Research Article
Special Issue: Geometric PDEs and Applications

Mohammad Ghomi* and Joel Spruck

Total mean curvatures of Riemannian hypersurfaces

https://doi.org/10.1515/ans-2022-0029
received April 27, 2022; accepted September 22, 2022

Abstract: We obtain a comparison formula for integrals of mean curvatures of Riemannian hypersurfaces via Reilly’s identities. As applications, we derive several geometric inequalities for a convex hypersurface $\Gamma$ in a Cartan-Hadamard manifold $M$. In particular, we show that the first mean curvature integral of a convex hypersurface $\gamma$ nested inside $\Gamma$ cannot exceed that of $\Gamma$, which leads to a sharp lower bound for the total first mean curvature of $\Gamma$ in terms of the volume it bounds in $M$ in dimension 3. This monotonicity property is extended to all mean curvature integrals when $\gamma$ is parallel to $\Gamma$, or $M$ has constant curvature. We also characterize hyperbolic balls as minimizers of the mean curvature integrals among balls with equal radii in Cartan-Hadamard manifolds.

Keywords: Reilly’s formulas, quermassintegral, mixed volume, generalized mean curvature, hyperbolic space, Cartan-Hadamard manifold

MSC 2020: Primary: 53C20, 58J05, Secondary: 52A38, 49Q15

1 Introduction

Total mean curvatures of a hypersurface $\Gamma$ in a Riemannian $n$-manifold $M$ are integrals of symmetric functions of its principal curvatures. These quantities are known as quermassintegrals or mixed volumes when $\Gamma$ is convex and $M$ is the Euclidean space. They are fundamental in geometric variational problems, as they feature in Steiner’s polynomial, Brunn-Minkowski theory, and Alexandrov-Fenchel inequalities [11,14,19,20], which were all originally developed in Euclidean space. Extending these notions to Riemannian manifolds has been a major topic of investigation. In particular, total mean curvatures have been studied extensively in hyperbolic space in recent years [2,22–24]. Here, we study these integrals in the broader setting of Cartan-Hadamard spaces, i.e., complete simply connected manifolds of nonpositive curvature and generalize a number of inequalities that had been established in Euclidean or hyperbolic space.

The main result of this article, Theorem 3.1, expresses the difference between the total $r$th mean curvatures of a pair of nested hypersurfaces $\Gamma$ and $\gamma$ in a Riemannian manifold $M$ in terms of the sectional curvatures of $M$ and the principal curvatures of a family of hypersurfaces that fibrate the region between $\Gamma$ and $\gamma$. This formula simplifies when $r = 1$, $\Gamma$ and $\gamma$ are parallel, or $M$ has constant curvature, leading to a number of applications. In particular, we establish the monotonicity property of the total first mean curvature for nested convex hypersurfaces in Cartan-Hadamard manifolds (Corollary 4.1). This leads to a
sharp lower bound in dimension 3 for the total first mean curvature in terms of the volume bounded by $\Gamma$ (Corollary 4.3), which generalizes a result of Gallego-Solanes in hyperbolic 3-space [10, Cor. 3.2]. We also extend to all mean curvatures some monotonicity results of Schroeder-Strake [21] and Borbely [4] for total Gauss-Kronecker curvature (Corollaries 4.4 and 4.5). Finally, we include a characterization of hyperbolic balls as minimizers of total mean curvatures among balls of equal radii in Cartan-Hadamard manifolds (Corollary 4.7).

Theorem 3.1 is a generalization of the comparison result we had obtained earlier in [13] for the Gauss-Kronecker curvature, motivated by Kleiner’s approach to the Cartan-Hadamard conjecture on the isoperimetric inequality [16]. Similar to [13], our starting point here, in Section 2, will be an identity (Lemma 2.1) for the divergence of Newton operators, which were developed by Reilly [18,17] to study the invariants of Hessians of functions on Riemannian manifolds. This formula, together with Stokes’ theorem, leads to the proof of Theorem 3.1 in Section 3. Then, in Section 4, we develop the applications of that result.

2 Newton operators

Throughout this work, $M$ denotes an $n$-dimensional Riemannian manifold with metric $\langle \cdot, \cdot \rangle$ and covariant derivative $\nabla$. Furthermore, $u$ is a $C^{1,1}$ function on $M$. In particular, $u$ is twice differentiable at almost every point $p$ of $M$, and the computations below take place at such a point. The gradient of $u$ is the tangent vector $\nabla u \in T_pM$ given by $\langle \nabla u(p), X \rangle = \langle u_X, p \rangle$ for all $X \in T_pM$. The Hessian operator $\nabla^2 u : T_pM \to T_pM$ is the self-adjoint linear map given by $\nabla^2 u(X) = \nabla_X \nabla u$. The symmetric elementary functions $\sigma_r : \mathbb{R}^n \to \mathbb{R}$, for $1 \leq r \leq k$, and $x = (x_1, \ldots, x_n)$ are defined by

$$\sigma_r(x) = \sum_{i_1 < \cdots < i_r} x_{i_1} \cdots x_{i_r}.$$  

We set $\sigma_0 = 1$ and $\sigma_r = 0$ for $r \geq k + 1$ by convention. Let $\lambda(\nabla^2 u) = (\lambda_1, \ldots, \lambda_n)$ denote the eigenvalues of $\nabla^2 u$. Then, we set

$$\sigma_r(\nabla^2 u) = \sigma_r(\lambda(\nabla^2 u)).$$  

These functions form the coefficients of the characteristic polynomial

$$P(\lambda) = \det(\lambda I - \nabla^2 u) = \sum_{i=0}^n (-1)^i \sigma_i(\nabla^2 u) \lambda^{n-i}.$$  

