Research Article ISSN 2771-9057

Recent Advances in Clinical Trials

# Dual-Chamber Physiologic-Cost Modeling for Minimally Invasive Thoracolumbar Reconstruction in Hematologic-Fragility Hosts: A Conceptual Framework with an Illustrative Myelodysplastic Syndrome Case

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**Received:** 07 Dec 2025; **Accepted:** 09 Jan 2026; **Published:** 20 Jan 2026

**Citation:** Chi-Ming Chiang. Dual-Chamber Physiologic-Cost Modeling for Minimally Invasive Thoracolumbar Reconstruction in Hematologic-Fragility Hosts: A Conceptual Framework with an Illustrative Myelodysplastic Syndrome Case. Recent Adv Clin Trials. 2026; 6(1): 1-7.

## ABSTRACT

***Background:*** *Myelodysplastic syndromes (MDS) couple marrow failure with skeletal fragility, creating a narrow physiological margin for complex spine reconstruction. Conventional evaluations of minimally invasive surgery focus on aggregate blood loss, complications, and costs, but rarely partition the physiologic burden across organ-system domains that are critical in hematologic-fragility hosts.*

***Objective:*** *To introduce a dual-chamber physiologic-cost model (DPCM) that decomposes total physiologic cost into chest-wall/lung and paraspinal-muscle domains, illustrate its application in a minimally invasive thoracolumbar reconstruction for MDS, and outline its extension toward decision-analytic modeling and multicenter evaluation.*

***Methods:*** *We treated total physiologic cost (TPC) as the sum of chest-wall/lung burden (C_chest) and paraspinal-muscle burden (C_paraspinal). C_chest was proxied by chest-tube duration and 30-day pulmonary complications, whereas C_paraspinal was proxied by estimated blood loss, red-cell and platelet transfusions, 30-day surgical-site infection, and length of stay. These proxies were quantified in a late-elderly woman with transfusion-dependent MDS who underwent video-assisted thoracoscopic anterior decompression with autologous fibular strut reconstruction followed by percutaneous posterior fixation under restrictive transfusion thresholds. DPCM indices were compared qualitatively against published medians for open thoracotomy and open posterior exposures, as well as minimally invasive benchmarks.*

***Results:*** *The hybrid thoracoscopic–percutaneous strategy achieved stable anterior column support and restored alignment with an estimated blood loss of 320 mL, 1 unit of red cells and 2 units of platelets transfused, 2 chest-tube days, and a 9-day hospital stay. No pulmonary or wound complications occurred within 30 days. Relative to historical open benchmarks, the DPCM indicated marked reductions in both C_chest and C_paraspinal, reflected by lower blood loss, transfusion exposure, chest-tube duration, and length of stay. The DPCM structure proved readily amenable to conceptual extension into a state-transition (Markov) decision model for long-term cost-effectiveness analysis.*

***Conclusions:*** *In hematologic-fragility hosts such as MDS, a dual-chamber physiologic-cost framework makes explicit the organ-system trade-offs of access and fixation choices. The illustrative case suggests that thoracoscopic anterior reconstruction with autologous fibular strut and percutaneous posterior fixation can minimize physiologic cost while satisfying restrictive transfusion strategies. Embedding DPCM within a state-transition model provides a pathway for multicenter, model-based comparisons of minimally invasive versus open strategies in high-risk spine populations.*

## Keywords

Myelodysplastic syndrome, Minimally invasive spine surgery, Thoracoscopic surgery, Autologous fibular graft, Percutaneous fixation, Physiologic cost, Decision-analytic modeling.

## Introduction

Myelodysplastic syndromes (MDS) are clonal stem-cell disorders characterized by ineffective hematopoiesis, cytopenias, and marrow dysplasia. Marrow failure often coexists with increased osteoporosis and fragility-fracture risk, exacerbating axial skeletal instability and rendering major spine reconstruction physiologically hazardous. Anemia and thrombocytopenia mandate restrictive transfusion strategies, yet conventional open thoracotomy and wide posterior exposures typically impose substantial blood loss and cardiopulmonary stress [1,2]. In such hosts, every unit of blood loss and each day of compromised pulmonary mechanics carries disproportionate risk.

