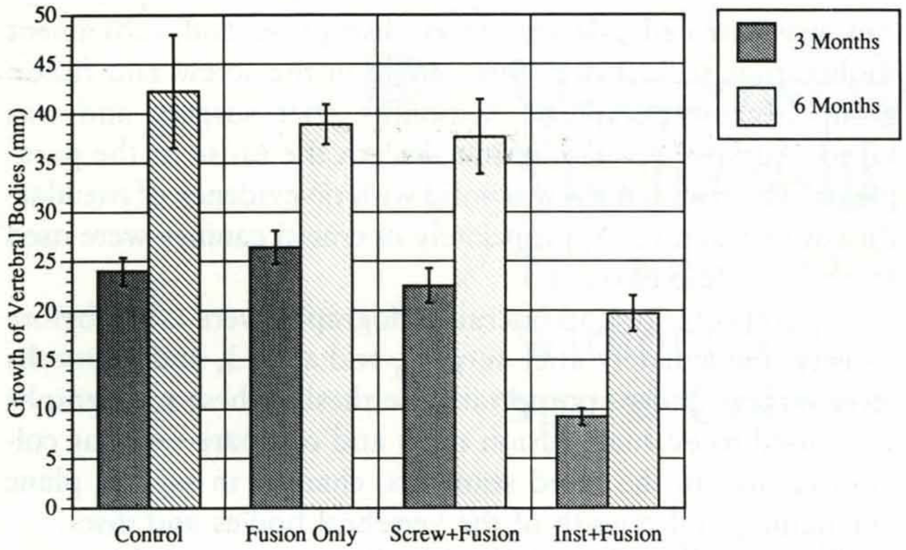


Figure 3. Growth of vertebral bodies (L2 + L3 + L4) over time elapsed since surgery.

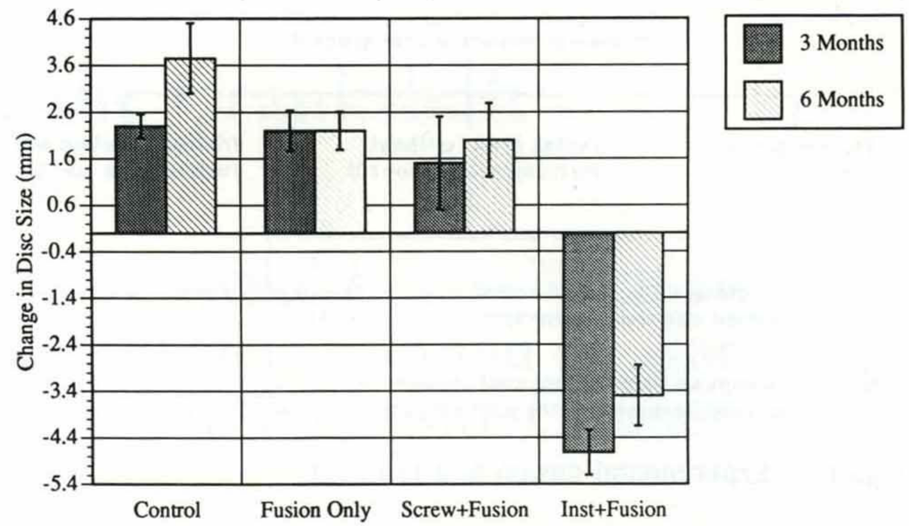


Figure 4. Change in heights of intervening disks (L1–L2 + L2–L3 + L3–L4 + L4–L5) over time elapsed since surgery.

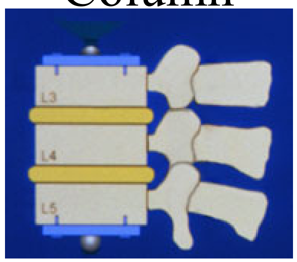
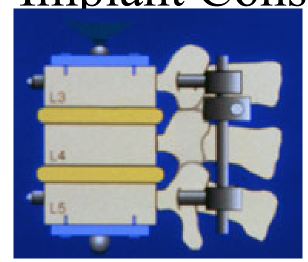
I + F v others $p<0.01$

Kioschos 1996

II. Effects on the Mature Spine

A. Arthrodesis (Fusion)

A-1 Baseline Flexion-compression stiffness (N/mm)