Let $\delta^i_{h_1 \cdots h_m}$ be the generalized Kronecker tensor, which is equal to 1 (−1) if $i_1, \ldots, i_m$ are distinct and $(j_1, \ldots, j_m)$ is an even (odd) permutation of $(i_1, \ldots, i_m)$; otherwise, it is equal to 0. Then [18, Prop. 1.2(a)],

$$\sigma_i(\nabla^2 u) = \frac{1}{r!} \delta^i_{h_1 \cdots h_r} u_{h_1 h_i} \cdots u_{h_r h_i}, \quad (1)$$  

where $u_{ij} = \nabla_{ij} u$ denote the second partial derivatives of $u$ with respect to an orthonormal frame $E_i \in T_pM$, which we extend to an open neighborhood of $p$ by parallel translation along geodesics. So $\nabla_{E_i}E_j = 0$ at $p$. We call $E_i$ a local parallel frame centered at $p$ and set $\nabla_i = \nabla_{E_i}$. Each of the indices in (1) ranges from 1 to $n$, and we employ Einstein’s convention by summing over repeated indices throughout the article. The Newton operators $\mathcal{T}^r_\lambda : T_pM \to T_pM$ [17,18] are defined recursively by setting $\mathcal{T}^0_\lambda = I$, the identity map, and for $r \geq 1$,

$$\mathcal{T}^r_\lambda = \sigma_r(\nabla^2 u) I - \mathcal{T}^{r-1}_\lambda \circ \nabla^2 u = \sum_{i=0}^r (-1)^i \sigma_i(\nabla^2 u)(\nabla^2 u)^{r-i}.$$  

Thus, $\mathcal{T}^r_\lambda$ is the truncation of the polynomial $P(\nabla^2 u)$ obtained by removing the terms of order higher than $r$. In particular, $\mathcal{T}^r_n = P(\nabla^2 u)$. So, by the Cayley-Hamilton theorem, $\mathcal{T}^n_n = 0$. Consequently, when $\nabla^2 u$ is non-degenerate, (2) yields that
\[ T_{n-1}^u = \sigma_n(V^2 u)(V^2 u)^{-1} = \det(V^2 u)(V^2 u)^{-1} = T^u, \]

where \( T^u \) is the Hessian cofactor operator discussed in [13, Sec. 4]. See [18, Prop. 1.2] for other basic identities that relate \( \sigma \) and \( T \). In particular, by [18, Prop. 1.2(c)], we have \( \text{Trace}(T^u \cdot V^2 u) = (r + 1)\sigma_{r+1}(V^2 u) \). So, by Euler’s identity for homogeneous polynomials,

\[ (T^u)_{ij} u_{ij} = \text{Trace}(T^u \cdot V^2 u) = (r + 1)\sigma_{r+1}(V^2 u) = \frac{\partial\sigma_{r+1}(V^2 u)}{\partial u_{ij}} u_{ij}. \]

Thus, it follows from (1) that

\[ (T^u)_{ij} = \frac{\partial\sigma_{r+1}(V^2 u)}{\partial u_{ij}} = \frac{1}{r!} \delta_{\delta i j \ldots k} u_{i j k} \cdots u_{i j k}, \]

Furthermore, by [17, Prop. 1(11)] (note that the sign of the Riemann tensor \( R \) in [17] is opposite to the one in this article), we have

\[ (\text{div}(T^u)) = \frac{1}{(r-1)!} \delta_{\delta i j \ldots k} u_{i j k} \cdots u_{i j k} - R_{\delta i j k} u_{\delta i j}, \]

where \( R_{\delta i j k} = R(E_i, E_j, E_k, E_l) = \langle \nabla_i E_k - \nabla_k E_i, E_j \rangle \). Another useful identity [17, p. 462] is

\[ \text{div}(T^u) = \langle T^u, V^2 u \rangle + \langle \text{div}(T^u), V u \rangle, \]

where \( \langle \cdot, \cdot \rangle \) here indicates the Frobenius inner product (i.e., \( \langle A, B \rangle = A_{ij}B_{ij} \) for any pair of matrices of the same dimension). The divergence of \( T^u \) may be defined by virtually the same argument used for \( T^u \) in [13, Sec. 4] to yield the following generalization of [13, (14a)]:

\[ (\text{div}(T^u)) = \nabla(T^u). \]

Recall that \( T^u = T_{n-1}^u \) by (3). Furthermore, \( T^u = 0 \) as we mentioned earlier. Thus, the following observation generalizes [13, Lem. 4.2].