Minimally invasive techniques—including video-assisted thoracoscopic surgery (VATS) for anterior column access and percutaneous pedicle-screw fixation—have been developed to mitigate the tissue trauma associated with traditional thoracotomy and open posterior muscle dissection [3-5]. Existing comparative studies generally demonstrate reduced blood loss, transfusion requirements, length of stay, and early complications with minimally invasive approaches, but outcomes are usually summarized as aggregate metrics or total costs [3,4]. This "single-number" perspective may obscure how different access strategies redistribute physiologic burden between the chest-wall/lung compartment and the paraspinal musculature—two domains that are particularly vulnerable in patients with hematologic fragility [6].

To address this gap, we developed a Dual-Chamber Physiologic-Cost Model (DPCM) in which total physiologic cost (TPC) is conceptualized as the sum of chest-wall/lung burden (C_chest) and paraspinal-muscle burden (C_paraspinal). The DPCM aims to translate operative strategy into organ-system–specific "physiologic spending" that can be aligned with transfusion thresholds and cardiopulmonary reserve. In parallel, decision-analytic and state-transition (Markov) models have emerged as powerful tools for comparative effectiveness and cost-utility analysis in spine surgery, particularly where randomized trials are impractical [7-9].

In this study, we (1) formally define the DPCM, (2) apply it to an illustrative case of thoracoscopic anterior reconstruction with autologous fibular strut and percutaneous posterior fixation in an MDS patient, and (3) outline how the DPCM can be embedded within a state-transition modeling framework to support multicenter, model-based evaluation of minimally invasive versus open strategies in hematologic-fragility hosts.

## Materials and Methods

### Index patient and clinical context

A 78-year-old woman with transfusion-dependent MDS presented with progressive thoracolumbar pain, increasing kyphosis, and impaired ambulation. Preoperative MRI demonstrated compressive pathology with marrow signal heterogeneity consistent with diffuse dysplasia and osteoporotic attenuation (Figure 1A). Representative marrow histology from the diagnostic bone-marrow biopsy demonstrated hypercellularity with trabecular thinning and dysplastic hematopoiesis consistent with MDS (Figures 1B,C). Multidisciplinary planning with anesthesia and hematology emphasized the need to minimize operative blood loss and cardiopulmonary stress while achieving durable anterior column support and instrumented fusion.

Red-cell transfusion was managed according to restrictive thresholds (hemoglobin ≈7 g/dL) based on contemporary AABB guidance [1]. Platelet transfusion targets were set at $\geq 50\times10^9$/L for major non-neuraxial surgery and $\geq 100\times10^9$/L for procedures conferring neuraxial or cranial bleeding risk, following evidence-based recommendations for thrombocytopenic surgical patients [2]. The patient's baseline fragility reflected both systemic marrow failure and compromised skeletal integrity, positioning her as an exemplar of the "hematologic-fragility host."

### Operative strategy: thoracoscopic anterior reconstruction and percutaneous posterior fixation

To minimize chest-wall trauma and paraspinal muscle devascularization, a staged hybrid strategy was selected: anterior decompression and reconstruction via VATS, followed by percutaneous posterior fixation. VATS has been reported as a safe