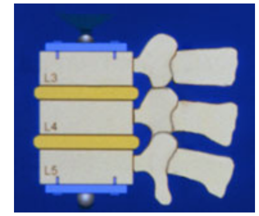
Implant Assembly	L3-5 Spinal Column 	L3-5 Implant Construct 	L3-5 Spinal Column + Implant Construct 
None	368 ± 45 [3] 376 ± 52 [5]	Not applicable	See below
4.76 mm	See Col. 4	152 ± 34 * [3] 154 ± 22 [5]	889 ± 125 [5]
6.35 mm	Not Done	283 ± 33 * [3]	Not Done

* P < 0.002

376 + 154 = 520 (<889) N/mm
Post Inst. Resists column buckling

[3] Craven 1994 [5] Asher 2007

A-2 Effect of sham operation on spinal column flexion-compression stiffness (N/mm)

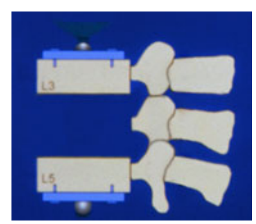


Control	Sham		
	6 months survival	12 months survival	6 & 12 mo. combined
376 ± 52* (n=4)	588 ± 162 (n=4)	776 ± 160 (n=2)	648 ± 156* (n=6)

*p = 0.0167

Sham surgery limits flexion buckling (?scar)

Control and sham (6 or 12 months
survival) operated specimens
had no posterior column stiffness



Asher 2007

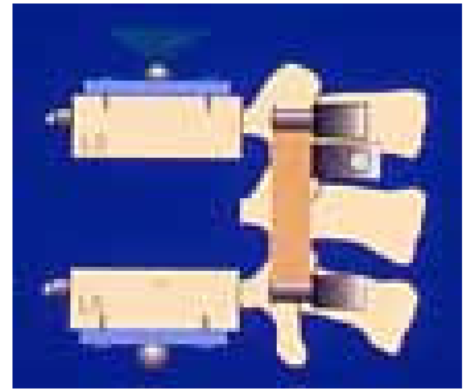
A-3 Effect of fusion type & survival time on spinal column flexion-compression stiffness (N/mm)

Implant Rod Diameter	Survival		
	24 weeks	6 months	12 months
	Facet	Facet + Posterior	
4.76 mm	1411 ± 361* (n=4)[3]	1147 ± 111‡ (n=4)[5]	1594 ± 482‡ (n=4)[5]
6.35 mm	727 ± 220* (n=4)[3]	1265 ± 252 (n=4)[5]	1244 ± 250 (n=4)[5]

* $P < 0.02$ ‡ $P = 0.0223$

[3] Craven 1994 [5] Asher 2007

A-4 Effect of fusion type & survival time on posterior column flexion-compression stiffness (N/mm)



Implant Rod Diameter	Survival		
	24 weeks	6 months	12 months
	Facet	Facet + Posterior	
4.76 mm	192 ± 9* (n=4)[3]	164 ± 73‡ (n=4)[5]	462 ± 247‡ (n=4)[5]
6.35 mm	112 ± 23* (n=4)[3]	153 ± 40 (n=4)[5]	280 ± 115 (n=4)[5]

* P < 0.003 ‡ P = 0.0047

[3] Craven 1994 [5] Asher 2007

A-5 Effect of implant removal at 12 weeks, following baseline instrumentation and facet fusion, on spinal column flexion-compression stiffness (N/mm) at 24 weeks

Implant Rod Diameter	Survival (24 weeks)	
	Implants Removed at 12 weeks	Implants Retained all 24 weeks
4.76 mm	1189 ± 436	1349 ± 233*
6.35 mm	885 ± 226	799 ± 225*

* $P < 0.05$

Implant removal at 12 weeks does not result in stiffer facet fusions at 24 weeks.