**Lemma 2.1.**

\[ \text{div}\left(T^u \left( \frac{V u}{|V u|^r} \right) \right) = \left( \text{div}(T^u), \frac{V u}{|V u|^r} \right) + \frac{r \langle T^u(V u), V u \rangle}{|V u|^{r+2}}. \]

**Proof.** By Leibniz rule and (8), we have

\[ \text{div}\left(T^u \left( \frac{V u}{|V u|^r} \right) \right) = \nabla\left(T^u \left( \frac{V u}{|V u|^r} \right) \right) = \left( \text{div}(T^u), \frac{V u}{|V u|^r} \right) + \frac{r \langle T^u(V u), V u \rangle}{|V u|^{r+2}}, \]

where the computation to obtain the second term on the right is identical to the one performed earlier in [13, Lem. 4.2]. To develop this term further, note that by (2)

\[ (T^u)_{ij} u_{ij} = \sigma_i(V^2 u)\delta_{ij} - (T^u)_{ij}, \]

which in turn yields

\[ (T^u)_{ij} u_{ij} \frac{u_{ij}}{|V u|^2} = \sigma_i(V^2 u) - (T^u)_{ij} \frac{u_{ij}}{|V u|^2}. \]

Hence,

\[ (T^u)_{ij} \left( \frac{u_{ij}}{|V u|^2} - \frac{u_{ij} u_{ij}}{|V u|^{r+2}} \right) = \sigma_i(V^2 u) - \frac{r \sigma_i(V^2 u) - (T^u)_{ij} \frac{u_{ij}}{|V u|^2}}{|V u|^2} = r(T^u)_{ij} \frac{u_{ij}}{|V u|^{r+2}}, \]

which completes the proof. \( \square \)
Below we assume, as was the case in [13, Sec. 4], that all local computations take place with respect to a principal curvature frame \( E_i \in T_p M \) of \( u \), which is defined as follows. Assuming \( |Vu(p)| \neq 0 \), we set \( E_n = \nabla u(p)/|Vu(p)| \), and let \( E_1, \ldots, E_{n-1} \) be the principal directions of the level set of \( u \) passing through \( p \). Then, we extend \( E_i \) to a local parallel frame near \( p \). The first partial derivatives of \( u \) with respect to \( E_i \), \( u_i = \nabla_i u \), satisfy

\[
    u_i = 0; \text{ for } i \neq n, \quad \text{and} \quad u_n = |Vu|.
\]

Furthermore, for the second partial derivatives, \( u_{ij} = \nabla_i \nabla_j u \), we have

\[
    u_{ij} = 0, \quad \text{for } i \neq j \leq n - 1, \quad \text{and} \quad \frac{u_{ij}}{|Vu|} = \kappa_i^u, \quad \text{for } i \neq n,
\]

where \( \kappa_i^u, \ldots, \kappa_n^u \) are the principal curvatures of level sets of \( u \) with respect to \( \kappa \), satisfy of the shape operator \( \kappa \), with respect to \( u \), are the \( \kappa_i^u \). Let \( X^\nu \) be the corresponding principal directions. Then, for passing through \( p \), we have

\[
    D_{\nu} X^\nu = \nabla_{\nu} X^\nu + \nabla_{\nu p} X^\nu.
\]

Moreover, for the second partial derivatives, \( u_{ij} = \nabla_i \nabla_j u \), we have

\[
    u_{ij} = 0, \quad \text{for } i \neq j \leq n - 1, \quad \text{and} \quad \frac{u_{ij}}{|Vu|} = \kappa_i^u, \quad \text{for } i \neq n,
\]

where \( \kappa_i^u, \ldots, \kappa_n^u \) are the principal curvatures of level sets of \( u \) with respect to \( \kappa \), i.e., they are eigenvalues corresponding to \( E_1, \ldots, E_{n-1} \) of the shape operator \( X \mapsto \nabla X \) on the tangent space of level sets of \( u \), where \( \nu = \nabla u/|Vu| \). We set \( \kappa_u = (\kappa_1^u, \ldots, \kappa_n^u) \). So \( \sigma_r(u) \) is the \( r \)th mean curvature of the level set of \( u \) at \( p \). In particular, \( \sigma_n(u) \) is the Gauss-Kronecker curvature of the level sets. The next observation generalizes [13, Lem. 4.1].