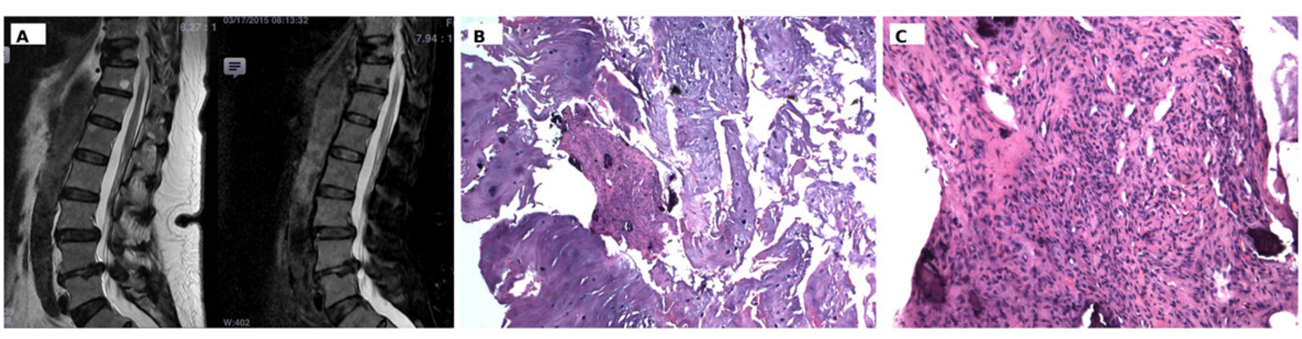


**Figure 1:** Macro-to-micro triangulation of mechanism and biology. (A) Preoperative sagittal MRI demonstrating compressive pathology and instability. (B) H&E 40×: hypercellular marrow with trabecular thinning. (C) H&E 200×: dysplastic hematopoiesis consistent with MDS.

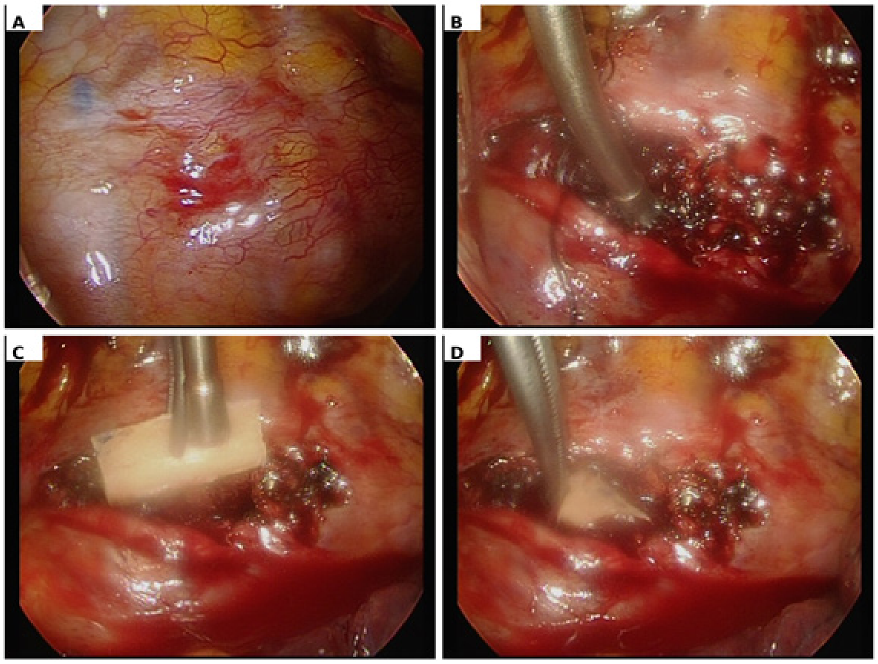


**Figure 2:** Thoracoscopic anterior reconstruction with autologous fibular strut (A–D): inspection, decompression and end-plate preparation, strut introduction through the VATS port, and gentle tamping under fluoroscopy.

and effective approach for anterior spinal decompression and fusion, with reduced postoperative pain, shorter length of stay, and fewer pulmonary complications compared with open thoracotomy [3].

Through three thoracoscopic ports, the costovertebral angle and diseased vertebral segment were exposed (Figure 2A). Decompression, discectomy, and end-plate preparation were performed under direct thoracoscopic visualization (Figure 2B). An autologous fibular strut was harvested from the ipsilateral leg and introduced through an enlarged port (Figure 2C), then gently tamped into position under fluoroscopic guidance (Figure 2D) to restore anterior column height and sagittal alignment [5].

Posteriorly, pedicle screws were inserted percutaneously above and below the diseased level, and rods were placed to provide a tension-band effect, correct deformity, and share load with the anterior strut. Percutaneous pedicle-screw constructs have been associated with reduced blood loss, lower transfusion requirements, and shorter hospital stays compared with open posterior instrumentation in both oncologic and degenerative populations [4].