Craven 1994

A-6 Effect of retained implants on spinal column flexion-compression stiffness (N/mm) after Facet + Posterior Fusion

Specimen	Control	4.76 mm		6.35 mm	
		6 Months	12 months	6 months	12 months
With Implants 	889 ± 125	1336 ± 78	1867 ± 579	1739 ± 329	1599 ± 249
Without Implants 	376 ± 52	1147* ± 111	1594* ± 482	1265 ± 252	1244 ± 250
% Implant Contribution	57.7 ± 0.7	14.3 ± 4.0	14.3 ± 3.6	27.4 ± 1.2	22.3 ± 8.5

* $p = 0.0233$

All implant groups significantly stiffer than comparable control

All with implant groups significantly stiffer than with implants removed

Asher 2007

B. Effect of Instrumentation and Fusion on Bypassed Bone

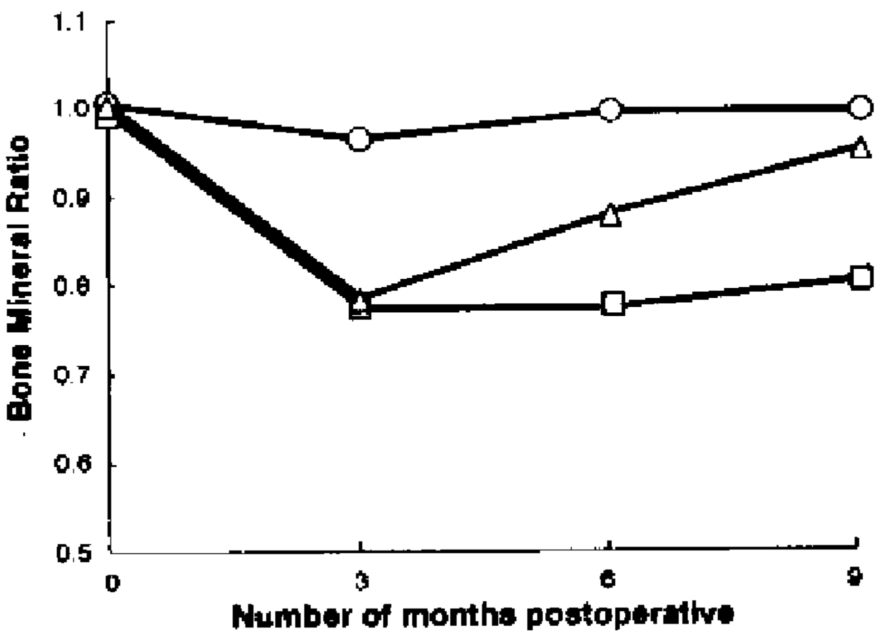
B-1 The effect of implant loosening in a non-fusion model

Two non-fusion implant experiments were done.

Without torque wrench tightening 1 of 6 constructs had loosening at 3 months and 4 of six constructs at 6 months. [Smith 1991]

With torque wrench tightening none of the implant-implant connections were loose at 9 months while 20 of 56 (36%) pedicle screws were loose in bone to the extent that they could either be toggled or easily removed by hand. [Dalenberg 1993]

The effect of implant-bone interface loosening on bypassed bone mineral density in a non-fusion model



	Mean Bone Mineral Ratios at: 3 months	6 months	9 months
○ Sham Operated Vertebrae (n=8)	0.959 ±0.105	0.982 ±0.059	0.986 ±0.073
△ Vertebrae Spanned by Loose Implants (n=6)	0.790 ±0.155 p<0.05	0.879 ±0.058 p=ns	0.943 ±0.115 p=ns
□ Vertebrae Spanned by Secure Implants (n=10)	0.791 ±0.116 p<0.01	0.767 ±0.133 p<0.001	0.793 ±0.127 p<0.002

Figure 5. Bone mineral change over time.

Dalenberg 1993

B-2 The effect of implant removal compared to implant retained on bypassed (L4) bone mineral density (BMD) following instrumentation and facet arthrodesis