**Lemma 2.2.**

\[
    \sigma_r(u) = \frac{\langle T^u_r(\nabla u), \nabla u \rangle}{|Vu|^{r+2}}.
\]

**Proof.** (5) together with (9) and (10) yields that

\[
    (T^u_r)_{ij} \frac{u_{ij}}{|Vu|^{r+2}} = \frac{1}{r!} \delta_{m_1 \cdots m_r}^{i_1 \cdots i_r} u_{i_1 \cdots i_r} \frac{u_{ij}}{|Vu|^{r+2}} = \frac{1}{r!} \delta_{m_1 \cdots m_r}^{i_1 \cdots i_r} \frac{u_{i_1 \cdots i_r}}{|Vu|^r} \frac{u_{ij}}{|Vu|^{r+2}} = \frac{1}{r!} \delta_{m_1 \cdots m_r}^{i_1 \cdots i_r} \kappa_i^u \kappa_j^u.
\]

\[\square\]

### 3 Comparison formula

Here, we establish the main result of this work. For a \( C^{1,1} \) hypersurface \( \Gamma \) in a Riemannian \( n \)-manifold \( M \), oriented by a choice of normal vector field \( \nu \), and \( 0 \leq r \leq n - 1 \), we let

\[
    M_r(\Gamma) = \int_\Gamma \sigma_r(\kappa)
\]

be the total \( r \)th mean curvature of \( \Gamma \), where \( \kappa = (\kappa_1, \ldots, \kappa_{n-1}) \) denotes principal curvatures of \( \Gamma \) with respect to \( \nu \). Note that \( M_0(\Gamma) = |\Gamma| \), the volume of \( \Gamma \), since \( \sigma_0 = 1 \), and \( M_{n-1}(\Gamma) \) is the total Gauss-Kronecker curvature of \( \Gamma \) (denoted by \( \mathcal{G}(\Gamma) \) in [13]). A domain \( \Omega \subset M \) is an open set with a compact closure \( \text{cl}(\Omega) \). If \( \Gamma \) bounds a domain \( \Omega \), then by convention we set \( M_r(\Gamma) = |\Omega|, \) the volume of \( \Omega \). The following theorem generalizes [13, Thm. 4.7], where this result had been established for \( r = n - 1 \). It also uses less regularity than was required in [13, Thm. 4.7].

**Theorem 3.1.** Let \( \Gamma \) and \( y \) be closed \( C^{1,1} \) hypersurfaces in a Riemannian \( n \)-manifold \( M \) bounding domains \( \Omega \) and \( D \), respectively, with \( \text{cl}(D) \subset \Omega \). Suppose there exists a \( C^{1,1} \) function \( u \) on \( \text{cl}(\Omega \setminus D) \) with \( \nabla u \neq 0 \), which is constant on \( \Gamma \) and \( y \). Let \( \kappa^u = (\kappa_1^u, \ldots, \kappa_n^u) \) be the principal curvatures of level sets of \( u \) with respect to \( E_u = \nabla u/|\nabla u| \), and let \( E_1, \ldots, E_{n-1} \) be the corresponding principal directions. Then, for \( 0 \leq r \leq n - 1 \),
Then, we may assume that

\[ M_r(\Gamma) - M_r(y) = (r + 1) \int_{\Omega \setminus D} \sigma_{r+1}(k^n) + \int_{\Omega \setminus D} \left( -\sum_{i=1}^{n} k_i^2 \ldots k_n^2, K_{in} + \frac{1}{|V u|} \sum_{i=1}^{n} k_i^2 \ldots k_n^2 \right) |V u| |_{i, \ldots, R_{ik, \ldots, in}} \]

where \( |V u| := \nabla u \), \( R_{ijkl} = R_{ijkl} \) are components of the Riemann curvature tensor of \( M \), \( K_{ij} = K_{ijkl} \) is the sectional curvature, and the summations take place over distinct values of \( 1 \leq i_1, \ldots, i_r \leq n - 1 \), with \( i_1 < \cdots < i_{r-1} \) in the first sum and \( i_1 < \cdots < i_{r-2} \) in the second sum.

**Proof.** By Lemmas 2.1 and 2.2,

\[
\text{div} \left( T^u_r \left( \frac{\nabla u}{|V u|} \right)^{r+1} \right) = (r + 1) \sigma_{r+1}(k^n) + \left\langle \text{div}(T^u_r), \frac{\nabla u}{|V u|} \right\rangle.
\]

By Stokes’ theorem and Lemma 2.2,

\[
\int_{\Omega \setminus D} \text{div} \left( T^u_r \left( \frac{\nabla u}{|V u|} \right)^{r+1} \right) = \int_{\Omega \setminus D} \left\langle T^u_r \left( \frac{\nabla u}{|V u|} \right)^{r+1}, \frac{\nabla u}{|V u|} \right\rangle = M_r(\Gamma) - M_r(y).
\]

So integrating both sides of (11) yields

\[
M_r(\Gamma) - M_r(y) = (r + 1) \int_{\Omega \setminus D} \sigma_{r+1}(k^n) + \int_{\Omega \setminus D} \left\langle \text{div}(T^u_r), \frac{\nabla u}{|V u|} \right\rangle.
\]