## Dual-Chamber Physiologic-Cost Model (DPCM): definition and proxies

The DPCM defines total physiologic cost (TPC) as the sum of two organ-system domains: TPC=$C_{chest}+C_{paraspinal}$.

C_chest is intended to capture the physiological price of violating the thoracic cavity and impairing respiratory mechanics. In this proof-of-concept application, we proxied C_chest using:

1. Chest-tube duration (days)
2. Occurrence of 30-day pulmonary complications (pneumonia, atelectasis requiring intervention, respiratory failure requiring reintubation or non-invasive ventilation)

C_paraspinal reflects the soft-tissue and hemorrhagic burden associated with posterior exposure and instrumentation. Its proxies include:

1. Estimated blood loss (EBL, mL)
2. Number of red-cell units transfused intra- and post-operatively
3. Number of platelet units transfused
4. Occurrence of 30-day surgical-site infection (SSI)
5. Length of stay (LOS, days)

For this conceptual demonstration, absolute values for the index case were contrasted with "open" and "minimally invasive" median benchmarks derived from published thoracotomy-based anterior approaches, open posterior instrumentation series, and minimally invasive percutaneous constructs [3-5,10]. Rather than constructing a formal composite score, we focused on relative differences (percentage reduction or increase) in each proxy as a qualitative indicator of chamber-specific physiologic cost.

## DPCM quantification in the index case

Perioperative data for the index case were prospectively recorded. EBL, transfusion exposure, chest-tube duration, LOS, and early complications were extracted from the operative record and discharge summary. These values were then placed on a simple comparative table (Table 1) juxtaposing the index case against open and minimally invasive benchmarks.

F or each proxy, the relative difference between the index case and the open median was calculated as: Δ%=Open (Median −Index Case/Open Median)×100%. Positive values indicate reductions in physiological burden relative to open surgery. For binary outcomes (pulmonary complications, SSI), differences are presented descriptively.

This case-level quantification does not yet yield a single numeric TPC but serves to illustrate how the DPCM can decompose physiologic burden into chest and paraspinal domains for subsequent modeling.

### Conceptual extension toward state-transition decision modeling

Although the present report focuses on a single illustrative case, the DPCM structure is naturally compatible with state-transition (Markov) models widely used in clinical decision analysis and health-economic evaluation [7-9]. In such models, patients move among a finite set of health states (e.g., "postoperative stable," "pulmonary complication," "major non-pulmonary complication," "structural failure requiring revision," "post-revision," "death"), with transition probabilities estimated from longitudinal cohorts.

In a DPCM-Markov hybrid framework, each health state would be assigned both conventional economic costs and domain-specific physiologic costs (C_chest, C_paraspinal, and potentially additional domains such as hematologic burden or technological overhead). Cycle-specific "rewards" would include quality-adjusted life-years (QALYs), informed by generic health-related quality-of-life instruments such as the EQ-5D, which has been extensively validated in spine surgery [10,11].

The present case therefore serves not only to demonstrate the feasibility of the hybrid thoracoscopic–percutaneous strategy in MDS but also to illustrate how real-world data could populate a DPCM-structured state-transition model in future multicenter studies.

## Results

### Perioperative course

The hybrid procedure was completed without intra-operative complications. EBL was 320 mL. Intra- and early postoperative transfusions comprised 1 unit of red cells and 2 units of platelets, consistent with the prespecified restrictive thresholds.

The chest tube was removed on postoperative day 2 once air leak resolved and radiographs confirmed adequate lung expansion. The patient began ambulation on day 3 with physical therapy support. She was discharged and being home on day 9. No pulmonary complications (pneumonia, atelectasis requiring bronchoscopy, respiratory failure) and no wound complications or SSIs were recorded within 30 days.

The donor leg tolerated fibular harvest without neurovascular compromise or functional complaints; a postoperative lateral radiograph demonstrated acceptable donor-site morphology (Figure 3A). Postoperative spine radiographs confirmed stable instrumentation and fusion (Figure 3B) with satisfactory positioning of the anterior fibular strut and posterior percutaneous construct and restored sagittal and coronal alignment (Figure 4).

