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The Golden Ratio Optimizes Cardiomelic Form and Function

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Abstract

Both cardiac structure and hand proportion have been linked with the Fibonacci Series and the associated Golden Ratio - the number 1.618 that has been postulated to be related to functional optimization. In this paper, evidence supporting the relation of the Golden Ratio to the hand and heart is presented. It is known that upper limb malformations are the commonest skeletal abnormalities in patients with congenital heart disease. Embryological studies on hand-heart syndromes have provided evidence for a cardiomelic developmental field, which is supported by candidate genes involved in patterning of the hand and heart. Precise molecular interactions govern a certain optimal model of cardiomelic development, for which the underlying physical rule remains unknown. It is hypothesized that the Golden Ratio may represent the mathematical basis for hand-heart development so as to achieve optimal form and function. Deregulation of this underlying patterning law may manifest as variation in hand-heart structure away from that as would be determined by the Golden Ratio. Altered hand proportion in turn may be of predictive value for cardiovascular defects and dysfunction.

Keywords
Holt-Oram Syndrome, Golden Ratio, Hand-heart, Upper limb-Cardiovascular Syndromes

Introduction

Cardiovascular disease remains the top cause of mortality in developed countries, particularly among the elderly, outranking other conditions such as cancer and communicable diseases [1]. In addition, congenital heart disease is the leading cause of infant morbidity and mortality in the Western world [2]. Identification of high risk persons for cardiac disease allows early screening and intervention through the avoidance of modifiable risk factors, including smoking, obesity, and hypertension. The utility of convenient bedside clinical markers for intrinsic susceptibility to acquired cardiac disease or the presence of congenital heart defects may be diagnostically useful without the use of modern equipment.

It is interesting that upper limb malformations are the commonest skeletal abnormalities in patients with congenital heart disease [3]. Some 107 Mendelian syndromes with altered limb patterns such as duplications, deficiencies, hypoplasias, or dysplasias are associated with cardiac anomalies [4], often collectively referred to as hand-heart syndromes. Perhaps the most well-known of which is the Holt-Oram Syndrome, which originally highlighted the familial transmission of upper extremity anomalies associated with ostium secundum atrial septal defects [5]. The underlying reason for the connection however, is still unknown.

In this paper, the connection between limb defects and cardiac disease is discussed. Notably, both cardiac structure as well as hand proportion has been linked with the Fibonacci Series and the associated Golden Ratio - the number 1.618 that has been postulated to be related to form and functional optimization. Yet to date, no studies have been attempted at the understanding of the physical basis of cardiomelic development, nor have explored the possible links between hand proportion and cardiac disease. It is thus hypothesized that cardiomelic development is governed by the Golden Ratio, possibly for optimal form and function. Deregulation of this underlying patterning law may manifest as variation in hand-heart structure away from that as would be determined by the Golden Ratio. Altered hand proportion in turn may be of predictive value for cardiovascular defects and dysfunction.

Hypothesis

During the 4th to 7th week of embryogenesis, cardiac and limb bud differentiation temporarily coincide. Both genetic and/or environmental insults during this period are known to contribute to the pathogenesis of concurrent upper limb-cardiovascular defects, suggesting a non-incidental basis for their association [6-7]. Furthermore, based on a large analysis of Mendelian syndromes that affect the limbs and/or the heart, a cardiomelic developmental field has been proposed [4].

The embryological relationship is supported by several studies suggesting the involvement of several genes, such as homeobox genes [8], tenascins [9] and receptor tyrosine kinase [10] in cardiac and limb development. Recently, Koshiba-Takeuchi et al. described the precise interaction between TBX5 and SALL4 transcription factors in the patterning of murine limb and heart, providing a unifying molecular mechanism for hand-heart syndromes [11]. There is thus an increasing amount of evidence supporting the intricate relationship of limb-heart development. However, this does not explain the relation fully. Is there also some patterning physical law guiding cardiomelic development that accompanies this temporal intersection? On the basis of current evidence from embryological, genetic, molecular and structural studies, we hypothesize that the Golden Ratio may represent the mathematical basis for hand-heart development so as to achieve optimal form and function.

Discussion

Until recently, the Fibonacci series has remained a mathematical wonder that fell short of clinical interest. Originally described by Leonardo Pisano Bigollo, the series is defined by a sequence of numbers generated by the sum of the preceding 2 numbers i.e. 0, 1, 1, 2, 3, 5, 8, 13, and so forth [12]. As the series progresses, the ratio of each term to the previous term approaches 1.618, this number being known as the Golden Ratio. This ratio has been reputed to be ubiquitously found within nature, including the spirals of the galaxies, seashells, flowers and DNA structure. Importantly, it has been suggested to be found in human structures, including the hand and heart. A self-replicating system which information is encoded by the Golden Ratio is mathematically efficient due to the nature of fractal geometry. Information required for scale-independent growth of such a structure is encoded within itself. It has also been suggested that the propensity for this ratio to appear in nature may be because this ratio optimizes the efficiency of packing structures in a limited space in such a way that wasted space is minimized and the supply of energy or nutrients is optimized [13].