Using (6) and (9), we have

\[
\left\langle \text{div}(T^u_r), \frac{\nabla u}{|V u|} \right\rangle = \frac{1}{(r - 1)!} \delta_{i_0, \ldots, i_r} \frac{u_{i_0} \ldots u_{i_r}}{|V u|} = \frac{1}{(r - 1)!} \delta_{i_0, \ldots, i_r} \frac{u_{i_0} \ldots u_{i_r}}{|V u|} R_{i_1, \ldots, i_r, n},
\]

The last expression may be written as the sum of two components, \( A \) and \( B \), which consist of terms with \( i = n \) and \( i \neq n \), respectively. Note that we may assume \( j_1, \ldots, j_r \neq n \), for otherwise \( \delta_{i_0, \ldots, i_r} = 0 \). To compute \( A \), note that if \( i = n \), then for \( \delta_{i_0, \ldots, i_r} \) not to vanish, we must have \( i_1, \ldots, i_r \neq n \). Then, by (10), \( u_{i_0, i_1} = 0 \) unless \( i_1 = j_1 \), which yields that

\[
A = \frac{1}{(r - 1)!} \delta_{i_0, \ldots, i_r} \frac{u_{i_0} \ldots u_{i_r}}{|V u|} R_{i_1, \ldots, i_r, n} = -\sum k_i^2 \ldots k_n^2 K_{in},
\]

where the sum ranges over all distinct values of \( 1 \leq i_1, \ldots, i_r \leq n - 1 \), with \( i_1 < \cdots < i_{r-1} \) as desired. To find \( B \) note that if \( i \neq n \), then for \( \delta_{i_0, \ldots, i_r} \) not to vanish, we must have \( i_k = n \) for some \( 1 \leq k \leq r \). If \( k = r \), then \( R_{i_1, \ldots, i_r, n} = R_{i_1, \ldots, i_r, m} = 0 \). In particular, \( B = 0 \) when \( r = 1 \). Now assume that \( r \geq 2 \). Then, we may assume that \( k \neq r \) or \( l \neq n \). Then, by (10), \( u_{i_0, i_1} = 0 \) unless \( i = j_1 \). So, we may assume that \( i_k = j_k \) for \( k \neq r \), which in turn implies that \( j_1 = i \). Thus, \( B = \sum_{k=1}^{r-1} B_k \), where

\[
B_k = \frac{1}{(r - 1)!} \delta_{i_0, \ldots, i_r} \frac{u_{i_0} \ldots u_{i_r}}{|V u|} = \frac{1}{(r - 1)!} \sum k_i^2 \ldots k_{i_r}^2 R_{i_1, \ldots, i_r, n} = \frac{1}{(r - 1)!} \sum k_i^2 \ldots k_{i_r}^2 R_{i_1, \ldots, i_r, n},
\]

since \( u_{i_0} = |V u| \). Hence, the sum ranges over all distinct indices \( 1 \leq i, i_1, \ldots, i_{r-1}, i_{k+1}, \ldots, i_{r-1} \leq n - 1 \), with \( i_1 < \cdots < i_{k-1} < i_{k+1} < \cdots < i_{r-1} \). Note that \( B_1 = \cdots = B_{r-1} \). Thus,

\[
B = (r - 1)B_{r-1} = \frac{1}{|V u|} \sum k_i^2 \ldots k_{i_r}^2 |V u| |R_{i_1, \ldots, i_r, n}|,
\]

which completes the proof (after renaming \( i \) to \( i_{r-1} \)).
4 Applications

Here, we develop some consequences of Theorem 3.1. A subset of a Cartan-Hadamard manifold \( M \) is convex if it contains the (unique) geodesic segment connecting every pair of its points. A convex hypersurface \( \Gamma \subset M \) is the boundary of a compact convex set with interior points. If \( \Gamma \) is of class \( C^{1,1} \), then its principal curvatures are nonnegative at all twice differentiable points with respect to the outward normal. Conversely, if the principal curvatures of a closed hypersurface \( \Gamma \subset M \) are all nonnegative, then \( \Gamma \) is convex \([1]\). See \([13, \text{Sec. 2 and 3}]\) for the basic properties of convex sets in Cartan-Hadamard manifolds. A set is nested inside \( \Gamma \) if it lies in the convex domain bounded by \( \Gamma \).

**Corollary 4.1.** Let \( \Gamma \) and \( \gamma \) be \( C^{1,1} \) convex hypersurfaces in a Cartan-Hadamard \( n \)-manifold. Suppose that \( \gamma \) is nested inside \( \Gamma \). Then,

\[
\mathcal{M}(\Gamma) \geq \mathcal{M}(\gamma).
\]