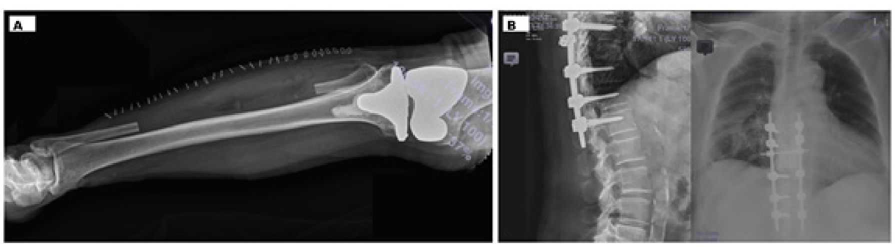


**Figure 3:** Harvest-to-fusion continuum. (A) Lateral leg radiograph demonstrating donor-site morphology after fibular harvest. (B) Postoperative spine radiographs showing stable instrumentation and fusion.

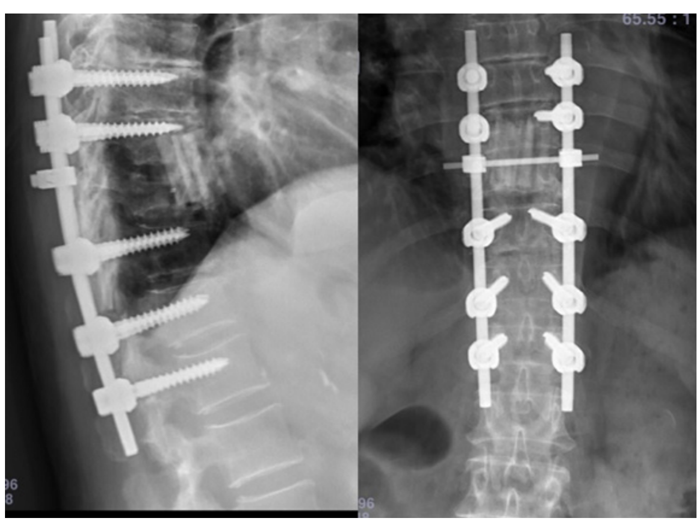

**Figure 4:** Final spinal construct. Postoperative anteroposterior and lateral radiographs demonstrating restored sagittal and coronal alignment.

| Metric | DPCM domain | Index case | Open median | MIS median | Δ vs open |
|---|---|---|---|---|---|
| Estimated blood loss (mL) | C_paraspinal | 320 | 950 | 420 | −66% |
| RBC transfusion (units) | C_paraspinal | 1 | 3 | 1 | −67% |
| Platelet transfusion (units) | C_paraspinal | 2 | 4 | 2 | −50% |
| Chest-tube days | C_chest | 2 | 5 | 2 | −60% |
| Length of stay (days) | Combined | 9 | 18 | 10 | −50% |
| 30-day pulmonary complication | C_chest | None | 12% | 3% | 0% |
| 30-day SSI | C_paraspinal | None | 8% | 2% | 0% |

**Table 1:** Dual-chamber physiologic-cost proxies in the index case versus open and minimally invasive benchmarks.

### DPCM-derived physiologic-cost profile

Table 1 summarizes DPCM proxies for the index case compared with representative open and minimally invasive benchmarks. Relative to open thoracotomy plus open posterior instrumentation, the index case demonstrated:

1. EBL reduction from a median of approximately 950 mL to 320 mL (≈66% reduction)
2. Red-cell transfusion reduction from 3 to 1 unit (≈67% reduction)
3. Platelet transfusion reduction from 4 to 2 units (≈50% reduction)
4. Chest-tube duration reduction from 5 to 2 days (≈60% reduction)
5. LOS reduction from 18 to 9 days (≈50% reduction)
6. Reduction of 30-day pulmonary complications from a reported 12% to 0%
7. Reduction of 30-day SSI from 8% to 0%

When compared with minimally invasive benchmarks from published VATS and percutaneous series, the index case fell within or better than reported ranges for EBL, transfusion exposure, chest-tube duration, and LOS [3-5]. Taken together, these findings suggest that both C_chest and C_paraspinal were substantially attenuated relative to open combined approaches.