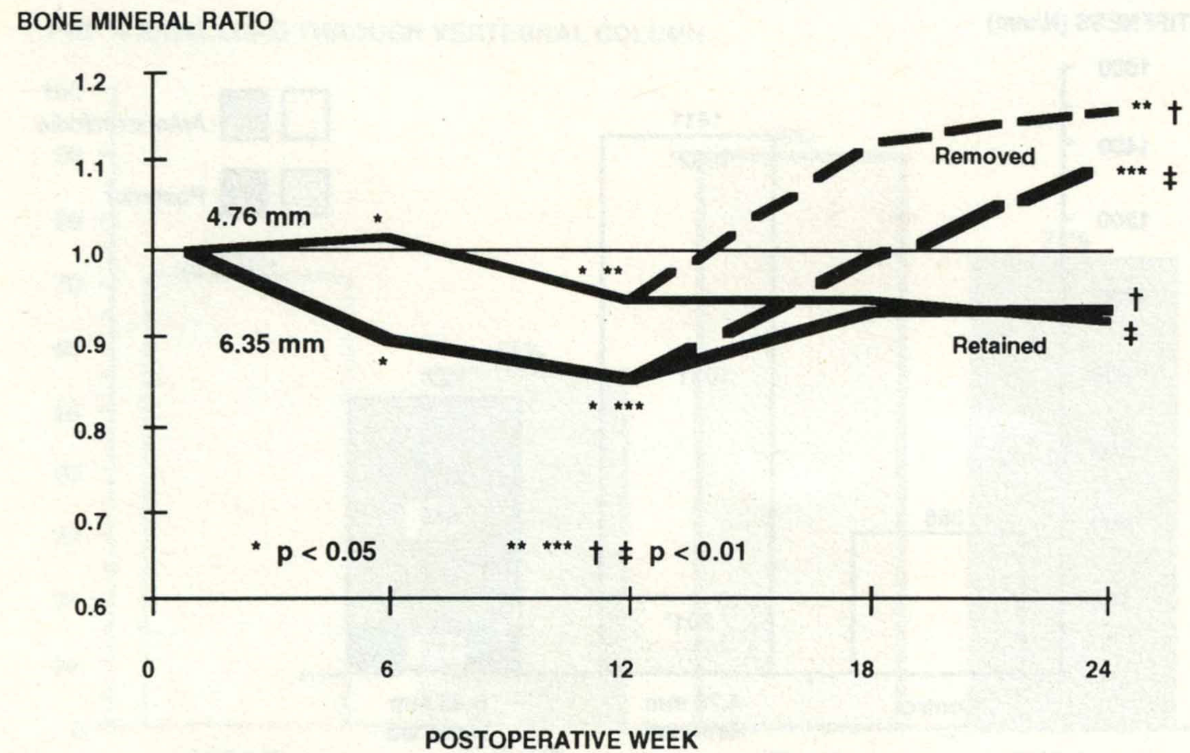


Figure 5. Bone mineral density ratio at 1, 6, 12, 18, and 24 weeks for 4.76 mm and 6.35 mm rod-retained and rod-removed groups.

Neither retained group significantly less than baseline at 24 weeks

Craven 1994

B-3 The effect of facet + posterior arthrodesis and retained implants on the bypassed (L-4) vertebral body compression stiffness (n=4)

Specimen	Control	4.76 mm Rods		6.35 mm Rods	
		6 months	12 months	6 months	12 months
Bypassed L4 Body	4900 ± 457 * **	3244 ± 534 *	2956 ± 808 **	2828 ± 887	3617 ± 861

* ** P = 0.0024

Interpretation: Similar to BMD studies that don't show progressive bone loss from 6 to 12 months

Asher 2007

C. Bypassed Disks

The effect of facet + posterior arthrodesis and instrumentation on the compression stiffness (N/mm) of the L3-4 and L4-5 bypassed disks (n = 4 animals/ 8 disks)

Specimen	Control	4.76 mm		6.35 mm	
		6 months	12 months	6 months	12 months
Bypassed Disks	1183 ± 138	1386 ± 314 *	1067 ± 218 *	1459 ± 341 ‡	1063 ± 307 ‡

* P = 0.0162 ‡ P = 0.0033

Interpretation: Bypassed disk stiffness appears to initially stiffen and then significantly loose stiffness

Asher 2007

D. Unbypassed Disks

The effect of facet + posterior arthrodesis and instrumentation on the compression stiffness (N/mm) of the L1-2, L2-3, and L5-6, L6-7 unbypassed disks (n = 4 animals/ 16 disks)

Specimen	Control	4.76 mm Rods		6.35 mm Rods	
		6 months	12 months	6 months	12 months
Unbypassed Disks	1105 ± 198	940 ± 166 *	873 ± 173 **	1039 ± 211	904 ± 183 ‡

Versus Control * P = 0.0088; ** = 0.0003; ‡ P = 0.0015
Regression: Control and 4.76 mm, P = 0.0003; Control and 6.35 mm, P = 0.0056

Interpretation:
1. Unbypassed (adjacent and periadjacent disks) progressively loose stiffness
2. Not rod size (4.76 mm vs. 6.35 mm) related