**Proof.** Setting \( r = 1 \) in the comparison formula of Theorem 3.1 yields

\[
\mathcal{M}(\Gamma) - \mathcal{M}(\gamma) = 2 \int_{\Omega \setminus D} \sigma_2(k^u) - \int_{\Omega \setminus D} \text{Ric}\left(\frac{\nabla u}{|\nabla u|}\right),
\]

where Ric stands for Ricci curvature; more explicitly, in a principal curvature frame where \( E_n = \nabla u / |\nabla u| \), \( \text{Ric}(E_n) \) is the sum of sectional curvatures \( K_{in} \), for \( 1 \leq i \leq n - 1 \). So \( \text{Ric}(E_n) \leq 0 \). If \( \Gamma \) and \( \gamma \) are smooth \((C^\infty)\) and strictly convex, we may let \( u \) in Theorem 3.1 be a function with convex level sets \([4, \text{Lem. 1}]\). Then, \( \sigma_2(k^u) \geq 0 \), which yields \( \mathcal{M}(\Gamma) \geq \mathcal{M}(\gamma) \) as desired. This completes the proof since we may approximate \( \Gamma \) and \( \gamma \) by smooth strictly convex hypersurfaces, e.g., by applying the Greene-Wu convolution to their distance functions, see \([12, \text{Lem. 3.3}]\); furthermore, total mean curvatures will converge here since they constitute “valuations” in the sense of integral geometry, see \([13, \text{Note 3.7}] \) or \([3, \text{Prop. 3.8}]\). □

Dekster \([9]\) constructed examples of nested convex hypersurfaces in Cartan-Hadamard manifolds where the monotonicity property in the last result does not hold for Gauss-Kronecker curvature. So the aforementioned corollary cannot be extended to all mean curvatures without further assumptions, which we will discuss below. First, we need to record the following observation.

**Lemma 4.2.** Let \( S_p \) be a geodesic sphere of radius \( p \) centered at a point in a Riemannian manifold. As \( p \to 0 \), \( \mathcal{M}(S_p) \) converges to \( 0 \) for \( r \leq n - 2 \) and to \( |S^n| \) for \( r = n - 1 \).

**Proof.** A power series expansion \([6, \text{Thm. 3.1}]\) of the second fundamental form of \( S_p \) in normal coordinates shows that the principal curvatures of \( S_p \) are given by \( \kappa_p^i = (1 + O(p^2))/p \). So

\[
\sigma_i(k^p) = \binom{n-1}{r} \frac{1}{p^r}(1 + O(p^2)).
\]

Another power series expansion \([15, \text{Thm. 3.1}]\) yields

\[
|S_p| = |S^{n-1}| p^{n-1}(1 + O(p^2)).
\]

So, it follows that

\[
\mathcal{M}(S_p) = \binom{n-1}{r} |S^{n-1}| p^{n-1-r}(1 + O(p^2)),
\]

which completes the proof. □

Gallego and Solanes showed \([10, \text{Cor. 3.2}]\) that if \( \Gamma \) is a convex hypersurface bounding a domain \( \Omega \) in a hyperbolic \( n \)-space of constant curvature \( a < 0 \), then

\[
\mathcal{M}(\Gamma) > -(n-1)^2 a |\Omega|.
\]
When comparing formulas, note that in \[10\], mean curvature is defined as the average of \(\kappa_i\), as opposed to the sum of \(\kappa_i\), which is our convention. Large balls show that the above inequality is sharp. Here, we extend this inequality to Cartan-Hadamard 3-manifolds as follows:

**Corollary 4.3.** Let \(\Gamma\) be a \(C^{1,1}\) convex hypersurface in a Cartan-Hadamard \(n\)-manifold \(M\) bounding a domain \(\Omega\). Suppose that curvature of \(M\) is bounded above by \(a \leq 0\). Then,

\[M_0(\Gamma) > -(n - 1)a|\Omega|.

Furthermore, if \(n = 3\), then

\[M_0(\Gamma) > -4a|\Omega|.

**Proof.** Let \(\gamma = \gamma_0\) in (12) be a geodesic sphere of radius \(\rho\). By Lemma 4.2, \(M_0(\gamma_0) \to 0\) as \(\rho \to 0\), which yields

\[M_0(\Gamma) = 2 \int_{\Omega} \sigma_2(\kappa^u) - \int_{\Omega} \text{Ric} \left( \frac{\nabla u}{|\nabla u|} \right) > -(n - 1)a|\Omega|,

as desired. When \(n = 3\), Gauss’ equation states that

\[\sigma_2(\kappa^u) = K^u - K_M^u,

where \(K^u\) is the sectional curvature of level sets of \(u\) and \(K_M^u\) is the sectional curvature of \(M\) with respect to tangent planes to level sets of \(u\). Thus,

\[M_0(\Gamma) = 2 \int_{\Omega} K^u - 2 \int_{\Omega} K_M^u - \int_{\Omega} \text{Ric} \left( \frac{\nabla u}{|\nabla u|} \right) > -4a|\Omega|,

which completes the proof. \(\Box\)

We say \(\Gamma\) is an outer parallel hypersurface of a convex hypersurface \(\gamma\) if all points of \(\Gamma\) are at a constant distance \(\lambda \geq 0\) from the convex domain bounded by \(\gamma\). Since the distance function of a convex set in a Cartan-Hadamard manifold is convex [5, Prop. 2.4], \(\Gamma\) is convex. Furthermore, \(\Gamma\) is \(C^{1,1}\) for \(\lambda > 0\) [13, Lem. 2.6]. The following corollary generalizes [13, Cor. 5.3] and a theorem of Schroeder-Strake [21, Thm. 3], where this result was established for Gauss-Kronecker curvature; see also [13, Note 6.9].