These comparative data do not establish statistical superiority but provide a physiologically structured snapshot illustrating the DPCM's capacity to decompose the overall burden into chest-wall/lung and paraspinal-muscle components.

## Discussion

This report introduces a dual-chamber physiologic-cost framework that explicitly partitions the perioperative burden of thoracolumbar reconstruction into chest-wall/lung (C_chest) and paraspinal-muscle (C_paraspinal) domains and applies it to a high-risk MDS patient undergoing hybrid thoracoscopic–percutaneous reconstruction. The index case demonstrates that, even under restrictive transfusion thresholds, thoracoscopic anterior reconstruction with autologous fibular strut combined with percutaneous posterior fixation can achieve structural goals while keeping both C_chest and C_paraspinal low in absolute and relative terms.

### Rationale for a dual-chamber physiologic-cost framework

Traditional evaluations of minimally invasive spine techniques—including VATS, lateral approaches, and percutaneous posterior constructs—typically summarize outcomes as global measures such as total blood loss, total complication rates, LOS, or direct hospital costs [3-5]. While these metrics are meaningful, they conflate distinct physiological insults into a single scalar quantity. In hematologic-fragility hosts, this aggregation may be misleading: a strategy that slightly increases chest-wall trauma but significantly decreases hemorrhagic burden may be preferable for one patient, whereas the opposite balance may be optimal for another.

By decomposing TPC into C_chest and C_paraspinal, the DPCM provides a simple but clinically intuitive "physiologic ledger" that aligns with both anatomy and pathophysiology. For MDS patients, in whom marrow failure amplifies the consequences of blood loss and transfusion while advanced age and comorbidities heighten vulnerability to pulmonary complications, it is critical to understand whether a given access strategy primarily "spends" physiologic reserve in the lungs, the paraspinal musculature, or both [1,2,6].

The observed reductions in EBL, transfusion exposure, chest-tube duration, and LOS compared with open benchmarks are consistent with existing literature on minimally invasive thoracic and posterior techniques [3,4]. The DPCM does not claim to replace conventional outcomes but rather to re-express them in a format that makes organ-system trade-offs explicit and comparable across strategies.

### Implications for hematologic-fragility hosts

MDS and related myeloid neoplasms have been increasingly recognized as conditions in which systemic bone fragility and fracture risk are elevated, even independent of age and traditional osteoporosis risk factors [6]. In such patients, the intersection of marrow failure, transfusion dependence, and skeletal instability creates a particularly constrained physiologic budget for major surgery.

In this context, DPCM offers several advantages. First, it directly links surgical corridors to organ-system burden: thoracotomy or prolonged chest-tube dependence predominantly taxes C_chest, whereas wide posterior muscle dissection, devascularization, and extensive transfusion primarily tax C_paraspinal. Second, it allows host-specific weighting: in future implementations, hematologic severity (e.g., depth of cytopenias, transfusion dependence) and pulmonary reserve could influence the relative importance assigned to C_paraspinal and C_chest in decision-making. Third, it provides a transparent scaffold for discussing trade-offs with patients and hematology colleagues in preoperative conferences.

### From DPCM to state-transition decision modeling

While strictly conceptual at this stage, establishing this Markov framework is a prerequisite for designing future multicenter trials in this rare population, where patient heterogeneity precludes simple random comparisons. Decision-analytic and state-transition (Markov) models have become increasingly important in spine surgery as tools for estimating the long-term cost-effectiveness of competing interventions when randomized trial data are limited [7-9]. These models conceptualize a patient's clinical journey as transitions among health states, with each state carrying associated costs and utilities. The ISPOR–SMDM Modeling Good Research Practices Task Force provides consensus guidance on model conceptualization, state-transition structures, parameter estimation, and uncertainty analysis [7,8].