The heart is a helical structure which is mathematically approximated by the Golden Ratio [14]. The cardiac helix was described in the 1660s by Lower as having an apical vortex, in which the muscle fibres go clockwise from outside in and counter clockwise from inside out. This combination of clockwise and anticlockwise vortices is referred to as a reciprocal spiral, or mathematically speaking - a logarithmic spiral that has a regular relationship between proportions (Figure 1). Thus during embryologic development, the primary heart tube must carry distinct axial information, in order to avoid any misstep in interpreting the left—right axial information [15]. Any disruption of the left—right axial information i.e. interruption of the spiral pattern of the heart can result in congenital heart defects, including atrial-ventricular septal defects, transposition of great arteries and Ebstein's anomaly [4, 16].

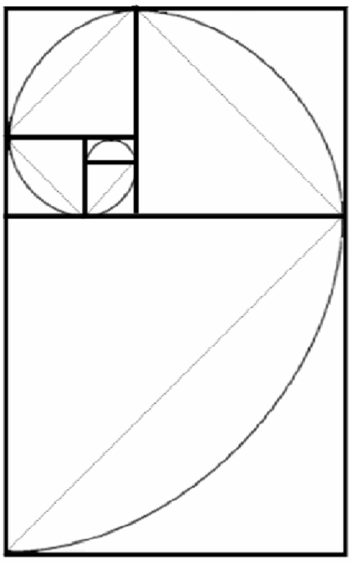

Fig. 1. Diagram depicting the equiangular logarithmic spiral that has a regular relationship between proportions, as determined by the Fibonacci sequence

The subsequent discovery of the helical ventricular myocardial band of Torrent-Guasp revealed unavoidable coherence and mutual coupling of form and function in the ventricular myocardium, which has been strongly evidenced by the advent of non-invasive cardiac imaging [17-18]. For a contractile shortening of 15%, as occurs in the normal heart, a spiral fibre formation (as would be predicted by the Golden Ratio) causes a 60% ejection fraction. This however, is halved when fibre orientation is horizontal or transverse, as occurs in a dilated failing heart [19].

In relation to the helical myocardial structure, Gibson et al. [13] demonstrated the appearance of the Fibonacci Cascade within the distribution of coronary artery lesions of 1533 patients with ST-segment elevation myocardial infarction, relating it to the location of branch points within the arborizing coronary anatomy. They speculated that on top of optimization of vasculature packing, the Fibonacci Relation optimizes the branching pattern in such a way that the coronary tree maximizes perfusion of the myocardial bed. Taken together, the Golden Ratio may indeed play an important role in cardiac development, deviation from which appears to compromise cardiac form and function.

It was initially observed by Thompson that naturally occurring logarithmic curves occur in the path of motion of digits [20]. Subsequently, it was inferred from this observation that the bone lengths would follow the Fibonacci relationship, known as Littler's hypothesis [21]. The motion path of digits was also confirmed to follow the equiangular spiral via motion analysis systems [22]. In the hand, the ratio of the middle to distal phalanx (1.5), followed by the ratio of the proximal to middle phalanx (1.67) would approach the Golden Ratio (1.618) (Figure 2). Park et al. explored the relationship between interarticular distances of 100 hands from healthy human subjects via standardized X-ray measurements and showed that the ratio of the middle to distal phalanx ranged from 1.15 to 1.54, while the ratio of the proximal to middle phalanx ranged from 1.56 to 1.74 [23]. The authors further pointed out that measurement from the functional axis of rotation may better correlate with the series instead of interarticular length. A comparison with a study on 197 cadaveric subjects by Hamilton and Dunsmuir revealed that measurements based on functional axis of rotation only better approximated the Golden Ratio in some cases [24]. In their study, the centres of rotation for the metacarpophalangeal, proximal interphalangeal and distal interphalangeal joints were approximated for each ray by flexing and extending the phalanx distal to the joint with its wire marker.

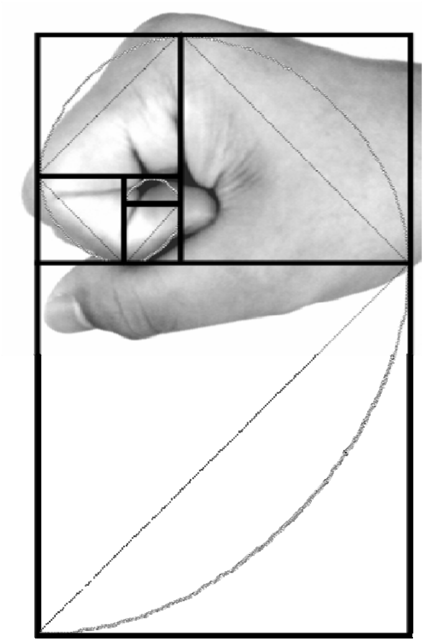

Fig. 2. Human hand superimposed on the equiangular logarithmic spiral. This diagram shows the relationship of the Fibonacci sequence to the functional axis of rotation of the hand joints

In line with this thinking, we performed a similar study using palmar flexion creases, which represent periarticular tissue strain from tensile and compressive forces during joint movement, as anatomical surrogates for the functional axis of rotation of the hand joints. Interestingly, our preliminary results agreed closely with the findings of Hamilton and Dunsmuir (Chan and Chang, unpublished results). Taken together, the current studies do support the mathematical relation of the Golden Ratio to form and functional optimization of the hand, although they are limited by small sample sizes and sub-ideal methodology to give definite results. A more robust method to obtain functional axis of rotation using computer guidance and motion analysis would provide more conclusive evidence.