**Corollary 4.4.** Let \(M\) be a Cartan-Hadamard \(n\)-manifold, and \(\Gamma\) and \(\gamma\) be \(C^{1,1}\) convex hypersurfaces in \(M\). Suppose that \(\Gamma\) is an outer parallel hypersurface of \(\gamma\). Then, \(M_r(\Gamma) \geq M_r(\gamma)\) for \(1 \leq r \leq n - 1\).

**Proof.** We may let \(u\) in Theorem 3.1 be the distance function of the convex domain bounded by \(\Gamma\). Then, \(|\nabla u|\) is constant on level sets of \(u\). So, \(|\nabla u| = 0\) for \(1 \leq i \leq n - 1\), which yields

\[M_r(\Gamma) - M_r(\gamma) \geq (r + 1) \int_{\Omega \setminus D} \sigma_{n+1}(\kappa^u) - a(n - r) \int_{\Omega \setminus D} \sigma_{n-r}(\kappa^u),

where \(a \leq 0\) is the upper bound for sectional curvatures of \(M\). Since \(u\) is convex, \(\sigma_{n}(\kappa^u) \geq 0\), which completes the proof. \(\Box\)

The next result generalizes [13, Cor. 5.2] and observation of Borbely [4, Thm. 1] for Gauss-Kronecker curvature.

**Corollary 4.5.** Let \(M\) be a Cartan-Hadamard \(n\)-manifold with constant curvature, and \(\Gamma\) and \(\gamma\) be \(C^{1,1}\) convex hypersurfaces in \(M\), with \(\gamma\) nested inside \(\Gamma\). Then, \(M_r(\Gamma) \geq M_r(\gamma)\), for \(1 \leq r \leq n - 1\).

**Proof.** Again we may assume that the function \(u\) in Theorem 3.1 is convex [4, Lem. 1]. If \(M\) has constant curvature \(a\), then \(R_{ijkl} = a(\delta_{ik}\delta_{jl} - \delta_{il}\delta_{jk})\). Thus, Theorem 3.1 yields
\[ M_\epsilon(\Gamma) - M_\epsilon(y) = (r + 1) \int_{\Omega \setminus B} \sigma_{r+1}(\kappa^u) - \alpha(n - r) \int_{\Omega \setminus B} \sigma_{r-1}(\kappa^u). \]  

(13)

By assumption \( a \leq 0 \), and since \( u \) is convex, \( \sigma_1(\kappa^u) \geq 0 \), which completes the proof.

The above result had been observed earlier by Solanes [22, Cor. 9]. It is due to the integral formula for quermassintegrals [22, Def. 2.1], which immediately yields that quermassintegrals of convex domains are increasing with respect to inclusion. Monotonicity of total mean curvatures follows due to a formula [22, Prop. 7] relating quermassintegrals to total mean curvatures. As an application of the last corollary, one may extend the definition of total mean curvatures to non-regular convex hypersurfaces as follows. If \( \Gamma \) is a convex hypersurface in a Cartan-Hadamard manifold, then its outer parallel hypersurface at distance \( \epsilon \), denoted by \( \Gamma^\epsilon \), is \( C^{1,1} \) for all \( \epsilon > 0 \) [13, Lem. 2.6]. So \( M_\epsilon(\Gamma^\epsilon) \) is well defined. By Corollary 4.4, \( M_\epsilon(\Gamma^\epsilon) \) is decreasing in \( \epsilon \). Hence, its limit as \( \epsilon \to 0 \) exists, and we may set \( M_\epsilon(\Gamma) = \lim_{\epsilon \to 0} M_\epsilon(\Gamma^\epsilon) \).

Next, we derive a formula that appears in Solanes [22, (1) and (2)] and follows from Gauss-Bonnet-Chern theorems [8,7]; see also [22, Cor. 8]. Here \( k!! \), when \( k \) is a positive integer, stands for the product of all positive odd (even) integers up to \( k \), when \( k \) is odd (even). For \( k \leq 0 \), we set \( k!! = 1 \).