Asher 2007

E. Effect of Instrumentation without Arthrodesis on Unbypassed Bone

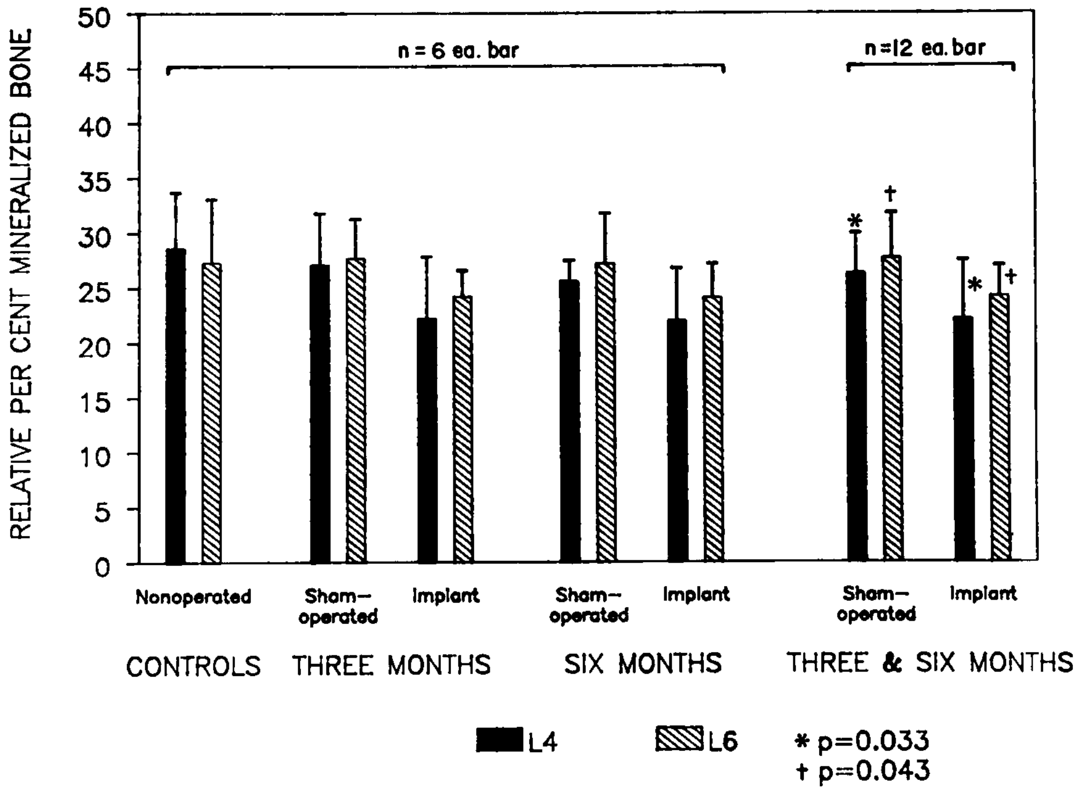


FIG. 5

Histomorphometric data showing the relative percentages of mineralized bone.

Adjacent (L6) bone mineral decrease ? 2nd load transfer posterior

? Early adjacent vertebra compression fracture

Smith 1991

III. Parameters Affecting Construct Stiffness

(Carson, in preparation)

Implant only constructs (n=24) from similar experiments compared [Craven 1994, Asher 2007]

Flexion-compression stiffness showed wide-overlapping data spread

4.76 mm rods: 120 N/mm to 275 N/mm

6.35 mm rods: 240 N/mm to 570 N/mm

More to stiffness than rod size!