Evaluation of the hypothesis

There is by far strong evidence for a unique relationship of the human hand to the heart, through the demonstration of the embryologic, etiologic and molecular connection of hand-heart defects, as well as the Golden Ratio as the patterning law in relation to their form and function. A possible counterargument to the hypothesis may be that the relation of hand-heart structure with the Golden Ratio is a spurious association due to chance. As proof-of-concept, we may design both in vitro and in vivo studies to strengthen the hypothesis further. In vitro studies that may support the relationship of the Golden Ratio to hand-heart form and function include genetic-molecular correlations. Specifically, one could compare function of genes involved in hand-heart patterning, such as those mentioned above [8-11], with degree of deviation of digit proportion or myocardial fibre orientation from the Golden Ratio. The ultrastructure of the hand and heart can also be further dissected in order to understand the intricate proportional relationship among cytoskeletal proteins that make up skeletal and cardiac myofibrils, respectively.

Deregulation of the underlying patterning law may manifest as variation in hand-heart structure away from that as would be determined by the Golden Ratio. Deviation from the Golden Ratio in hand proportion could possibly correlate with a similar interruption of the helical ventricular myocardial band and perhaps even of the coronary network, resulting in compromise of cardiac structure and function. If true, this speculation may turn out to have important medical implications in terms of disease screening and prediction.

Deviation from the underlying Golden ratio that governs the arrangement of myocardial fibres may correlate with developmental anomaly of the fetal heart, thereby affecting cardiac function. In the normal cardiac structure, clockwise and counterclockwise spirals are present at the apex, previously known as the bulbospiral and sinospiral loops. At 25 days of life, a venous and an arterial system as well as single pump form. At 30 days, the embryologic heart develops a patent ventricular septal defect and an atrial septal defect and the defect is closed by an atrial and ventricular septum respectively at 50 days of life [14]. Due to the importance of congenital heart disease in relation to infant mortality, the identification of fetal cardiac abnormalities has been the subject of great interest. The current standard, antenatal ultrasound screen involves a four chamber view of the fetal heart which is able to detect major distortions of cardiac anatomy. Unfortunately, the sensitivity for major heart disease has been highly inconsistent due to variable operator experience, gestational age, maternal obesity, fetal position, and type of defect [25]. In particular, anterior ventricular septal defects and outflow tract abnormalities that do not distort the four chamber view (e.g. transposition of the great arteries) are easily undetected. As discussed, interruption of the spiral heart pattern can result in congenital heart defects such as atrial-ventricular septal defects and transposition of great arteries. If the hypothesis holds true, screening for fetal hand disproportion away from that predicted by the Fibonacci Series may predict co-existing cardiac defects.

Selecting children and young adults as the target group, a prospective clinical study may be carried out looking at how hand proportion eventually affects an individual's risk of a well-defined cardiac condition such as heart failure as a result of ischemic heart disease [26]. Apart from the well-described spiral structure relating the Golden Ratio to myocardial form and function, a previous large study involving 1533 patients with ST-segment elevation myocardial infarction has shown the Fibonacci Series to be associated with the distribution of coronary artery lesions [13], supporting the importance of the Golden Ratio in ischemic heart disease. It would be speculated that deviation from the Fibonacci Series should correspond to altered myocardial fibre orientation and further compromise ejection fraction upon ischemic stress [19], as well as a suboptimal coronary reserve for myocardial perfusion. These end points may be objectively measured using 2-dimensional echography or 2-methoxy isobutyl isonitrile (MIBI) perfusion scans. A follow-up autopsy study would then provide the clinico-pathologic correlation. Interestingly, Schaumann in the Birth Defects Original Article Series proposes that palmar creases provide important clues of early fetal development which may be of clinical predictive value of birth defects in otherwise apparently normal infants [24]. Since palmar creases are consequence of the joints' functional axis of rotation, hand proportions may theoretically and easily be inferred from inter-crease distance.

Conclusion

Taken together, existing evidence suggest the Golden Ratio is the mathematical basis for optimal hand-heart development. If proven true, this would be the first indication for an arithmetic basis governing fundamental human growth and development. In addition, measurement of hand proportion may be a convenient clinical marker for intrinsic susceptibility to acquired cardiac disease or the presence of congenital heart defects, which may be diagnostically useful in poorer areas without modern equipment.

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