**Corollary 4.6.** Let \( \Gamma \) be a closed \( C^{1,1} \) hypersurface in an \( n \)-manifold \( M \) bounding a domain \( \Omega \). Suppose that \( M \) has constant curvature \( a \), and \( \text{cl}(\Omega) \) is diffeomorphic to a ball. Then,

\[ M_{n-k}(\Gamma) = |S^{n-1}| - \sum_{i=1}^{n-(n \text{ mod } 2)} \frac{(2i - 1)!!(n - 2i - 2)!!}{(n - 2)!!} a^i M_{n-2i-1}(\Gamma). \]

**Proof.** Let \( \phi : \text{cl}(\Omega) \to B^n \) be a diffeomorphism to the unit ball in \( \mathbb{R}^n \) and set \( u(x) = |\phi(x)|^2 \). All regular level sets \( y \) of \( u \) satisfy (13). Furthermore, these level sets are convex near the minimum point \( x_0 \) of \( u \), since \( u \) has positive definite Hessian at \( x_0 \). So by Corollary 4.5, for these small level sets,

\[ M_\epsilon(S) \leq M_\epsilon(y) \leq M_\epsilon(S'), \]

where \( S \) and \( S' \) are geodesic spheres centered at \( x_0 \) such that \( S \) is nested inside \( y \) and \( y \) is nested inside \( S' \). Consequently, by Lemma 4.2, as \( y \) shrinks to \( x_0 \), \( M_{n-k}(\Gamma) \) converges to \( |S^{n-1}| \), while \( M_\epsilon(y) \) vanishes for \( r \leq n - 2 \). Thus, since \( \sigma_0(\kappa^u) = 0 \), (13) yields

\[ M_{n-k}(\Gamma) = |S^{n-1}| - \alpha \int_{\Omega} \sigma_{n-k}(\kappa^u) \]

and

\[ \int_{\Omega} \sigma_r(\kappa^u) = \frac{1}{r} M_{r-k}(\Gamma) + \frac{\alpha(n - r + 1)}{r} \int_{\Omega} \sigma_{r-2}(\kappa^u) \]

for \( r \leq n - 2 \). Using these expressions iteratively completes the proof.

Finally, we include a characterization for hyperbolic balls, which extends to all mean curvatures a previous result of the authors on Gauss-Kronecker curvature [13, Cor. 5.5].

**Corollary 4.7.** Let \( M \) be a Cartan-Hadamard \( n \)-manifold with curvature \( \leq a \leq 0 \), and \( B_\rho \) be a ball of radius \( \rho \) in \( M \). Then, for \( 1 \leq r \leq n - 1 \),

\[ M_r(\partial B_\rho) \geq M_r(\partial B_{\rho}^a), \]

where \( B_{\rho}^a \) denotes a ball of radius \( \rho \) in a manifold of constant curvature \( a \). Equality holds only if \( B_\rho \) is isometric to \( B_{\rho}^a \).
Proof. For $r = n - 1$, the desired inequality has already been established [13, Cor. 5.5]. Suppose then that $r \leq n - 2$. We will show that
\begin{equation}
M_r(\partial B_\rho) \geq (r + 1) \int_{\partial B_\rho} \sigma_{r+1}(\kappa^\nu) - a(n - r) \int_{\partial B_\rho} \sigma_{r-1}(\kappa^\nu) \geq M_r(\partial B_\rho^n).
\end{equation}

Letting $u$ be the distance squared function from the center $o$ of $B_\rho$, and $\gamma$ shrink to $o$ in Theorem 3.1, yields the first inequality in (14) via Lemma 4.2. The principal curvatures of $\partial B_\rho$ are bounded below by $\sqrt{-\rho} \coth(\sqrt{-\rho})$ [16, p. 184], which are the principal curvatures of $\partial B_\rho^n$. Hence, the mean curvatures of $\partial B_\rho$ satisfy
\begin{equation}
\sigma_r(\kappa^\nu) \geq \left(\frac{n - 1}{r}\right)(\sqrt{-\rho} \coth(\sqrt{-\rho}))^r = \sigma^0(\kappa^\nu),
\end{equation}
where $\sigma^0(\kappa^\nu)$ are the mean curvatures of $\partial B_\rho^n$. Furthermore, if $A(\rho, \theta)d\theta$ denotes the volume element of $\partial B_\rho$ in geodesic spherical coordinates, then by [16, (1.5.4)],
\begin{equation}
A(\rho, \theta) = \frac{\sinh(\sqrt{-\rho} \theta)}{\sqrt{-\rho}} = A^0(\rho, \theta),
\end{equation}
where $A^0(\rho, \theta)d\theta$ is the volume element of $\partial B_\rho^n$; see [13, Cor. 5.5]. Thus,
\begin{equation}
\int_{\partial B_\rho} \sigma_r(\kappa^\nu) \geq \int_{\partial B_\rho} \sigma^0(\kappa^\nu)A^0(\rho, \theta)d\theta \int_{\partial B_\rho} \sigma^0(\kappa^\nu),
\end{equation}
which yields the second inequality in (14). If $M_r(\partial B_\rho) = M_r(\partial B_\rho^n)$, then equality holds in the first inequality of (14). So $K_r = a$, i.e., the radial sectional curvatures of $B_\rho$ are constant, which forces $B_\rho$ to have constant curvature $a$ [13, Lem. 5.4]. Hence, $B_\rho$ is isometric to $B_\rho^n$. \hfill \Box

**Funding information**: The research of M.G. was supported by National Science Foundation grant DMS-2202337 and a Simons Fellowship. The research of J.S. was supported by a Simons Collaboration Grant.

**Conflict of interest**: Authors state no conflict of interest.

**References**