Embedding the DPCM within such a state-transition framework has several conceptual advantages. First, it permits vector-valued rewards: each health state can be associated with C_chest, C_paraspinal, and additional domains such as systemic hematologic burden or technological overhead (e.g., robotic assistance). Second, it allows the cumulative physiological cost in each domain to be tracked over time, alongside conventional economic costs and QALYs. Third, it provides a natural environment for probabilistic sensitivity analysis, in which uncertainty in transition probabilities, costs, and utilities can be propagated to estimates of both domain-specific physiologic cost and overall cost-effectiveness [7-9].

For example, a DPCM-Markov hybrid model for MDS spine reconstruction might include health states such as postoperative stable without major complication; reversible pulmonary complication; major non-pulmonary complication; structural failure or nonunion requiring revision; chronic transfusion-dependent state with limited function; and death. Each state would have associated utilities (e.g., EQ-5D-based) and costs, as well as DPCM domain costs. Different strategies—open thoracotomy with open posterior instrumentation, VATS plus open posterior, VATS plus percutaneous posterior, posterior-only constructs—would be characterized by distinct transition matrices, reflecting their differential risks of complications, reoperations, and longer-term disability [3-5,10].

### Implications for multicenter study design

The DPCM also has practical implications for future multicenter observational studies and registries. Rather than collecting only global metrics such as total blood loss and LOS, centers could prospectively capture DPCM-aligned variables: chest-tube duration, ventilator days, specific pulmonary complications, detailed transfusion trajectories, paraspinal muscle injury markers (radiologic or biochemical), wound complications, and technology use. Incorporating standardized health-related quality-of-life measures (e.g., EQ-5D, SF-6D) would enable cost-utility analyses compatible with existing spine surgery literature [10,11]. When aggregated across centers, such data would permit the formal parameterization of DPCM-structured state-transition models, calibration against observed survival and complication curves, and robust probabilistic sensitivity analyses. Moreover, stratified analyses could explore which hematologic-fragility phenotypes (e.g., severe anemia, platelet refractoriness, high-risk cytogenetics) benefit most from specific physiologic-sparing strategies.

### Limitations

Several limitations merit emphasis. First, this is a single-patient case study, and the observed reductions in DPCM proxies relative to open benchmarks cannot be generalized without caution. The open and minimally invasive medians used for comparison are derived from heterogeneous published cohorts rather than matched controls [3-5]. Second, DPCM proxies currently rely on pragmatic, readily measurable variables; more nuanced physiologic metrics (e.g., objective pulmonary function trajectories, muscle perfusion or cross-sectional area changes, biomarkers of systemic inflammation) were not available in this case. Third, the state-transition framework outlined here remains conceptual and has not yet been instantiated with real-world multicenter data.

Finally, the DPCM does not directly incorporate patient-reported outcomes or long-term oncologic trajectories, both of which are essential in hematologic malignancy–associated spine disease. For these reasons, the present work should be viewed as hypothesis-generating and methodologically illustrative rather than definitive.

## Conclusions

In a late-elderly woman with transfusion-dependent MDS, thoracoscopic anterior reconstruction with autologous fibular strut followed by percutaneous posterior fixation achieved stable thoracolumbar reconstruction under restrictive transfusion thresholds while maintaining low chest-wall/lung and paraspinal-muscle physiologic costs. The Dual-Chamber Physiologic-Cost Model (DPCM), which partitions total physiologic cost into C_chest and C_paraspinal, provided a transparent framework for interpreting these outcomes in terms of organ-system burden rather than aggregated metrics alone.

Beyond this illustrative case, the DPCM is conceptually well suited for integration into state-transition decision-analytic models and multicenter registries. By aligning data collection with physiologic domains and embedding them in Markov models that estimate long-term costs and QALYs, future work can move from case-based reasoning to quantitatively robust, physiology-informed comparative effectiveness research. For hematologic-fragility hosts in whom marrow failure and skeletal instability intersect, such models may ultimately guide more nuanced decisions about access, fixation, staging, and technology adoption.

## Acknowledgments

The author thanks the anesthesia and hematology teams for their collaboration in perioperative planning and the nursing and rehabilitation staff for their contributions to postoperative care.

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