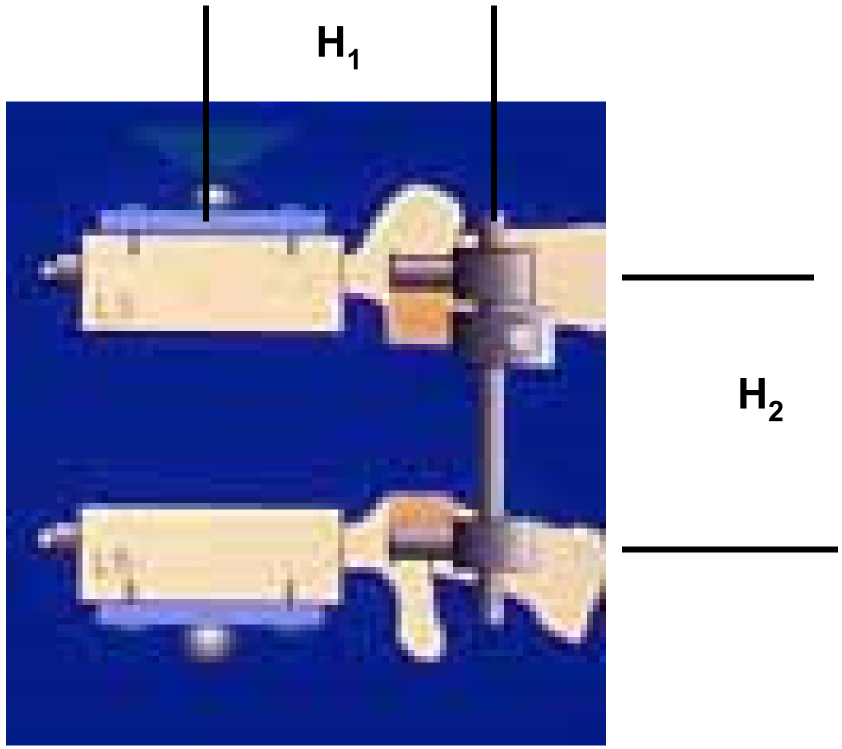
Using strain-energy techniques the following equation was derived for implant construct flexion-compression stiffness, and measured stiffness values validated the equation

$$K_i = \frac{1}{f_i}$$

Stiffness K_i is inversely related to flexibility f_i

$$K_i = \frac{1}{f_i}$$

$$fi = \frac{H_1^2}{3E_sI_s} + \frac{(H_1^2 + H_0^2)H_2}{2E_lI_l} + \frac{H_2}{2E_lA_l} + \frac{H_1^2}{k_c}$$



The stiffness of pedicle screw anchored, rigid/stiff connection rod constructs can be predicted using this formula.

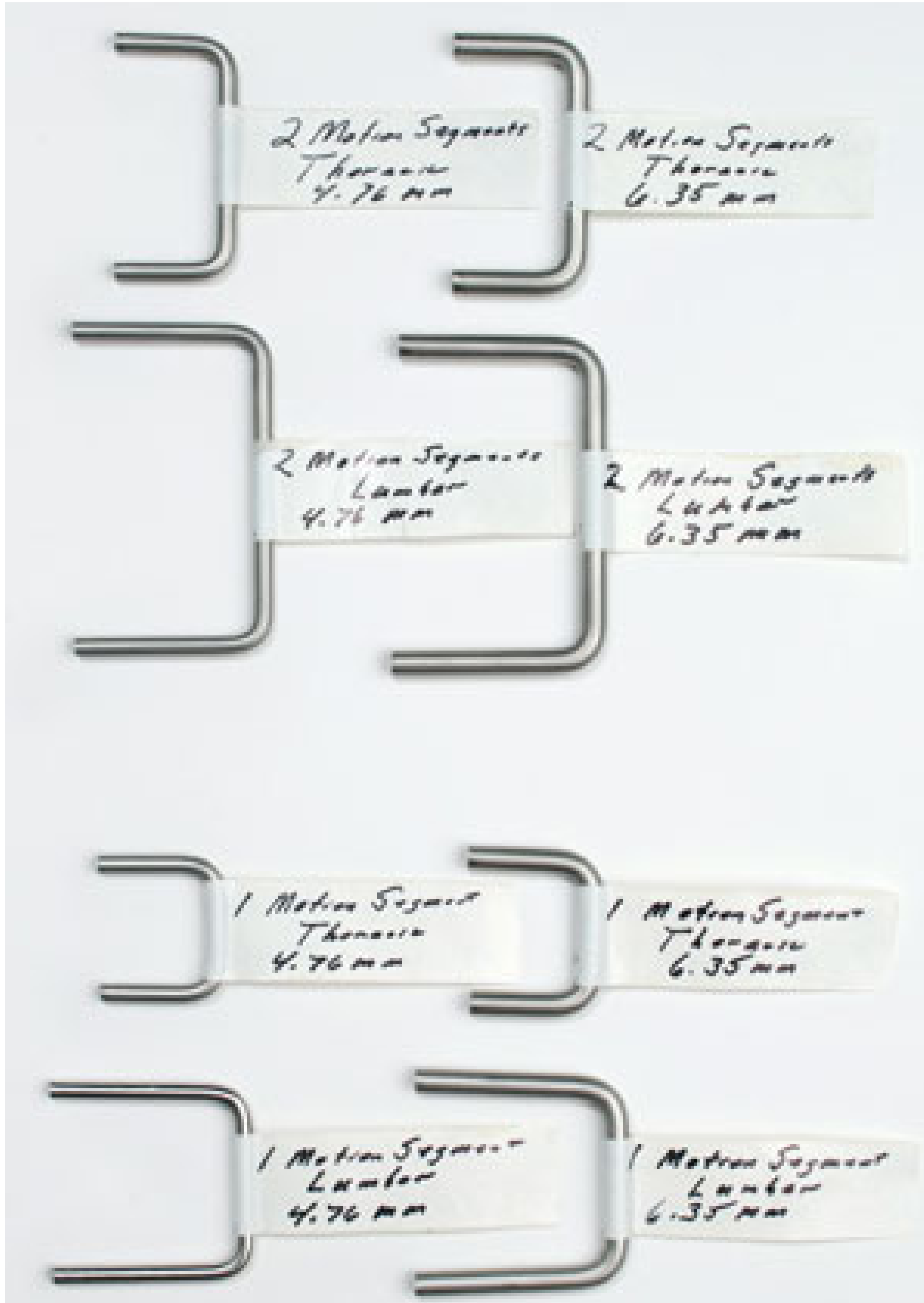
The following calculations are for stainless steel constructs.

Two motion segments

Anatomical Level	Screw length	Rod length	Rod Diameter	
	H_1 (mm)	H_2 (mm)	4.76 mm	6.35 mm
Thoracic	25	50	222 N/mm	433 N/mm
Lumbar	45	70	53 N/mm	144 N/mm

One motion segment

Anatomical Level	Screw length	Rod length	Rod Diameter	
	H_1 (mm)	H_2 (mm)	4.76 mm	6.35 mm
Thoracic	25	25	344 N/mm	555 N/mm
Lumbar	45	35	87 N/mm	154 N/mm


2 Motion Segments
Thoracic
4.76 mm
2 Motion Segments
Thoracic
6.35 mm
2 Motion Segments
Lumbar
4.76 mm
2 Motion Segments
Lumbar
6.35 mm
1 Motion Segment
Thoracic
4.76 mm
1 Motion Segment
Thoracic
6.35 mm
1 Motion Segment
Lumbar
4.76 mm
1 Motion Segment
Lumbar
6.35 mm

Discussion

Limitations

- Canines (Healthy)
  - Negative: Quadripedal
  - Positive: Biological system that responds to Wolff's Law
- Survival only from 6 months to one year
- Limited though significant (p=0.002)implant stiffness
  - differences: ~150 N/mm vs. ~300 N/mm
- Flexion-compression and compression mechanical testing
  - Negative: Blind to other loading modes
  - Positive: Antigravity axial load resistance critical

Conclusions

Growing Spines

- Pedicle screw, stiff connection constructs restrict anterior column growth

Mature spines

- Implants or sham surgery limit flexion compression buckling
- Without fusion
  - Implant connections loosen unless properly tightened, then
  - Implant – bone interface loosens
  - Unbypassed bone, mild/significant bone mineral loss (3 and 6 months)

Mature Spines (with Fusion)

All arthrodeses healed to fusion

Less Stiff vs. More Stiff Constructs

- Fusion
  - Increased stiffness
  - Better stiffness maturation
- Bypassed bone
  - Initially less bone mineral loss
  - Later equalizing and stabilizing at ~ 90% baseline
- Bypassed disks
  - Similar biphasic response
    - Not significant increase then significant decrease
- Unbypassed disks
  - Similar, significant progressive stiffness loss

Some Possible Clinical Correlations

- Limits need for concurrent anterior surgery
- Questions long term viability of instrumentation without fusion after maturity
- Temporary increase (?) in risk of adjacent fracture may be due to posterior load shunting posterior from “sham” scar
- Suggests importance of an extensive arthrodesis
- May explain some post instrumentation removal fractures

Remaining Questions

- Is residual implant stiffness detrimental to unbypassed disks
- Other

Thank You